Seeing without a fovea?
Eye movements in reading and visual search
with an artificial central scotoma

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eingereicht am: 30. September 2004
mündliche Prüfung am: 21. Dezember 2004
Druckjahr: 2005
Vorveröffentlichungen der Dissertation

Teilergebnisse aus dieser Arbeit wurden mit Genehmigung der Gemeinsamen Naturwissenschaftlichen Fakultät, vertreten durch den Mentor, in folgenden Beiträgen vorab veröffentlicht:

Tagungsbeiträge


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Summary

The effects of the loss of foveal vision on eye movement control were investigated in the present study. A gaze-contingent display technique was developed to study the effects of a central scotoma on visual search performance in normal-sighted subjects. Within five hours of training, subjects developed a stable pseudofovea location.

A further aim was to investigate the effects of particular pseudofovea locations on performance in tasks like reading and visual search. Reading performance was superior with a pseudofovea to the right of fixation, intermediate with a pseudofovea to the left and worst with a pseudofovea below fixation. Eye movement patterns indicated that the congruence between the pseudofovea location and the direction of eye movements required by the task can explain this finding: if the pseudofovea is to the right of fixation, both the identification of details presented at the pseudofovea location and the requirement to execute eye movements in the direction of the text require covert attention shifts to the right. This assumption was further investigated in a visual search task that requires eye movements either on the horizontal (from left to right/ right to left) or the vertical meridian (i.e., from top to bottom/ bottom to top). Performance was best whenever the pseudofovea was congruent with the direction required by the task (e.g., a pseudofovea above fixation when the task requires eye movements from bottom to top). There was no overall superiority for directions on the horizontal as compared to the vertical meridian. This finding rules out hard-wired properties of the visual system as the underlying reason for the observed eye movement behaviour. Instead, I suggest that the pseudofovea location serves as a potential saccade target, competing with task-relevant targets (e.g., the upcoming word or the next visual search target). Consequently, performance is superior whenever attention is drawn in a direction that is also the target of an upcoming saccade.
1. Introduction

When we look around in our environment, we typically have the impression of a sharp representation of the whole visual field. On the other hand, if we fixate an object and try to describe what we can see in the periphery, we note that detailed vision is restricted to a rather small area. It is known that this area roughly subtends 1° around fixation (Perry & Cowey, 1985), with a dramatic drop in visual acuity the further we move away from fixation. Reduced visual acuity in the periphery is caused by the architecture of the retina: if we fixate an object, it is projected to the fovea and its surrounding, which contains highest density of photoreceptors and provides highest resolution. Consequently, to explore a larger area, we continuously have to move the eyes to objects of interest.

The question arises which mechanism determines potential goals of saccades and the identification of irrelevant locations. As will be shown later, visuospatial attention is widely assumed to be involved in this selection process. Moreover, it is known that salient visual objects that suddenly appear in the periphery can automatically attract attention and gaze. Consequently, we have to be able to suppress saccades to distracting stimuli and irrelevant locations.

The present study was concerned with the question how these requirements can be fulfilled if foveal input is interrupted: Can we explore visual objects without the use of foveal vision? Is it possible to adequately perform saccades to objects of interest if the fovea cannot be used? Can peripheral parts of the retina take over tasks typically restricted to the fovea?

Covert attention shifts. Already in the beginning of the last century, W. Wundt (1912) described the ability to separate the line of fixation from the line of attention. This ability to shift attention away from the fovea by an effort of will is typically used to study the effects of visuospatial attention on tasks like luminance detection and form information at the attended location. Apart from laboratory situations, we are seldom confronted with situations that require such covert attention shifts. An exception is the strategy of a soccer player during a penalty shoot-out: to confuse the goalkeeper, he directs gaze to the left...
corner, but shoots to the right corner. Likewise, astronomers are known to fixate next to a star instead of directly fixating it. As a consequence, the star is projected to parafoveal regions of the retina that yield higher contrast sensitivity because of the higher amount of light sensitive rods. The current study deals with still another situation that requires covert shifts of attention away from the fovea: In macular degeneration (MD), the foveal part of the retina is destroyed due to progressive photoreceptor degeneration. The corresponding affected region in the visual field is called scotoma, i.e. an area of deteriorated or absent vision. Objects presented in the area of the scotoma appear highly blurred or even absent. Patients often describe objects as “vanishing, jumping out of nowhere”, or “having parts missing or blurry” (Fletcher & Schuchard, 1997).

