Adaptive strategies for reading with a forced retinal location

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Forcing normal-sighted participants to use a distinct parafoveal retinal location for reading, we studied which part of the visual field is best suited to take over functions of the fovea during early stages of macular degeneration (MD). A region to the right of fixation lead to best reading performance and most natural gaze behavior, whereas reading performance was severely impaired when a region to the left or below fixation had to be used. An analysis of the underlying oculomotor behavior revealed that practice effects were accompanied by a larger number of saccades in text direction and decreased fixation durations, whereas no adjustment of saccade amplitudes was observed. We provide an explanation for the observed performance differences at different retinal locations based on the interplay of attention and eye movements. Our findings have important implications for the development of training methods for MD patients targeted at reading, suggesting that it would be beneficial for MD patients to use a region to the right of their central scotoma.

Keywords: central visual field loss, preferred retinal location, macular degeneration, oculomotor reference, attention, eye movements

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Introduction

Under normal viewing conditions, we continuously scan our environment with saccadic eye movements, bringing important details to the foveal part of the retina. In macular degeneration (MD), the central retina is damaged, such that stimuli that are projected to the fovea appear as strongly blurred or even absent. As a result, MD patients often loose their ability to read (Trauzettel-Klosinski & Tornow, 1996). Restoring this ability is one of the most important goals for MD patients (Elliott et al., 1997).

According to the World Health Organization, MD is the leading cause of blindness in developed countries (see also Friedman et al., 2004). In the United States, more than 1.75 million individuals are affected, with a prevalence of 11.8% for advanced stages of MD above the age of 80 (Friedman et al., 2004). So far, damage to the retina caused by MD cannot be reversed; medical treatment can at best slow down the progress of the disease (Rattner & Nathans, 2006).

To compensate for their central visual field loss, MD patients have to learn to move their eyes such that a target is projected to an intact peripheral part of the retina instead of the fovea. The peripheral retinal location a patient chooses for detailed vision is called pseudofovea (Guez, Le Gargasson, O'Regan, & Rigaudiere, 1993) or preferred retinal location (PRL; Timberlake et al., 1986). This strategy typically develops without instructions and often even without the patient noticing a change in gaze behavior (Fletcher, Schuchard, & Watson, 1999).

Most MD patients develop a PRL to the left or below the central scotoma in visual field coordinates (Fletcher & Schuchard, 1997; Guez et al., 1993; Sunness, Applegate, Haselwood, & Rubin, 1996; Trauzettel-Klosinski & Tornow, 1996; White & Bedell, 1990), which corresponds to preferred retinal locations to the right or above the fovea in retinal coordinates. We will refer to visual field coordinates in the remaining article when describing nonfoveal viewing.

It is controversial whether a PRL to the left or below the central scotoma is optimal for reading. There are

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different factors that allow arguing for different preferred retinal locations: Attentional resolution (He, Cavanagh, & Intriligator, 1996; Mackeben, 1999) as well as reading speed (Fine & Rubin, 1999; Petre, Hazel, Fine, & Rubin, 2000) have been reported to be highest in the lower visual field, suggesting that patients might benefit from a PRL below the central scotoma. In contrast, anatomical studies show an overrepresentation of the horizontal versus the vertical meridian (Curcio & Allen, 1990; Galletti, Fattori, Gamberini, & Kutz, 1999; Van Essen, Newsome, & Maunsell, 1984), indicating performance benefits for preferred retinal locations to the left and right of the central scotoma. It is well known that during reading, the region to the right of the current fixation is attended to plan the upcoming saccade (Rayner, Well, & Pollatsek, 1980), with performance deficits if information from that region is withheld from the reader (De Luca, Spinelli, & Zoccolotti, 1996; Fine & Rubin, 1999; Rayner, Well, Pollatsek, & Bertera, 1982; Trauzettel-Klosinski & Brendler, 1998). This *parafoveal preview benefit* suggests that a PRL to the right of the central scotoma might lead to highest performance. In contrast, the importance to locate the beginning of a text line could suggest that a PRL to the left of the central scotoma should be chosen (Guez et al., 1993).

Despite the unresolved debate concerning the best candidate preferred retinal location (for a review, see Cheung & Legge, 2005), several studies recommend developing a PRL below the central scotoma, that is, placing the central scotoma above any visual target (Faye, 1984; Nilsson, Frennesson, & Nilsson, 2003; Peli, 1986).

In the light of the aforementioned considerations, it is not surprising that there is no consensus among practitioners about the criteria for choosing the best suited preferred retinal location (Stelmack, Massof, & Stelmack, 2004), albeit its high clinical relevance.

Anatomical, attentional, and functional asymmetries lead to conflicting predictions regarding the best candidate PRL, and these predictions have not yet been convincingly tested against each other. We address this question in a within-subjects design, as described below.

Our aims were two-fold: (1) to find out empirically the retinal location that is best suited for substituting the fovea in normal-sighted participants and (2) to investigate the mechanisms underlying performance differences between different retinal locations. Note that using normal-sighted participants allowed us investigating oculomotor behavior corresponding to the initial development of a PRL.

We developed an experimental reading procedure that blurs all visual information on the retina except within a small circumscribed region, thus forcing the reader to focus attention on an off-foveal location (*forced retinal location,* FRL; see Figure 1). We trained normal-sighted participants to read with an FRL, which could either be 2.41° to the left, below, or to the right of fixation. We compared these three locations since the controversy in the literature described above concentrates on them. To separate the effects of visual blur and a restricted field of view per se from those of the off-foveal location, we also studied reading when the nonblurred region was centered on the fovea.

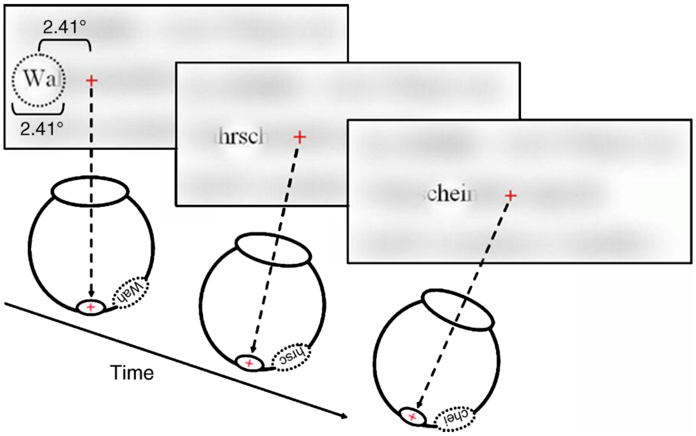

Figure 1. Illustration of the gaze-contingent display (for technical details, see Appendix A). The cross (not shown during the experiment) marks a sequence of fixation positions made by a participant. The whole display except a small circular window is blurred. The forced retinal location moves with the eye (example shown: FRL-Left).

Our results show highest reading rates for FRL-Right, intermediate reading rates for FRL-Left, and lowest reading rates for FRL-Below. Fixation durations were longest under FRL-Below. These results are in contrast to several studies suggesting a preference for a performance advantage for a PRL below (Fine & Rubin, 1999; Nilsson et al., 2003; Petre et al., 2000) or to the left of the central scotoma (Guez et al., 1993). Our data suggest that reading performance with an FRL is strongly modulated by the interaction between shifts of attention and eye movements, with highest reading rates when the direction of attention shifts and eye movements are in spatial register.

Methods

General

We used a gaze-contingent display that forced healthy participants to use a particular retinal location when reading single lines of text. The retinal location for reading was controlled by blurring the display except at a small region with location fixed relative to momentary gaze position (see Figures 1 and A1). This forced participants to extract visual information from the nonblurred area, which always fell on a particular part of the retina. We called this nonblurred area *forced retinal location* in contrast to the naturally occurring *preferred retinal location*. Reading performance at different PRLs was compared across five 1-hour sessions, with participants serving as their own control.

Participants

Six participants from Technical University Braunschweig (5 female, mean age 28.5 years) participated in experiment 1. Six different participants (all female, mean age 26.3 years) were tested in experiment 2. Each participant performed five 1-hour sessions and received 7,50 per hour or credit points for course requirements. All participants had normal or corrected-to-normal visual acuity.

Apparatus

Eye movements from both eyes were recorded by a video-based eye tracking system (EyeLink I; for further details, see Appendix A). Stimuli were presented on an Iiyama Vision Master 451 monitor (18 in.), with screen resolution of 800 × 600 pixel and refresh rate of 85 Hz. The monitor was positioned 76 cm from the participant. Gaze-contingent stimulus presentation and randomization was programmed in C, using the MS Visual C++ 6.0 platform.

Participants wore a headband with cameras attached. At the start of each block of trials, a gaze calibration task was performed, which required fixating targets that randomly appeared on a 3 by 3 grid. To validate the accuracy of the recorded positions, calibration was repeated with the same 9 points. Calibration was repeated if gaze position deviated from the initial calibration measurements by more than 0.5 degrees. A chin rest was used to minimize head movements.

Design

In both experiments, FRL was varied as a within-subjects factor. In experiment 1, FRL was either to the left (FRL-Left) or below (FRL-Below) fixation, and in experiment 2, FRL was either to the left or to the right (FRL-Right) of fixation. In both experiments, an additional control condition with FRL at the center of fixation (FRL-Centre) served as a baseline.