**Covert attention shifts in MD.** To explore details of an object despite the presence of a central scotoma, most MD patients use the ability to shift attention away from the fovea as described above: typically, patients fixate adjacent locations of an object while covertly attending the object. Due to this strategy, objects are projected to parafoveal and peripheral retinal locations not affected by the disease. The new retinal location used for detailed vision is called preferred retinal location (Timberlake et al., 1986) or pseudofovea (Guez, Le Gargasson, & Rigaudiere, 1993). For ease of communication, I will use the term pseudofovea to describe the corresponding region in the visual field with respect to the fixation location (see figure 1.1 for an illustration).
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Figure 1.1: Macular degeneration results in a central scotoma in the visual field. As a result, a peripheral retinal location or pseudofovea is used for object identification.

**Pseudofovea locations.** A standard technique to determine the pseudofovea location is to have patients identify visual objects (e.g., words) presented through a scanning laser ophthalmoscope (SLO). This instrument allows to observe the retina while the stimulus is projected to that retinal part currently used by the patient. The location of the stimulus can be related to anatomical landmarks of the retina, which allows the examiner to identify the pseudofovea location of the subject (see figure 1.2 for an illustration). It is important to note that the pseudofovea location determined by SLO depends on the stimulus used for fixation. For example, if the target is a small letter, patients may use a small island of residual vision close to the fovea (note that these islands typically vanish with progress of the disease). This strategy, however, cannot be used if stimuli subtend a larger visual angle. As studies differ with respect to both stimulus shape and size (e.g., letters, words, sentences, digits), it is easy to understand that different studies lead to contradictory results. For example, Guez et al. (1993) and Sunness, Applegate, Haselwood, and Rubin (1996) reported that most patients used a pseudofovea to the left of fixation. In contrast to this finding, in the studies of Fletcher and Schuchard (1990), White and Bedell (1990) and Trauzettel-Klosinski et al. (1993) most patients used a pseudofovea below fixation. As pointed out by Sunness et al. (1996), patients with juvenile
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forms of macular degeneration tend to place their pseudofovea below their scotomas. In general, most studies report that a pseudofovea right or above fixation is chosen less often than a pseudofovea left or below fixation.

![Figure 1.2: Determination of the pseudofovea location by SLO. Fixation targets (left column) and text (right column) were fixated by a subject with normal vision (upper row) and a patient with juvenile maculopathy Stargardt (lower row). The ellipsoid darker grey area in the middle indicates the area of the macula lutea surrounding the fovea. As can be seen, the normal-sighted subject fixates stimuli centrally, whereas the patient uses retinal locations above the macula (i.e., below fixation in the visual field). Note that stimuli are projected upside down on the retina. (From: Trauzettel-Klosinski, Teschner, Tornow, & Zrenner, 1994).](image)

**Determination of the pseudofovea location.** Several factors are involved in the determination of the choice of a pseudofovea location, among them scotoma shape and appearance as well as visual field asymmetries. Therefore, it is difficult to predict which location a patient will spontaneously choose. Furthermore, it is unclear which location leads to superior performance in tasks like reading.

**Methodological problems.** Studying these questions directly in patients with a central visual field loss is problematic for several reasons. First of all, MD patients typically differ in many important aspects, among them size, shape and exact location of the central scotoma. An additional technical problem concerns the fact that most devices for the measurement of eye movement require
stable central fixation for calibration, a task almost impossible for MD patients.¹

**Alternative approach.** An alternative technique to study the effects of visual field defects on eye movement behaviour is to use a gaze-contingent display (see Appendix for details). This method was used in two slightly different versions. In the *central scotoma* condition, the gaze-contingent display blurs a circular area around the current fixation while the rest of the visual display is left unchanged (see figure 1.3, left panel). In the *pseudofovea* condition, all visual information except at a small circular area (i.e., the artificial pseudofovea) is blurred (see figure 1.3, right panel). The location of the artificial pseudofovea is fixed with respect to the fovea (in the example shown: below fixation) and moves with the eyes. With this technique, it is possible to control the pseudofovea location used by the participants. Consequently, the pseudofovea location can be varied within subjects. This allows to use each subject as his own control, with the advantage that the impact of between-subject variability (e.g. due to different reading skills) is reduced.

The *central scotoma* condition was used to investigate whether normal sighted subjects performing a visual search task with an artificial central scotoma spontaneously develop a stable pseudofovea location within a few hours of training (see chapter 2). The *pseudofovea* condition was used to study the effect of pseudofovea location on performance in reading (chapter 3) and visual search (chapter 4). Moreover, I was interested whether the underlying eye movement patterns can give insights into the mechanisms that cause differential performance at different pseudofovea locations.

¹ Note, however, that in early stages of the disease, small islands of residual vision can sometimes be used for stable fixation.
Figure 1.3: Illustration of the gaze-contingent display (see Appendix for technical details). The small red cross marks potential fixation positions made by a subject (not shown during the experiment). In the **central scotoma** condition (left panel), a circular area around the current fixation (marked by a red cross for illustrative purposes only) is blurred, while the rest of the display is unchanged. In the **pseudofovea** condition (right panel), the whole display except a small circular window is blurred. Note that both the central scotoma and the pseudofovea move with the eye.
2. Visual search with an artificial central scotoma

2.1 Summary

The aim of this study was to investigate what kind of eye movement patterns participants spontaneously develop when they have to perform a visual search task while their central visual field is blurred. More specifically, I explored whether a unique pattern of eye movements develops, or whether the pattern depends on the locations of targets relatively to fixation (e.g., participants might always use a pseudofovea location as close as possible to fixation). To distinguish between these two alternatives, I investigated how the spatial relations between successively to be scanned locations affected the strategy chosen by the participant. All participants developed a single pseudofovea location. Individual pseudofovea locations were independent of the target location relative to fixation, ruling out task-specific strategies. Instead, the data indicate that a stable pseudofovea has developed spontaneously within five hours of training.
2.2 Introduction

To perceive details of an object, we usually perform saccades that bring the object of interest to the fovea. With such a foveating saccade, the stimulus is projected to that part of the retina that yields highest density of receptors and highest acuity. If foveal input is disrupted by an artificial scotoma (Rayner & Bertera, 1979) or a naturally occurring macular scotoma (Legge, Rubin, Pelli, & Schleske, 1985), parafoveal or peripheral retinal locations must be used for detailed vision instead. Tasks like reading become extremely difficult under such conditions, with reading rates as low as a few words per minute (Legge et al., 1985; Rayner & Bertera, 1979). Worse performance in the presence of a central scotoma is not simply a result of lower resolution in the periphery, as reading rates are still substantially lower if type size is enlarged appropriately (Latham & Whitaker, 1996).

One possible reason underlying the problems in the use of parafoveal and peripheral locations instead of the fovea lies in the configuration of the saccadic system. As described above, under normal viewing conditions foveating saccades are performed with the fovea as the point of reference. A central scotoma, on the other hand, requires to perform saccades that bring objects to peripheral regions instead. This task is not easy to solve, as patients often show the tendency to foveate objects despite their central scotoma in early periods of the disease (White & Bedell, 1990). As a result, objects are frequently described to suddenly appear or disappear (Fletcher & Schuchard, 1997).

To overcome the progressive loss of visual abilities like reading, many patients begins to use a distinct peripheral part of their retina, typically called preferred retinal location (Timberlake et al., 1986) or pseudofovea (Guez et al., 1993). According to Whittaker et al. (Whittaker, Budd, & Cummings, 1988), the pseudofovea can be defined as the retinal locus where images are placed for 68% of a trial.