FRL was defined by its center coordinates relative to fixation, which were −2.41°/0° (FRL-Left), 0°/2.41° (FRL-Below), 2.41°/0° (FRL-Right), and 0°/0° (FRL-Centre) visual angles, respectively. FRL was constant within but varied between blocks of on average 19 trials for the experimental conditions and 11 trials for the control condition in a counterbalanced order (for further details, see Layout of experimental sessions section).

Task

On each trial, participants had to read a single line of text, nonblurred at the FRL only. They indicated by button press when they finished reading, which ended the trial. Reading rates (words per minute) are based on these finishing times. Silent rather than overt reading was used to minimize slippage of the eye-tracker headband due to head movement. After each block of trials, text comprehension was tested by a single content question, which was read to the participant and was to be answered orally.

Material

Stimulus material were excerpts from the novel “Der Ruinenbaumeister” (Rosendorfer, 2000). Text was presented in single horizontal lines, extending 10.6° on average. The text line was sandwiched between two lines of pseudotext 2.1° above and below to resemble normal reading conditions. The pseudotext consisted of word-like letter strings, randomly arranged from text lines from other sessions. Text was written in Arial (horizontal × vertical size of lower case letters: 0.42 × 0.48°), with up to 34 letters per line (average: 23.9). Lines contained 4.2 words on average. For each text frame, a blurred version was created applying a Gaussian filter (full width at half maximum: 36 pixel, equal to 1.09°) to the original image (for an example of a blurred and unblurred text frame, see Appendix A and Figure A2). The Gaussian filter was chosen such that bitmaps were blurred strongly enough to delete any information concerning the identity of letters, whereas letter spaces between words and the location of the three text lines were still available.

Trial procedure

Participants started a trial by pressing a button while fixating a dot on the center of the screen. Coordinates of the current fixation were used as the reference point for screen center, thereby removing drift from the data. Each trial started with the presentation of three single dots on a horizontal line for 6 seconds, followed by the presentation of the blurred version of the current text. If the participant did not finish reading the line within 60 s, the trial ended automatically.

Instruction

In the first session, participants were instructed to move as little as possible during eye tracking. After a practice block of normal text reading, further instructions on reading with an FRL were given. Because pilot studies had shown that reading under these conditions is extremely demanding, participants were informed that the FRL is centered on the target word if they fixate the appropriate neighboring location (e.g., to the right of a word in the FRL-Left condition). At the beginning of each block, participants were informed about the upcoming forced retinal location.

Layout of experimental sessions

Participants served five 1-hour sessions, with five blocks per session. The first four blocks consisted of two successive blocks of the two experimental conditions (experiment 1: FRL-Left vs. FRL-Below; experiment 2: FRL-Left vs FRL-Right) each, with order of conditions counterbalanced across participants and sessions. The fifth block contained the control condition (FRL-Centre). To permit keeping track of the narrative content, trial blocks terminated at the end of logical units within a text passage. Due to this constraint, experimental blocks were of unequal length, consisting of 17 to 24 trials and control blocks of 9 to 13 trials. Altogether, participants read either 191 or 195 single lines under the experimental conditions and 53 lines under the control condition. Reading performance was assessed by reading rate (words per minute), number of fixations per text line, fixation duration, saccade direction, and amplitude.

Data analysis

Eye movements were identified as saccades when velocity exceeded 30°/sec or acceleration exceeded 8000°/sec^2. Further analysis was carried out using MATLAB 7.1 and SPSS.

Off-screen fixations were removed from the data. All reported statistics are based on these preprocessed data. Since initial tests showed no difference in the eye movement patterns between left and right eye, data from the left eye are reported.

Reading rates in terms of words per minute as well as fixation durations were summarized by trimmed means per participant and condition, trimming 5% from the left and right tails of the sample, respectively (Wilcox, 1997). Since t tests revealed no significant difference between the two experiments, data for FRL-Left and FRL-Centre were collapsed across the two experiments.

Reading rates and fixation durations were subjected to separate 4 × 5 repeated-measures ANOVAs, with FRL (Centre, Right, Left, Below) and experimental session (sessions 1–5) as within-subject factors. Degrees of freedom were adjusted by the Huyn–Feldt procedure when appropriate (associated p-values denoted as p_{HF}).

Overall gaze direction was computed by (a) determining horizontal and vertical saccade amplitudes of successive saccades (see Figure 7), (b) classifying saccade directions into either of the four main directions (forward, backward, upward, downward), (c) trimming saccade amplitudes separately per participant and condition as described above, and (d) computing mean amplitudes and frequencies based on these trimmed amplitudes.

Mean trimmed frequencies and saccade amplitudes were subjected to a 4 × 4 × 5 repeated-measures ANOVA, with FRL (Centre, Right, Left, Below), saccade direction (forward, backward, upward, downward), and experimental session (sessions 1–5) as within-subject factors.

Results

The effect of FRL on reading rate and fixation duration

Figure 2 illustrates that both reading rate and fixation duration strongly depended on FRL: participants reached highest reading rates and shortest fixation durations under FRL-Centre and FRL-Right, whereas they reached lowest reading rates and required longest fixation durations under FRL-Below.

The effect of FRL on reading rate and fixation duration is backed by significant main effects of FRL on reading rate [$F(3, 15) = 22.367$, $p < .0001$] and fixation duration [$F(3, 15) = 3.695$, $p = .036$]. Reading rate differed between all four FRL (for details, see Table 1). Fixation durations were longer under FRL-Below as compared to FRL-Centre and FRL-Left, as revealed by a Helmert contrast comparing fixation duration under FRL-Below with the mean fixation duration under FRL-Centre and FRL-Left [$F(1, 5) = 6.761$, $p = .048$] (for further details, see Table 2).

Reading rates increased monotonically across experimental sessions (Figure 3) for all FRLs [$F(4, 20) = 45.92$, $p < .0001$; linear term of polynomial contrast: $F(1, 5) =$

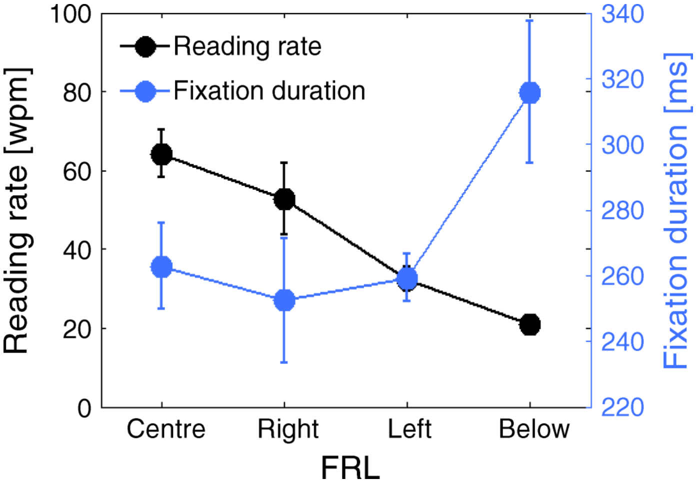

Figure 2. Effect of forced retinal location on reading rate (black; left y-axis) and fixation duration (blue; right y-axis), averaged across participants and experimental sessions. Error bars show the standard error of the mean.

	F(1, 5)	*p*
FRL-Centre vs. FRL-Right	8.110	.036
FRL-Centre vs. FRL-Left	69.391	<.0001
FRL-Centre vs. FRL-Below	48.158	.001
FRL-Right vs. FRL-Left	9.903	.025
FRL-Right vs. FRL-Below	12.237	.017
FRL-Left vs. FRL-Below	12.653	.016

Table 1. Repeated simple contrasts for the effect of FRL on reading rate, averaged across experimental sessions.

104.024; $p < .0001$]. FRL and session did not interact [$F(12, 60) = .974$, $p = .483$]. Separate ANOVAs for each FRL revealed a significant increase of reading rate across experimental session under all forced retinal locations (for further details, see Table 3).

Reading rates differed between FRL even in the last experimental session [$F(3, 15) = 19.754$, $p < .0001$]. There was no difference between FRL-Centre and FRL-Right in the last experimental session. Reading rate was higher under FRL-Right than under FRL-Left and higher under FRL-Left than under FRL-Below (for details, see Table 4).

Figure 4 depicts that fixation duration decreased across experimental sessions [$F(4, 20) = 7.558$, $p = .001$; linear term of polynomial contrast: $F(1, 5) = 17.417$, $p = .009$]. As for reading rate, there was no interaction between FRL and session [$F(12, 60) = .748$, $p = .699$]. Fixation duration decreased across experimental sessions for FRL-Right and FRL-Left, but not for FRL-Centre and FRL-Below (for details, see Table 5).

The effect of FRL on saccade direction

Figures 5 and 6 show example scanpaths observed in the first (Figure 5) and last (Figure 6) session for participants with highest and lowest reading rates. Under FRL-Centre (Figures 5A and 6A), participants moved their eyes in text direction most of the time, with some corrective saccades in the opposite direction. Under FRL-Right (Figures 5B and 6B), most saccades went either in text direction or opposite to text direction, with few saccades directed upward or downward. Similar to reading with FRL-Right, participants mainly made forward and backward saccades under FRL-Left (Figures 5C and 6C), although more fixations were required to read a single text line. A very different pattern emerges under FRL-Below (Figures 5D and 6D): Participants made little systematic movement in reading direction but made a large number of upward and downward saccades.