Is the extensive use of a parafoveal or peripheral location instead of the fovea accompanied by a changed sensation of the pseudofovea? In other words, is the pseudofovea perceived as straight ahead instead of being shifted to either side of the original fovea after prolonged use? Schuchard and Fletcher (1994)
suggested to distinguish between eccentric viewing and eccentric fixation: In eccentric viewing, the patient has the sensation to look above, below, or either side of the fixation target, whereas eccentric fixation describes the sensation to directly look at the target. It is possible that eccentric viewing is used in the beginning of the disease, whereas prolonged use of the same retinal location for tasks formerly done with the fovea finally results in eccentric fixation.

After prolonged use of a stable pseudofovea location over a period of years, a certain amount of patients with a central visual field loss perform saccades that move the image directly to functioning retinal parts instead of directing it to the fovea first (White & Bedell, 1990; Whittaker et al., 1988). Furthermore, centripetal drift tendencies often observed in earlier stages of the disease where almost absent. In other words, both the perception of the pseudofovea and the oculomotor behaviour reorganized considerably in these patients. The authors discuss these observations as evidence for a shift of the oculomotor reference from the fovea to the pseudofovea location.

To study the time course of the development of a pseudofovea as well as the shift of the oculomotor reference system, Heinen and Skavenski (1992) investigated the adaptation of both fixations and saccades following bilateral foveal lesions in adult monkeys. Monkeys developed a stable pseudofovea location for fixation within a few days. Weeks to months were required, however, until monkeys were able to perform saccades that immediately brought targets to the pseudofovea. In conclusion, the adaptation of fixation and saccades differ substantially with respect to their underlying time scales. Furthermore, the amount of time required for the adaptation of saccades suggests that the underlying mechanisms differ from those postulated for rapid saccadic adaptation induced by systematic displacements during saccades (Albano & King, 1989; Deubel, 1987).

In principle, any retinal location not affected by the disease might be used as a pseudofovea. There are preferences for particular retinal locations: Using a scanning laser ophthalmoscope (SLO) that projects stimuli directly onto the retina, several studies observed a preference for a pseudofovea to the left of fixation (Guez et al., 1993; Sunness et al., 1996). In contrast, Fletcher and Schuchard (1997), White and Bedell (1990) and Trauzettel-Klosinski et al.
(1994) observed that most patients used a pseudofovea below fixation. Despite this inconsistency, there seems to be agreement about the observation that a pseudofovea right or above fixation is chosen less often than a pseudofovea to the left of or below fixation. Note that part of the controversy between studies reporting pseudofovea locations is due to the fact that, in addition to substantial variability between patients, studies differed with respect to fixation targets. For example, a row of digits was used in the study of Guez et al. (1993), whereas the tip of a stick, emerging from the lower part of the screen, had to be fixated in the study of White and Bedell (1990). Considering that the periphery of a target serves for coarse orientation in the absence of foveal vision, it is easy to imagine that patients use different fixation strategies for such different targets.

It should be noted that an individual patient can develop a pseudofovea at several different locations. Which one is used depends on the type (e.g., fixation cross, letter, words, sentences) and size of the fixation target used for determination of the pseudofovea location (Sunness et al., 1996).

What are the factors that lead to the development of a pseudofovea location? There seems to be no simple answer to this question. Rather, several factors seem to determine the pseudofovea location, among them scotoma size and location (Sunness et al., 1996), area of best residual visual acuity as well as topographic variations in sustained attention (Altpeter, Mackeben, & Trauzettel-Klosinski, 2000; Mackeben, 1999). As argued by Timberlake et al. (1986), the pseudofovea develops at a location that results in the largest field of view, the least obstrusive location or a location that allows for retinal correspondence for binocular viewing. Timberlake et al. (1986) report that the majorities of patients with a dense scotoma develop a pseudofovea as close as possible to the margins of the scotoma.