	F(1, 5)	*p*
FRL-Centre vs. FRL-Right	0.317	.598
FRL-Centre vs. FRL-Left	0.063	.812
FRL-Centre vs. FRL-Below	6.538	.051
FRL-Right vs. FRL-Left	0.260	.632
FRL-Right vs. FRL-Below	3.800	.109
FRL-Left vs. FRL-Below	5.720	.062

Table 2. Repeated simple contrasts for the effect of FRL on fixation duration, averaged across experimental sessions.

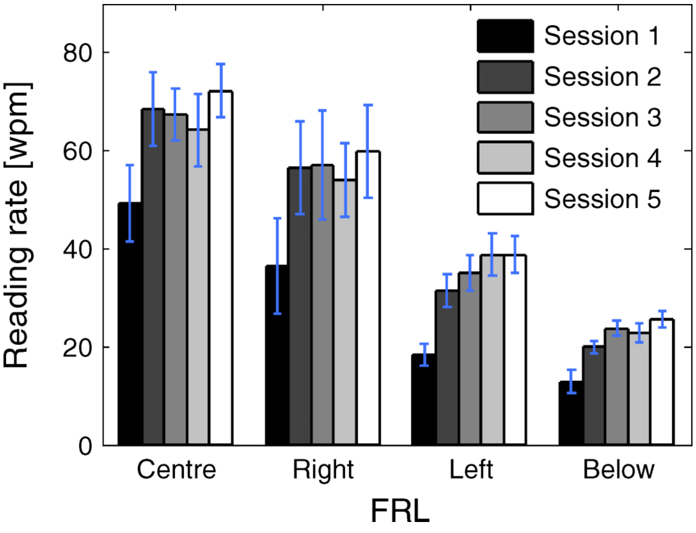

Figure 3. Reading rates as a function of FRL and experimental session. Error bars indicate the standard error of the mean.

To quantify the effect of FRL on saccade direction and amplitude, we determined the horizontal and the vertical saccade amplitude relatively to the previous fixation position (for an illustration, see Figure 7).

Figures 8 and 9 show horizontal and vertical saccade amplitudes as well as the corresponding marginal distributions for the fastest (Figure 8) and slowest (Figure 9) reader, collapsed across experimental sessions. Experimental conditions are shown in separate panels. Under FRL-Centre (Figures 8 and 9, upper middle panel), the horizontal saccade component follows a bimodal distribution: The distribution for forward saccades is narrower and contains more cases than the backward saccade

	Main effect		Linear term of polynomial contrast	
	F(4, 20)	*p*	*F*(1, 5)	*p*
FRL-Centre	6.374	.002	9.254	.029
FRL-Right	7.291	.001	56.129	.001
FRL-Left	24.700	<.0001	47.150	.001
FRL-Below	9.157	<.0001	27.401	.003

Table 3. The effect of experimental session (averaged across blocks) on reading rate, based on separate ANOVAs and polynomial contrasts for each FRL.

	$F(1, 5)$	p
FRL-Centre vs. FRL-Right	4.058	.1
FRL-Centre vs. FRL-Left	48.542	.001
FRL-Centre vs. FRL-Below	55.971	.001
FRL-Right vs. FRL-Left	9.782	.026
FRL-Left vs. FRL-Below	9.669	.027

Table 4. Repeated simple contrasts for the effect of FRL on reading rate in the last experimental session (averaged across blocks).

distribution, i.e., most saccades were in the forward reading direction and had roughly equal amplitudes, whereas backward saccades were less frequent and had shorter, variable amplitudes.

Similar to normal reading, there was little variability in the vertical dimension, evidenced by a narrow, unimodal distribution for the vertical saccade amplitudes.

Under FRL-Right (Figures 8 and 9, upper right panel), most saccades either went in text direction or opposite to text direction, evidenced by horizontal saccade amplitudes that follow bimodal distributions. Vertical saccade components were distributed tightly around zero, indicating that participants managed to keep their eyes on the text line.

Under FRL-Left (Figures 8 and 9, upper left panel), the horizontal saccade component follows a bimodal distribution, whereas the vertical saccade component follows a narrow unimodal distribution. This indicates that participants moved their eyes in text direction or backward most of the time.

Eye movement patterns look very different for FRL-Below (Figures 8 and 9, lower panel): Horizontal saccade amplitudes follow a unimodal distribution with center closely around zero, indicating little systematic saccades in text direction. At the same time, the distribution of vertical saccade amplitudes is clearly much broader. Vertical saccade amplitudes are bimodal for the two fastest participants only, indicating upward and downward saccades of distinct amplitudes, whereas they are unimodal for the remaining participants, indicating saccades of varying amplitudes. This observation implies that the two fastest participants were not able to prevent upward and downward saccades but were able to immediately compensate for them by a corrective saccade of the same amplitude in the opposite direction, thus allowing them to read faster.

	Main effect		Linear term of polynomial contrast	
	$F(4, 20)$	p	$F(1, 5)$	p
FRL-Centre	1.530	.231	3.668	.114
FRL-Right	3.439	.027	28.070	.003
FRL-Left	12.066	<.0001	15.902	.01
FRL-Below	1.150	.362	1.100	.342

Table 5. The effect of experimental session (averaged across blocks) on fixation duration, based on separate ANOVAs and polynomial contrasts for each FRL.

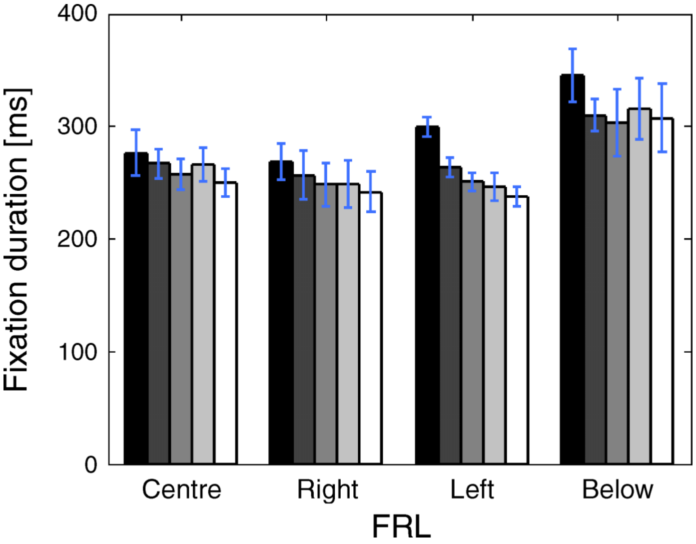

Figure 4. Fixation durations as a function of FRL and experimental session (same color code as in Figure 3).

These observations are summarized in Figure 10, showing percentage of forward, backward, upward, and downward saccades as a function of FRL, averaged across participants and experimental sessions. Averaged across FRLs, 49% of all saccades were directed in text direction, whereas every third saccade (36%) was directed backward. Only a minor part of all saccades was directed upward (7%) or downward (8.4%). This observation is backed by a significant main effect of saccade direction on the percentage of saccades [$F(3,15) = 177.899$, $p < .0001$].

A separate ANOVA for forward saccades revealed that the number of forward saccades was modulated by FRL [$F(3, 15) = 14.805$, $p = < .0001$]: under FRL-Centre and FRL-Right, slightly more than half of all saccades (FRL-Centre: 55.8%, FRL-Right: 56.4%) were directed in text direction. Under FRL-Left, 48.9% of all saccades were directed in text direction, whereas only every third saccade (34.2%) was executed in text direction under FRL-Below. There was a higher percentage of forward saccades under FRL-Centre than under FRL-Left and a higher percentage of forward saccades under FRL-Left than under FRL-Below. There was a trend for more forward saccades under FRL-Right as compared to FRL-Left, whereas there was no difference in the percentage of forward saccades between FRL-Centre and FRL-Right (for details, see Table 6).