Can subjects learn eccentric fixation? Whittaker and Cummings (1986) let normal sighted subjects perform a visual acuity task with an artificial scotoma. Within a few trials, subjects learned to keep the target image out of the scotoma, using small corrective saccades. However, after 53 trials, no preference for a particular retinal location was observed. Instead, subjects used several different locations around the margin of the scotoma. It is doubtful,
however, that 53 trials where enough for the development of a stable pseudofovea.

The aims of the current study is to provide answers to the following questions:

(1) Do normal sighted subjects with an artificial central scotoma develop a stable pseudofovea location in a visual search task if more time (more than 300 trials) is provided?

(2) Do subjects use a single pseudofovea location, irrespective of target location? To answer this question, the location of the target (eight possible locations on an imaginary circle) was systematically varied.

(3) Is the development of a pseudofovea location accompanied by an adaptation of the saccadic system? In this case, saccades should be observed that bring critical objects directly to the pseudofovea.

To study these questions, subjects successively had to identify two targets in a visual search display (see figure 2.1). The first target (T1) was defined by its colour (a red square among green distractors or vice versa). A gap in its contour pointed to the location of the second target (T2). This arrangement allowed to study the pseudofovea location in two slightly different conditions: a saccade to T1 always started at the centre of the screen, whereas a saccade to T2 started at or next to either of the eight target locations. Suppose a subject has the strategy to minimize the distance between the centre of the screen and T1. If this is the case, subjects should fixate below the target if it is at the top of the screen and above if the target is at the bottom of the screen. Does the same strategy, however, apply for the saccade from T1 to T2? In contrast, it is possible that the pseudofovea location chosen for T1 determines the pseudofovea location relatively to T2 (i.e., if T1 was at the top of the screen, the subject fixates below T1 and below T2, irrespective of the location of T2).

To investigate whether subjects develop a stable pseudofovea location within five hours of training, it was studied whether mean fixation location varied across training sessions. Next, the influence of both target location and target type (T1 vs T2) on fixation location was estimated. The adaptation of the saccadic system was studied by analyzing whether the first, second and third fixation are directed to the mean fixation location.
2.3 Materials and methods

Subjects. Six female psychology students, aged 19-25 years, took part in the experiment, either as a course requirement or for a pay of € 7.50 per session. Vision was normal or corrected to normal.

Apparatus. Eye movement recording was performed by a video-based eye tracking system (Eyelink I; see Appendix for further details). Stimuli were presented on an Iiyama Vision Master 451 monitor (18’’), with screen resolution of 800x600 pixel and refresh rate of 85 Hz. Distance between monitor and eyes of the subject was 76 cm, the diameter of the central scotoma was 2.41°. Gaze-contingent stimulus presentation and randomization was programmed in C (MS Visual C++ 6.0 platform). Standard libraries supplied with EyeLink were used for eye movement recording and online saccade detection.

Subjects wore a headband with cameras attached. At the beginning of each block, gaze calibration was performed by fixing targets that appear randomly on a 3 by 3 grid, followed by a validation.

Task. The task consisted of several steps: First of all, subjects had to locate a target (T1) among seven distractors, indicated by an odd colour (either a green square among seven red squares or a red square among seven green squares). Each square had a gap at either of eight possible locations (one of the corners or the midpoint of one of the sides; see figure 2.2 for an example). The location of the gap of T1 pointed in the direction of T2 (see figure 2.1). As soon as T2 was located, a button had to be pressed (marking the end of the trial in the logfile), and the location of the gap of T2 had to be said (e.g. “upper right”).

Design. Location of target 1 (T1) and target 2 (T2) were varied as main independent variables. Both T1 and T2 occurred with equal probability at one of eight possible locations at equal eccentricity (7.02°) to the central fixation point. Relatively to the location of T1, T2 was located either two locations clock-wise or counter-clock-wise on the circle (see figure 2.1). The location of the gap was chosen randomly, with the restriction that the gap of T2 did not point to T1 to prevent detection on the direct way from T1 to T2. The colour of T1 (red or green) was chosen randomly trial by trial. The main dependent variable was the fixation location relatively to the locations of T1 and T2.
Figure 2.1: Example trial. The subject starts in the middle of the screen, indicated by a fixation cross (blurred by the central scotoma). First, the subject has to locate the target with the odd colour (T1). The location of the gap of T1 (in this example: lower left) points to the location of T2. Relatively to the location of T1, T2 is located either two locations clock-wise (as shown in the example) or counter-clock-wise (indicated by the dashed arrow) on the circle. The subject has to name the location of the gap of T2 after pressing a button (in this example: “lower left”).

Figure 2.2: Example stimulus. **Left panel:** original, **right panel:** blurred (as the stimulus appears when blurred by the central scotoma). To increase the difficulty to identify the location of the gap, a dotted line surrounds the stimulus. Pilot studies ensured that this kind of lateral masking prevents to identify the location of the gap when fixating neighbouring target locations.
Visual search with an artificial central scotoma

**Material.** Each stimulus consisted of eight squares, arranged on an invisible circle with a diameter of 14.03°. The first target (T1) could be either red or green, with the remaining rectangles having the opposite colour (i.e., green or red). Rectangles subtended 0.75x0.75°, the size of the gap was 0.083°. Gap size was chosen on the basis of pilot studies, ensuring that the gap was large enough to be identifiable without central fixation, but small enough to prevent identification if the central fixation point or neighbouring target locations are fixated.

For each stimulus, a blurred version was created using the functions *Pixelize* and *Blur* of IrfanView 3.61. Figure 2.2 shows an example stimulus, both in its original (left panel) and blurred (right panel) version.

**Trial procedure.** Subjects started a trial by pressing a button while fixating a dot in the centre of the screen. Trials continued with presentation of three single dots on a horizontal line for 6 seconds. Next, the stimulus was presented, consisting of eight rectangles (T1, T2 + six distractors; see figure 2.1). As soon as the subject came close to a rectangle or directly fixated it, it was blurred from view. Accordingly, subjects were only able to identify the location of the gap if they fixated a neighbouring location instead (e.g., slightly left or below the stimulus).

Subjects located T1 and moved the eyes to T2, as indicated by the location of the gap of T1. As soon as subjects felt sure about the location of the gap of T2, they had to press a button and say the location (e.g., “lower right”). If subjects did not press the button within 60 seconds, the trial terminated automatically.

**Instruction.** In the first session, subjects were informed to move head and body as little as possible during data recording. A description of the task was read to the subject. Before the start of the main experiment, a short practise block was performed to ensure that the subject understood the task correctly.

**Layout of experimental sessions.** Subjects performed 5 sessions consisting of 8 blocks each. A block consisted of 9 trials, with the first trial serving as a warm-up trial, excluded from data analysis. Altogether, subjects performed 8x5x8 =320 trials used for analysis.
2.4 Results

2.4.1 Visual Search Performance

Accuracy. Subjects made an average of 5.1% errors (first session: 12.5%, last session: 0.5%), indicating that they performed the task in the intended way.

Training effects. Overall, subjects improved performance throughout the experiment, as evidenced by main effect of training sessions on number of fixations \[F(4,20) = 3.812, p_{HF} = .064; \text{number of fixations session 1: 35.8, session 5: 17.8} \] and trial duration \[F(4,20) = 5.41; p_{HF} = .042; \text{trial duration session 1: 17.2 sec., session 5: 8.5 sec.} \]. Fixation duration did not vary across experimental sessions \[F(4,20) = 0.259; p_{HF} = 0.259; \text{fixation duration session 1: 463.0 msec., session 5: 453.3 msec.}\].