The percentage of backward saccades depended on FRL [$F(3, 15) = 23.55$, $p < .0001$]. More backward saccades were observed under FRL-Left than under FRL-Centre [$F(1, 5) = 83.042$, $p < .0001$], and there was a trend for

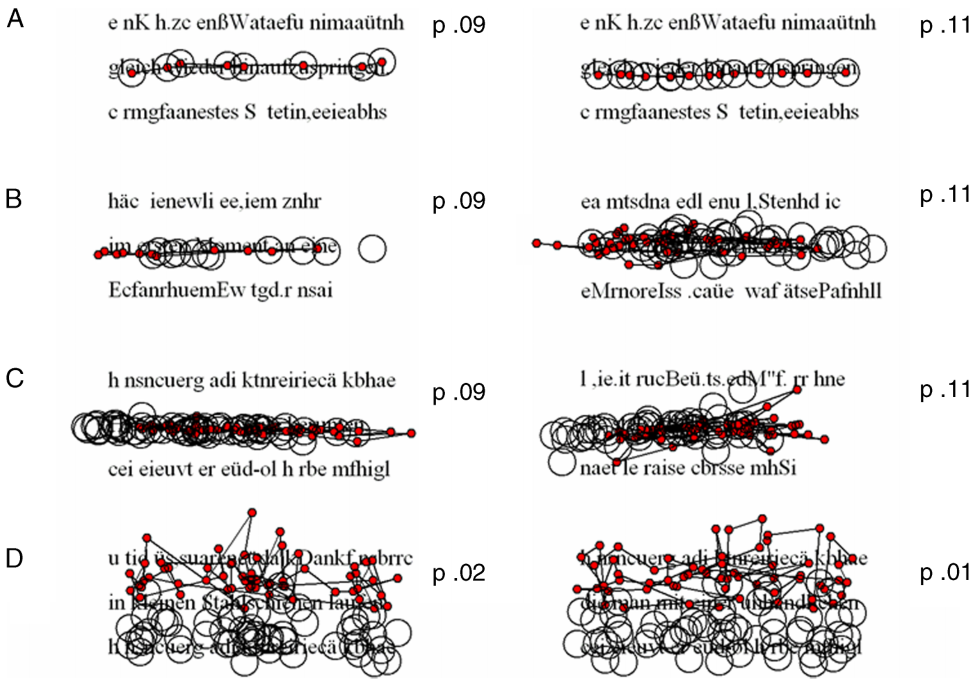

Figure 5. Example scanpaths from the first experimental session for participants with highest (left column) and lowest (right column) reading rates. Red dot shows fixation position, larger circle marks the FRL. (A) FRL-Centre, (B) FRL-Right, (C) FRL-Left, (D) FRL-Below.

less backward saccades under FRL-Right than under FRL-Left [$F(1, 5) = 5.222$, $p = .071$]. Note that even with a central FRL, participants made 35% of backward saccades, which is clearly higher than the number of regressions in normal reading (10–15%; e.g., Rayner, 1998).

Participants made more forward saccades than backward saccades under FRL-Right [$F(1, 5) = 17.853$, $p = .008$], whereas the percentage of forward and backward saccades was about equal under FRL-Left [$F(1, 5) = .754$, $p = .425$].

The percentage of forward, backward, upward, and downward saccades changed across experimental sessions (Figure 11): Averaged across FRL, the percentage of forward saccades increased across experimental sessions

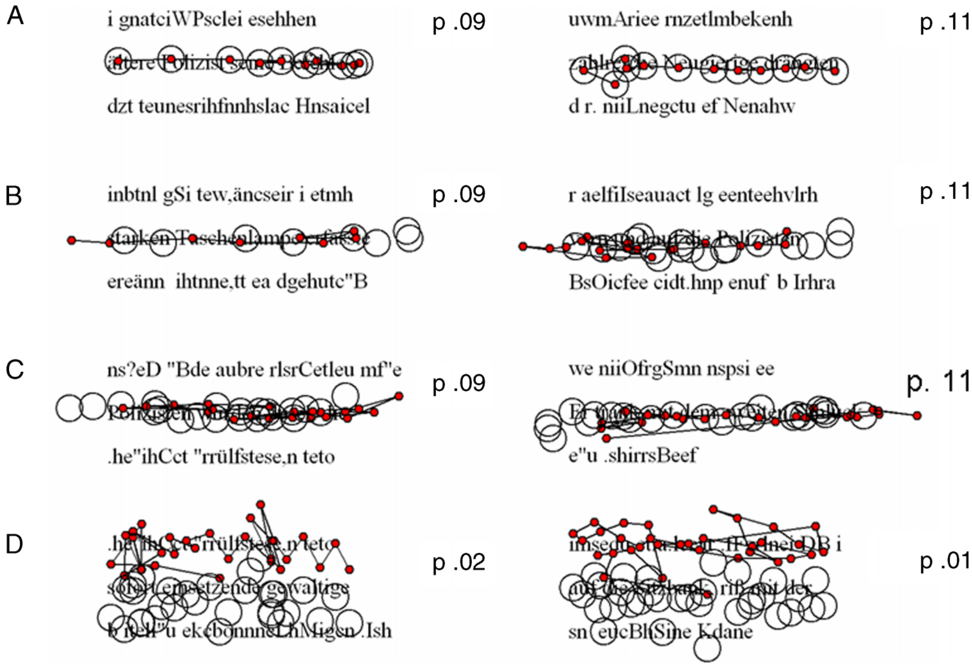

Figure 6. Example scanpaths from the last experimental session for participants with highest (left column) and lowest (right column) reading rates. Red dot shows fixation position, larger circle marks the FRL. (A) FRL-Centre, (B) FRL-Right, (C) FRL-Left, (D) FRL-Below.

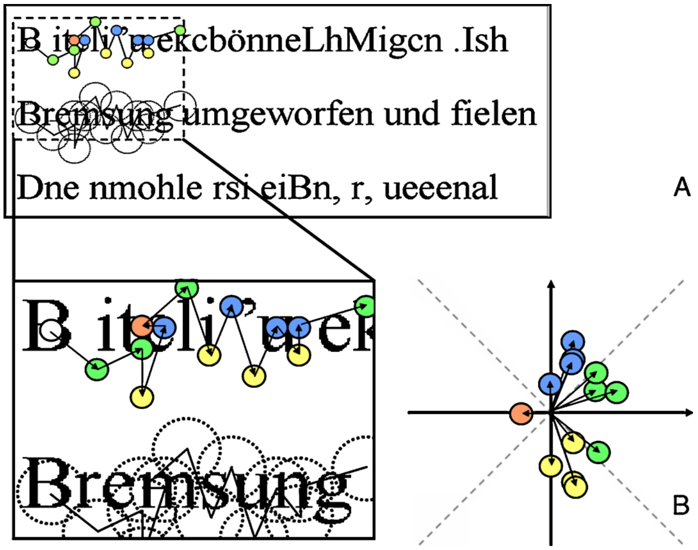

Figure 7. Illustration of the bivariate frequency distributions. For each fixation position, the horizontal and the vertical amplitude component relatively to the previous fixation position is plotted, with the previous fixation position being the center of the coordinate system. (A) Example text with hypothetical eye movement data overlaid. Small colored circles represent fixations, larger dotted circles indicate the corresponding positions of the FRL (in this example, FRL-Below). The inlay gives an enlarged view on the window indicated in panel A. Green: forward saccades; red: backward saccades; blue: upward saccades; yellow: downward saccades. (B) Example bivariate frequency distribution as derived from panel A. Color code is the same as in panel A.

[$F(4, 20) = 6.755$, $p = .001$; linear term of polynomial contrast: $F(1,5) = 9.226$, $p = .029$]. The percentage of backward saccades varied slightly across experimental sessions [$F(4, 20) = 3.008$, $p = .043$], but there was no significant increase or decrease under any of the four different FRL (all $p > .1$). The amount of both upward and downward saccades did not vary consistently across sessions [upward: $F(4, 20) = 1.705$, $p = .188$; downward: $F(4, 20) = 2.312$, $p = .093$]. For all four saccade directions, there was no interaction between FRL and experimental session (all $p > .1$).

The effect of FRL on saccade amplitudes

Figure 12 shows that saccade amplitudes were modulated by the interaction of FRL and saccade direction [$F(9, 27) = 8.5$, $p < .0001$; main effect of saccade direction: $F(3, 9) = 112.685$, $p < .0001$; main effect of FRL: $F(3, 9) = 1.341$, $p = .321$]. Importantly, forward saccade amplitudes were longest under FRL-Right and FRL-Left, intermediate under FRL-Centre, and shortest under FRL-Below. This observation is backed by a significant main effect of FRL on forward saccade amplitude [$F(3, 15) = 15.235$, $p < .0001$]. Forward saccade amplitudes were longer under FRL-Right than under FRL-Centre. Furthermore, forward saccade amplitudes were longer under FRL-Centre as compared to FRL-Below. Forward saccade amplitudes did not differ between FRL-Right and FRL-Left (for details, see Table 7). Note that mean forward saccade amplitudes (5 character spaces) were slightly

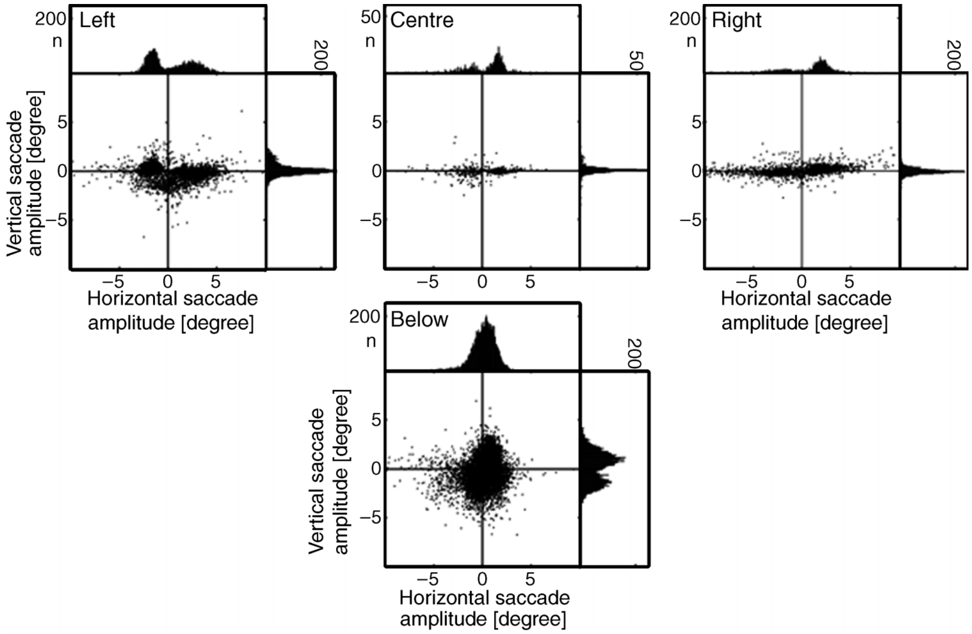

Figure 8. Bivariate frequency distributions of horizontal and vertical saccade components and the corresponding marginal frequency distributions pooled across the whole experiment for participants with highest reading rates in experiment 1 (FRL-Left, FRL-Below, FLR-Centre; participant 2) and experiment 2 (FRL-Right; participant 9).

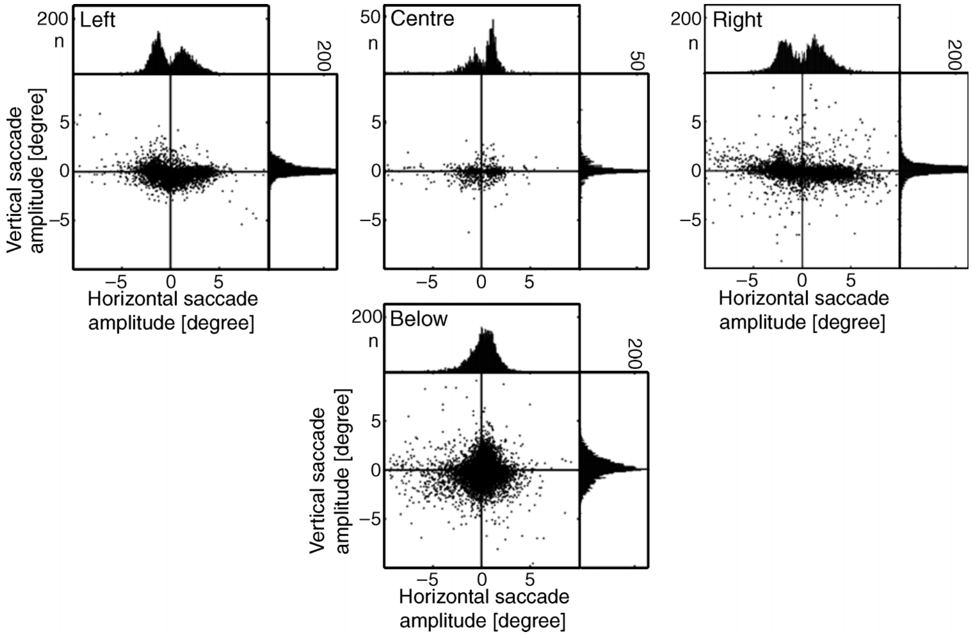

Figure 9. Bivariate frequency distributions for participants with lowest reading rates in experiment 1 (FRL-Left, FRL-Below, FLR-Centre; participant 1) and experiment 2 (FRL-Right; participant 11).

shorter than in normal reading (8 character spaces; Rayner, 1998).

Backward saccade amplitudes were modulated by FRL [*F*(3, 15) = 6.966, *p* = .004]. Backward saccade amplitudes were longer under FRL-Right than under FRL-Centre [*F*(1, 5) = 9.183, *p* = .029] and longer under FRL-Right than under FRL-Left [*F*(1, 5) = 8.805, *p* = .031]. There were no significant differences between the remaining comparisons (all $p > .1$).

The effect of FRL on forward, backward, upward, and downward saccade amplitudes was relatively stable across experimental sessions (Figure 13), as evidenced by a nonsignificant main effect of experimental session [*F*(4, 12) = .858, *p* = .516]. Neither FRL nor saccade direction did interact with experimental session [FRL × session: *F*(12, 36) = .456, *p* = .927; saccade direction × session: *F*(12, 36) = .898, *p* = .557].

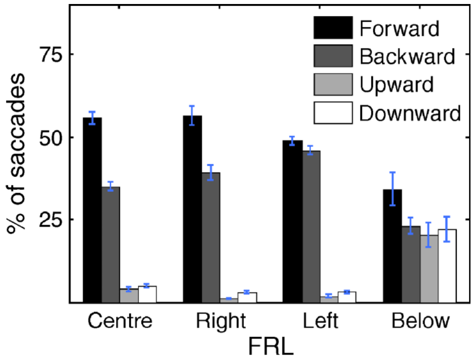

Figure 10. Percentage of forward, backward, upward, and downward saccades as a function of FRL, averaged across participants. Error bars show the standard error of the mean.

Discussion

Forcing normal-sighted participants to read with a distinct retinal location instead of the central fovea, we demonstrated that a forced retinal location to the right of fixation is best suited for reading. Better performance under FRL-Right than under FRL-Left and FRL-Below remained stable across 5 hours of practice (Figure 3), making it unlikely that FRL-Right is overtaken by the other two conditions with even longer practice.

In the following paragraphs, we will discuss our results in the light of the aforementioned anatomical, attentional, and functional asymmetries. We will introduce an alternative account, which suggests that the use of a forced retinal location is influenced by the interplay between

	F(1, 5)	*p*
FRL-Centre vs. FRL-Right	0.036	.858
FRL-Centre vs. FRL-Left	15.464	.011
FRL-Right vs. FRL-Left	4.611	.085
FRL-Left vs. FRL-Below	9.547	.027

Table 6. Repeated simple contrasts for the effect of FRL on the percentage of forward saccades, averaged across experimental sessions.

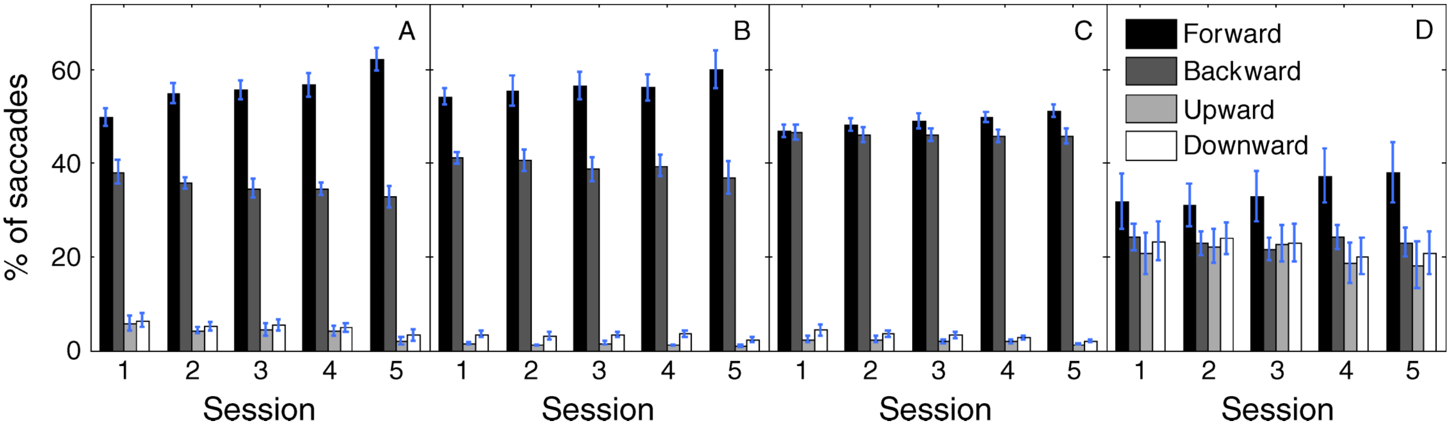

Figure 11. Percentage of forward, backward, upward, and downward saccades as a function of FRL and experimental session (averaged across blocks). (A) FRL-Centre, (B) FRL-Right, (C) FRL-Left, (D) FRL-Below.

attention and eye movements, with best performance if both have to be moved in the same direction.

Anatomical asymmetries

An anatomical overrepresentation of the horizontal meridian (Curcio & Allen, 1990; Galletti et al., 1999; Van Essen et al., 1984) can explain better performance for FRL-Left and FRL-Right with respect to FRL-Below (Figure 2; Table 1). However, such an anatomical asymmetry can neither explain a preference for FRL-Right over FRL-Left nor the patterns of eye movements we observed, in particular fewer and shorter forward saccades and a larger number of upward and downward saccades under FRL-Below as compared to FRL-Left and FRL-Right. Therefore, anatomical asymmetries alone cannot explain the present findings.