2.4.2 Eye movement patterns

Figure 2.3 shows individual scanpaths of subject 4 (best subject in terms of number of fixations) in the first (upper panel) and the last session (lower panel). This subject immediately moves the eyes from the central location to T1 (surrounded by a red square). A series of fixations around T1 follows, with no identifiable directional preference. After a few fixations, the eyes are moved to T2 (surrounded by a green square). Again, a number of fixations around T2 follow. This pattern looks quite different at the end of the experiment (see lower panel of figure 2.3). As soon as the subject has moved the eyes to either T1 or T2, a small number of fixations (in this example: 2) are made above the target. Figure 2.4 shows the corresponding figures for subject 2 (worst subject with respect to the number of fixations). The upper panel of figure 2.4 shows that this subject made fixations above or directly centered on the target location (typical for most subjects in the beginning of the experiment). In contrast, subject 2 fixates locations to the right of/ above the target in the last session (see figure 2.4, lower panel).
Figure 2.3: Eye trajectories of single trials, subject 4 (best subject in terms of number of fixations per trial); upper panel: first session, lower panel: last session.
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Figure 2.4: Eye trajectories of single trials, subject 2 (worst subject); **upper panel**: first session, **lower panel**: last session.
Red and green squares in figures 2.3 and 2.4 indicate the regions of interest (ROI) used to pool fixation locations relatively to target locations. The size of the ROI (6.03 x 6.03°) was carefully chosen to prevent an overlap between neighbouring ROI). To allow averaging across target locations, relative fixation locations were calculated in each ROI with target location set to (0,0).

**Individual fixation locations.** To estimate mean fixation location, relative fixation locations in each ROI were pooled across all eight target locations, separately for each subject. Next, normal distributions were fitted separately to horizontal and vertical fixation locations, using the `normfit` function of the statistic toolbox of MATLAB 5.3. Estimated mean fixation locations are shown in figure 2.5 (subject indicated by number in the circle). The horizontal and vertical extent of the ellipse indicates the standard deviation of the estimate of horizontal and vertical fixation position across experimental sessions. As is clearly seen, subjects developed idiosyncratic fixation locations. For example, mean fixation position of subject 1 is clearly below the target, indicating a pseudofovea above fixation.

As most studies (Nilsson, Frennesson, & Nilsson, 1998; Trauzettel-Klosinski et al., 1994; White & Bedell, 1990; Whittaker, Cummings, & Swieson, 1991) distinguish between pseudofovea above, below, left, right, and central, diagonal lines where added to the plots for ease of comparison. As can be seen, subject 2 and 4 continuously fixated above the target, indicating the development of a pseudofovea below fixation. Subject 3 fixated to the right of fixation (i.e., a pseudofovea to the left of fixation was used). Subject 1 typically fixated below the target and thus used a pseudofovea above fixation. The pseudofovea of subjects 5 and 6 was central, possibly due to a strong tendency to fixate targets despite the absence of foveal input.
Stability of the fixation location across experimental sessions. Next, I was interested in the variability of the fixation locations across experimental sessions. Therefore, separate estimates of the fixation where computed for each session. Results are shown in figure 2.6. Each subplot shows results for an individual subject. Small circles mark estimated fixation locations (from white: session 1 to black: session 5). Horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position. As can be clearly seen, estimates are quite stable across experimental sessions with respect to the classification into the four quadrants (and central fixation, respectively). Moreover, in subjects 1-4, mean fixation location moves to the periphery across experimental sessions.
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Figure 2.6: Effect of experimental session on estimated horizontal and vertical fixation location, averaged across target location and target type. Each small circle (from white: session 1 to black: session 5) indicates separate estimates for each of the five training sessions. Each subplot shows data for an individual subject (sub.). The horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position. The large grey circle marks the size of the central scotoma if the target is fixated centrally.
To quantify the effect of experimental session on fixation location, a repeated measures ANOVA for the factor *session*, computed separately for estimated horizontal and vertical fixation location subject and each subject. A significant modulation of both horizontal and vertical fixation location by session was found for each subject (results summarized in table 2.1). Next, post-hoc comparisons where computed for the comparison between first and last session. These contrasts revealed significant differences in all but two cases (subject 3 and 6, vertical fixation location). Importantly, for subjects 1-4, both horizontal and vertical fixation locations moved to higher eccentricities at the end of the training. In contrast, subjects 5 and 6 tended to use locations more in the centre by the end of the training, fitting well with the observation that their overall fixation location was central.