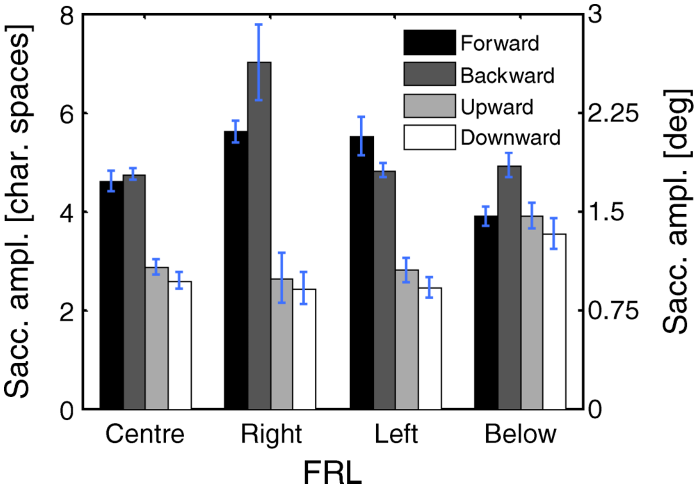

Figure 12. Mean forward, backward, upward, and downward saccade amplitudes (left *y*-axis: character spaces, right *y*-axis: degree) as a function of FRL. Error bars show the standard error of the mean.

Attentional asymmetries

Altpeter, Mackeben, and Trauzettel-Klosinski (2000) observed that preferred retinal locations in MD patients corresponded well with individual regions of superior attentional resolution. These findings suggest that topographic variations of attention might influence the choice of a PRL. However, choosing a location with superior attentional resolution does not necessarily imply that this location leads to better reading performance since most likely more factors than attentional resolution alone determine reading performance at a specific location. In the present study, FRL-Below resulted in lowest reading rates in all participants, despite the fact that typically the lower part of the visual field yields superior attentional resolution (He et al., 1996; Mackeben, 1999).

Functional asymmetries

Models on eye movement control differ with respect to the assumed role of attention (for reviews, see Radach, Inhoff, & Heller, 2002; Rayner, 1998; Starr & Rayner, 2001). Several models assume that covert attention shifts to the region to the right of fixation for selecting the next target location (e.g., Henderson & Ferreira, 1990; Morrison, 1984; Rayner, 1998; Reichle, Pollatsek, Fisher, & Rayner, 1998). In line with this view, the parafoveal

	F(1, 5)	*p*
FRL-Centre vs. FRL-Right	10.058	.025
FRL-Centre vs. FRL-Below	9.784	.026
FRL-Right vs. FRL-Left	.059	.818
FRL-Left vs. FRL-Below	25.806	.004

Table 7. Repeated simple contrasts for the effect of FRL on forward saccade amplitudes (averaged across experimental sessions).

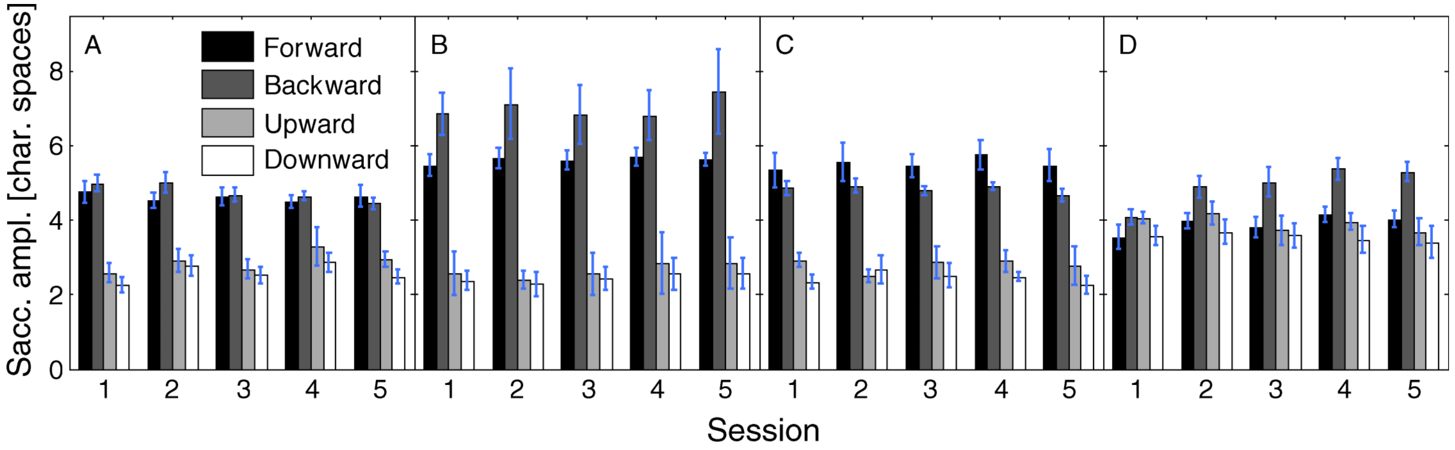

Figure 13. Mean forward, backward, upward, and downward saccade amplitudes (in character spaces) as a function of FRL and experimental session (averaged across blocks). (A) FRL-Centre, (B) FRL-Right, (C) FRL-Left, (D) FRL-Below.

preview benefit (Rayner et al., 1982) describes the finding that reading performance is more severely reduced if information from the right as compared to the left of fixation is withheld. This observation is thought to result from extraction of useful information from the upcoming word that in turn facilitates processing of that word during the next fixation (e.g., Starr & Rayner, 2001). The parafoveal preview benefit predicts severe performance deficits for reading with a PRL to the left of the scotoma since processing of the upcoming word is not possible if the central scotoma is to the right of the PRL. While this prediction is compatible with our data, the parafoveal preview benefit can neither account for the substantial performance difference between FRL-Below and FRL-Left, nor for the observation of fewest and shortest forward saccades under FRL-Below.

In contrast to the present study, Petre et al. (2000) and Fine and Rubin (1999) observed higher reading rates in the lower visual field as compared to the left and right visual field. Note that Petre et al. used an RSVP task that did not require eye movements and therefore could not cause a conflict between shifts of attention and eye movements.

The main observation by Fine and Rubin (1999) is a higher reading rate in the right as compared to the left visual field, which is in line with our current study. Their observation of increased reading rates in the lower visual field is based on an additional experiment they did on the same three participants after they studied reading with the left or the right visual field. It cannot be excluded that their observation is partially affected by practice effects. A further difference between the experiments reported by Fine and Rubin and our study concerns their rectangular mask in contrast to our viewing window (see Methodological considerations section).

The oculomotor reference

When describing the oculomotor behavior of MD patients, it is often implied that patients fixate with their PRL, but this is not necessarily the case: White and Bedell (1990) determined the oculomotor reference of MD patients at various stages of the disease by instructing them to fixate targets and recording the position of the

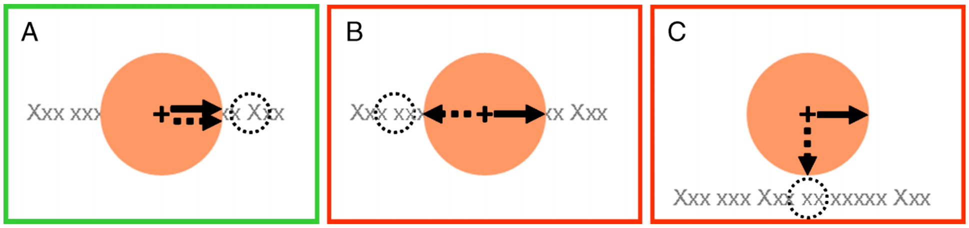

Figure 14. Reading performance as predicted by the conflicting motor activations account with the oculomotor reference at the fovea. Large red disk: central scotoma; letter string: example text line; dotted circle: PRL; +: current gaze position; straight line: required eye movement in text direction; dotted line: required shift of attention toward the PRL. (A) PRL to the right of the central scotoma. (B) PRL to the left of the central scotoma. (C) PRL below the central scotoma. If the oculomotor reference remains at the fovea, best reading performance is predicted for a PRL to the right of the central scotoma (indicated by the green rectangle), whereas worse reading rates are predicted for a PRL to the left and below the central scotoma (red rectangle).

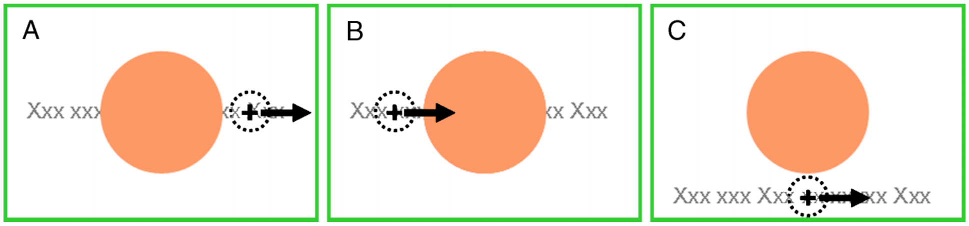

Figure 15. Reading performance as predicted by the conflicting motor activations account with the oculomotor reference at the PRL (same legend as in Figure 14). (A) PRL to the right of the central scotoma. (B) PRL to the left of the central scotoma. (C) PRL below the central scotoma. If the oculomotor reference has shifted to the PRL, the conflicting motor activations account predicts equally good performance for all preferred retinal locations.

target on the retina by means of a fundus camera. Most patients made a foveating saccade before bringing the target to the PRL. Some patients, however, did not require such a foveating saccade, which indicates a shift of the oculomotor reference toward the PRL. A shift of the oculomotor reference was more likely to be observed the longer MD patients suffered from the disease (White & Bedell, 1990), which demonstrates that the oculomotor reference does not easily shift away from the fovea. This view is supported by Heinen and Skavenski (1992), who investigated saccadic adaptation following bilateral foveal lesions in monkeys. Saccade accuracy, measured as the difference between target location and PRL after the initial saccade, increased with practice, but 2 of 3 monkeys did not recover completely even after 2 months. The authors conclude that "…the long time course and incompleteness of the adaptation seen for saccades suggests that the use of the fovea as the origin of the visual signal is particularly resistant to change" (Heinen & Skavenski, 1992, p. 371f). Taken together, these studies suggest that during the first couple of years, the oculomotor reference remains at the fovea whereas visual information is processed at the PRL, thus requiring a shift of attention away from the fovea toward the PRL (see also Altpeter et al., 2000).

Conflicting motor activations

We believe that conflicting motor activations resulting from shifting attention to the FRL and moving the eyes in text direction provide the most complete account for the observed data. According to the premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umiltá, 1987), attention shifts are an integral part of saccadic programming. In support of this view, it has been shown that covert attention shifts and eye movements are mediated by widely overlapping cortical networks (e.g., Corbetta et al., 1998). We therefore hypothesize that whenever participants prepare a saccade in text direction, attention is automatically shifted in the same direction. Whether this shift is transient (Yantis et al., 2002) or sustained (Nakayama & Mackeben, 1989) is yet an open question. We further assume that as long as the oculomotor reference remains at fixation (Figure 14), processing information at the PRL requires covert shifts of attention toward the PRL.

Following this reasoning, reading performance with a PRL to the right of the scotoma (PRL-Right; Figure 14A) should be unimpaired since both the attention and the eyes have to be directed in the same direction. In support of this view, participants in our study made clearly more forward than backward saccades under FRL-Right and made a larger number of forward saccades than under FRL-Below and FRL-Left. Overall, gaze patterns as well as reading performance under FRL-Right were most similar to that of foveal reading (e.g., Figures 10 and 11). In contrast, with a PRL to the left of the central scotoma (PRL-Left; Figure 14B), attention has to be redirected in the opposite direction by inverting the eye movement vector that resulted in the shift of attention in text direction. This conflict between moving the eyes in text direction and shifting attention to the PRL should impair reading performance. In support of this view, participants made an equal number of forward and backward saccades and reached lower reading rates under FRL-Left.

With a PRL below the central scotoma (PRL-Below; Figure 14C), the eye movement vector resulting from preparing a saccade in text direction has to be rotated by 90°. Based on the neurophysiology of the saccadic system (Bergeron, Matsuo, & Guitton, 2003; Corbetta et al., 1998; Munoz & Wurtz, 1995; Sparks, Lee, & Rohrer, 1990), we suggest that vector inversion can be performed by inhibiting a population of neurons that coded the original vector, whereas an additional population needs to get activated to rotate the vector by 90° (Schwarzbach, 1999; Schwarzbach & Vorberg, 2006). It therefore seems plausible that vector rotation requires more time and produces more errors than vector inversion. In line with this argumentation, FRL-Below resulted in increased fixation durations, a larger number of upward and downward saccades, fewer and shorter forward saccades, and lower reading rates as compared to FRL-Left and FRL-Right.

The conflicting motor activations account gives rise to different predictions for reading performance before and after the shift of the oculomotor reference. As pointed out before, as long as the oculomotor reference remains at the fovea, reading performance with a PRL to the left or below the central scotoma should suffer from the conflict between eye movements in text direction and shifts of attention toward the PRL (Figures 14B and 14C). No such conflict should be present for a PRL to the right of the scotoma (Figure 14A), thus reading performance under PRL-Right > PRL-Left > PRL-Below. The situation changes when the oculomotor reference moves to the PRL: Given the close coupling between attention and eye movement control (Corbetta et al., 1998; Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Rizzolatti, Riggio, & Sheliga, 1994), we hypothesize that a shift of the oculomotor reference to the PRL is accompanied by a similar shift of the reference for visual attention. If both attention and gaze are centered around the PRL, the use of the PRL no longer requires shifts of attention (see Figure 15). As a result, reading performance with a PRL to the left and below the scotoma should no longer suffer from the conflict resulting from the spatial separation between the oculomotor reference and the PRL after the shift of the oculomotor reference, thus reading performance under PRL-Right ≈ PRL-Left ≈ PRL-Below.

The observation that a forced retinal location below fixation clearly lead to worst performance in our study strongly indicates that our participants used the fovea as their oculomotor reference.

Methodological considerations

Previous studies led to conflicting results about the best candidate preferred retinal location (Fletcher et al., 1999; Guez, et al., 1993; Nilsson et al., 2003; Petre et al., 2000; Trauzettel-Klosinski & Brendler, 1998). This lack of agreement is not surprising for several reasons:

a. Predictions of attentional, anatomical, or functional asymmetries do not necessarily imply that the predicted locations are best suited for reading, which involves a variety of different components, e.g., spatial resolution, covert attention shifts, and eye movements.

b. Improved performance at a trained location as compared to an untrained location (e.g., Nilsson et al., 2003) does not rule out that there exist alternative locations that would have profited from training even more, and it is misleading to conclude a general performance advantage of the trained location from such findings.

c. Confounding factors in patient studies such as age, time since onset of the disease, size, and location of the scotoma are hard to control for. It is possible to circumvent these problems by masking larger parts of the visual field (e.g., the left or the right hemifield) in normal-sighted participants and measuring the resulting reading performance. Several studies have used this approach (e.g., Fine & Rubin, 1999; Rayner et al., 1982; Varsori, Perez-Fornos, Safran, & Whatham, 2004), but these studies suffer from several other disadvantages. First, masking larger parts of the visual field does not provide control over the precise retinal location chosen by the participant and therefore is of limited use for studying the underlying oculomotor processes. Similar to our approach, Fornos, Sommerhalder, Rappaz, Pelizzone, and Safran (2006) used a large rectangular viewing window that was shifted with respect to current fixation, but these authors did not vary the location of the viewing window. Second, standard gaze-contingent displays consist of rectangular masks with sharp borders, features that are unlikely to be seen with natural scotomas. Sharp transitions cause clearly visible boundaries that might serve as a reference for participants in controlling eye movements (Bertera, 1988) and therefore can result in strategies that otherwise would not be seen. We circumvented these problemsby smooth transitions and a circular rather than a rectangular viewing window (see Figures A1 and A3).

Note that patients with age-related macular degeneration (AMD) are typically much older than our participants, so it cannot be ruled out that AMD patients reach lower overall performance in comparison to our participants, and that their learning curves look different from those we observed.

One could argue that the task used in our study, i.e., reading single lines of text, does not take into account the importance of finding the beginning of the next line, as is the case in normal text reading. However, single lines in our study were embedded between two lines of pseudotext to resemble normal text reading while keeping trial durations short enough for preventing drift. Since each trial started at the center of the screen, participants had to find the beginning of each single text line. The example eye traces (Figures 5 and 6) show that this required additional fixations at the beginning of the text line both under FRL-Left and FRL-Right. Given the substantial performance differences between FRL-Left and FRL-Right even after 5 hours of practice, it seems unlikely that a potential benefit for FRL-Left for finding the beginning of the line can override the overall disadvantage of this condition for the remaining text.

It is unclear why patients tend to choose preferred retinal locations below and to the left of the central scotoma (Fletcher & Schuchard, 1997; Guez et al., 1993; Sunness et al., 1996; Trauzettel-Klosinski & Tornow, 1996; White & Bedell, 1990), given that our data suggest that this is disadvantageous for reading. Attentional asymmetries (Altpeter et al., 2000) could explain the tendency to establish a PRL below the central scotoma, whereas the importance to locate the beginning of the text line might lead to a preference for a PRL to the left of the central scotoma (Guez et al., 1993). It is important to keep in mind that macular degeneration is a progressive disease, and that patients are often neither aware of a defect nor a change in gaze behavior at early stages of the disease. Thus, patients might initially develop a strategy by pure chance or due to characteristics of their scotoma that only later on in the progress of the disease turns out to become less suited for the purpose of reading.

Practical implications and conclusions

Our study may relate best to early stages of MD when patients learn to use the PRL and the oculomotor reference has not yet shifted. Its clinical importance lies in suggesting training strategies for MD patients targeted at reading and in pointing out which particular aspects of oculomotor behavior might benefit from training.

Our experiments indicate that during the early stages of macular degeneration, before the oculomotor reference may have shifted toward the PRL, patients might benefit from using a PRL that results in least conflict between shifts of the attention and the eye. This implies that MD patients should benefit from training to use a PRL to the right of the scotoma (i.e., placing the central scotoma to the left of a target).

Increased reading rates were accompanied by a higher percentage of saccades in text direction (Figure 11) and decreased fixation durations (Figure 4). The latter is likely to indicate a decrease in processing difficulty (Rayner, 1998; Starr & Rayner, 2001). Improved reading rates cannot be explained by a flexible adjustment of saccade amplitudes, as saccade amplitudes remained stable across experimental sessions. These observations suggest that training procedures could be improved by concentrating on the aspect of performing saccades in text direction without slipping into the opposite direction or above or below the text line. In support of the importance of oculomotor factors for training, Seiple, Szlyk, McMahon, Pulido, and Fishman (2005) demonstrated a substantial improvement in reading rate in MD patients that received a training on oculomotor control rather than a training that focused on reading. Furthermore, our study indicates that patients might require different training strategies depending on whether their oculomotor reference has already shifted toward the PRL or still remains at the central scotoma.

The observation that participants in our study reach the same level of performance under FRL-Right as under FRL-Centre within 5 hours of practice at a relatively low eccentricity suggests that the technique described in this paper could be helpful in training MD patients to use a beneficial preferred retinal location already at early stages of the disease. This could prevent a long-term development of a preferred retinal location that turns out to be less suited for substituting the fovea.

Appendix A

The gaze-contingent display procedure blurs all visual information except at a small circular area (the forced retinal location) at a fixed distance from fixation (see Figure A1). The diameter of the FRL (2.41°) provided access to approximately 4–5 letters at the same time. The shape of the edges is described by a weight matrix (Figure A3).

As the eyes move, the FRL moves correspondingly, momentarily unblurring the text. To do so, eye movements are continuously monitored by a video-based eye tracking system (EyeLink I, SR Research), which tracks the pupil of both eyes at a sampling rate of 250 Hz.

The problem in real-time implementation of the procedure is speed. To minimize computational effort, we developed an algorithm that achieves local sharpening of the display in a given region around the FRL center through weighted pixel-by-pixel averaging of a blurred and an un-blurred image of the same stimulus. Before a trial, two bitmaps are created, called Sharp and Blur, respectively (for an example, see Figure A2). Blur is derived from Sharp by smoothing

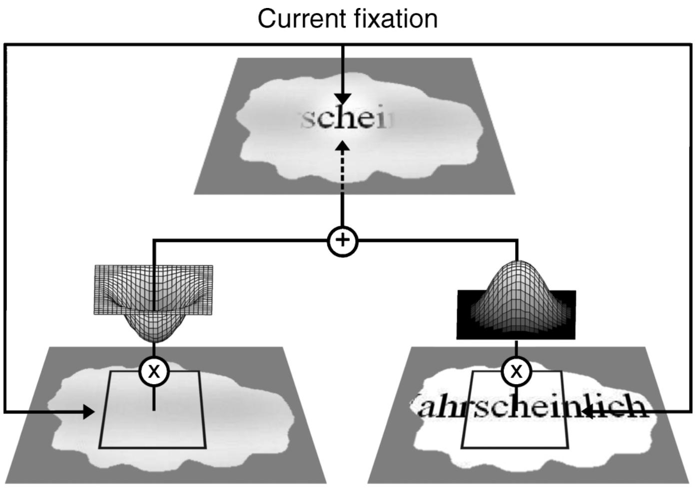

Figure A1. Illustration of the gaze-contingent display procedure. For each trial, two bitmaps of the same stimulus picture are created, called *Blur* (lower left) and *Sharp* (lower right). *Blur* is derived from *Sharp* by smoothing with a Gaussian filter. The forced retinal location (see top of the figure) is generated by forming a weighted average of the corresponding pixels of *Sharp* and *Blur* at the desired location. Computation is restricted to an 81 × 81 pixel region (corresponding to 2.41 × 2.41°) around the current fixation, as indicated by the grid on *Sharp* and *Blur*. Within this region, the intensity values of *Sharp* and *Blur* are averaged and weighted by the corresponding weight matrix. The weight matrix $\omega(l, u)$ defines the extent and shape of the forced retinal location, with smooth transitions at the (lower and upper) boundaries. The resulting matrix containing the computed intensity values at the forced retinal location is copied to the screen. See text for details.

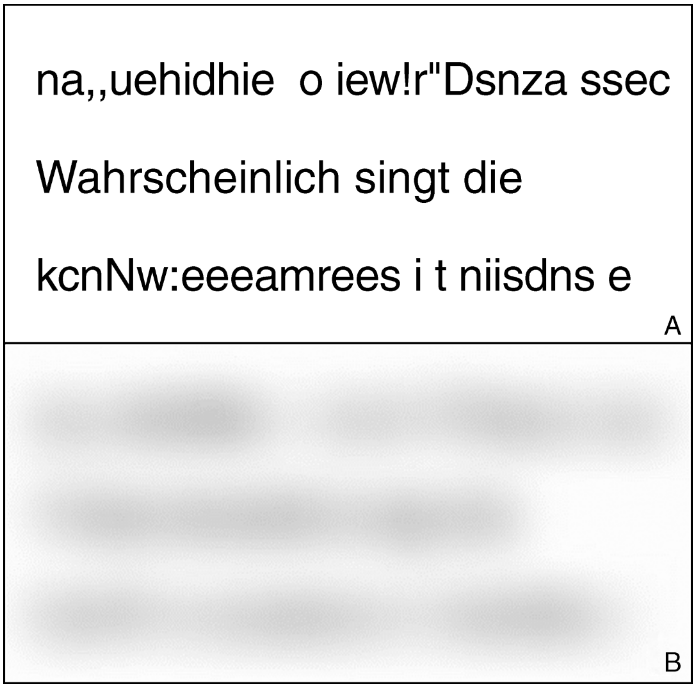

Figure A2. Example bitmaps used for the gaze-contingent window procedure. (A) Sharp; (B) Blur.

with a Gaussian filter (full width at half maximum: 36 pixel). The new bitmap is identical to Blur except for a small window formed by a weighted average of the corresponding pixels of Sharp and Blur.

Let (i, j) be the screen coordinates of a pixel and $d(i, j)$ its Euclidean distance from the FRL center (pi, pj). The weights that define the extent and shape of the FRL, with smooth transitions at the boundaries, are then given by the following function:

$$\omega(i,j) = \begin{cases} 1 & p > 1 \\ 1 - 2p^2 & \frac{1}{2} \le p \le 1 \\ 2(1-p)^2 & 0 \le p < \frac{1}{2} \\ 0 & p \le 0, \end{cases} \tag{A1}$$

where

$$p \equiv \frac{d(i,j) - l}{u - l}, \tag{A2}$$

and u and l stand for some upper and lower distance, respectively, beyond which all weights equal zero or one (Figure A3).

We sketch the algorithm for the FRL centered at the point of gaze (x, y):

1. Read in RGB values of Blur and Sharp.
2. Display Blur.
3. Determine gaze coordinates (x, y).
4. Compute RGB values within $(2n + 1)$ by $(2n + 1)$ area, defining FRL:

$$\begin{aligned} &\mathrm{RGB}_{\mathrm{FRL}}(x+i, y+j) \\ &\quad = \mathrm{RGB}_{\mathrm{Sharp}}(x+i, y+j) * \omega(i,j) \\ &\quad + \mathrm{RGB}_{\mathrm{Blur}}(x+i, y+j) * [i - \omega(i,j)], \end{aligned} \tag{A3}$$

   where $|i|, |j| \le n$.
5. Display FRL on screen, centered at (x, y).
6. Wait until gaze position change is detected.
7. Go to step 2.

The routine is the same for an FRL shifted from fixation, except that the shift distance with respect to fixation (e.g., 80 pixel to the left) is added to the current gaze position.

We used the BitBlt function (see Petzold, 2000) in step 5. BitBlt provides a fast copy of rectangular regions of a bitmap to the current screen. Gaze position data were collected at 250 Hz and were available for further processing within 10 msec. Using an Intel P4 computer (1.8 Ghz, 256MB ram) and an Aopen MX400 graphics processor, our procedure is completed within one frame refresh, such that the maximum lag between a change in eye position and the update of the screen was 4 + 10 +

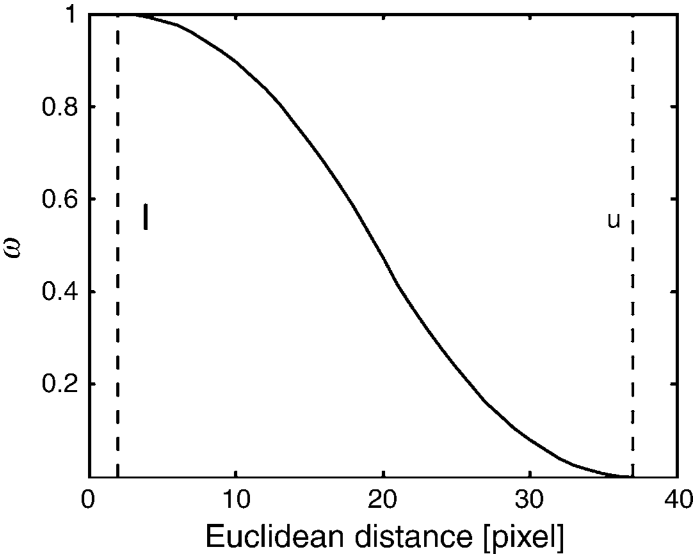

Figure A3. Illustration of the weight matrix used for computation of the intensity values within the 81 × 81 matrix. Weight decreases with Euclidian distance.

1000/85 = 25.76 msec. Visual response latencies in macaque cortex are no faster than 35 msec (Lamme & Roelfsema, 2000; Maunsell & Gibson, 1992; Schmolesky et al., 1998), and saccadic suppression is known to both anticipate and outlast saccades by 50 msec (e.g., Diamond, Ross, & Morrone, 2000). Therefore, this delay was short enough to prevent advance glimpses of the stimulus.

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