**Effect of target location.** Examples of pooled fixation locations within a ROI relatively to target location (averaged across T1 and T2) are shown in figures 2.7 (subject 1) and 2.8 (subject 5). Upper and lower panels show all fixations observed in the corresponding ROI in session 1 and 5, respectively. As can be seen in figure 2.7 (upper panel), subject 1 preferentially fixates below the target in the first session. The same is true in the last session (figure 2.7, lower panel), whereas clearly less fixations are required to solve the task.

As can be seen in figure 2.8, subject 5 performs a large number of fixations centered on the target, as well as fixations above and below fixation. Besides a decrease in the number of fixations, this pattern does not change dramatically by the end of the experiment (figure 2.8, lower panel).
Figure 2.7: Fixation locations relatively to the eight possible target locations for subject 1, averaged across T1 and T2. **Upper panel:** session 1, **lower panel:** session 5. For better visualization, grey circles indicate the size of the central scotoma around each target location. To associate fixation locations to target locations, fixation locations to neighbouring target locations are indicated with either bright or dark dots.
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Figure 2.8: Fixation locations relatively to the eight possible target locations for subject 5, averaged across T1 and T2. **Upper panel**: session 1, **lower panel**: session 5. Larger grey circles indicate the size of the central scotoma around each target location.

To examine whether mean fixation location differed between target location, mean fixation location was estimated separately for each target location. Indi-
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Individual results are shown in figures 2.7-2.11. Visual inspection indicates that mean fixation location did not vary considerably with target location. For ease of comparison, mean fixation location for each of the eight possible target locations are plotted in the same coordinate system in figure 2.12, separately for each subject. As seen, mean fixation location is in the same quadrant for subjects 1-4, irrespective of target location. For subject 5 and 6, mean fixation location is central, with only slight modulation by target location.
Figure 2.9: Effect of target location on estimated fixation location (marked by small white circles) for subject 1 (upper panel) and subject 2 (lower panel). The horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position.
Figure 2.10: Effect of target location on estimated fixation locations (marked by small white circles) for subject 3 (upper panel) and subject 4 (lower panel). The horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position. Grey circles indicate the size of the central scotoma around each target location.
Figure 2.11: Effect of target location on estimated fixation locations (marked by small white circles) for subject 5 (upper panel) and subject 6 (lower panel). The horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position. Grey circles indicate the size of the central scotoma around each target location.
I have demonstrated that mean fixation location does not vary with respect to the four quadrants plus central fixation, but it is possible that mean fixation location varies to a certain degree within these regions. As shown in figure 2.12, mean fixation location varies within the quadrants (subjects 1-4) as well as around the centre (5-6). To quantify the amount of this variation, individual ANOVAs for the factor target location were computed, separately for
estimated horizontal and vertical fixation location (see table 2.2 for individual results). To summarize the main findings, for each subject, either horizontal or vertical fixation location (or both) was modulated by target location. Post-hoc contrasts (see table 2.2 for details) revealed those target locations that differed significantly from the mean effect of the remaining target locations. Note that, according to table 2.2, no obvious pattern emerges: those target locations that modulate fixation location differ substantially between subjects.

**Effect of target type (T1 vs T2).** Next, I wanted to explore whether mean fixation location depended on target type (T1 vs T2). Mean fixation location for T1 and T2 are shown in figure 2.13. As before, mean fixation location does not vary qualitatively as a function of target type.
Figure 2.13: Effect of target type (T1: grey, T2: black) on estimated horizontal and vertical fixation location. Small circles mark the estimated mean fixation location, horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position. Each subplot presents data for an individual subject. Large grey circles indicate the size of the central scotoma around the target location.

As before, to provide a finer analysis of the effect of target type on mean fixation location, a repeated-measures ANOVA for the factor target type on estimated horizontal and vertical mean fixation location were performed separately for each subject (for individual results, see table 2.3). Modulation of mean fixation location by target type varied substantially between subjects,
from no modulation (subject 6) to clear modulation of both horizontal and vertical fixation location (subject 3).

**Effect of fixation number into ROI.** Finally, I was interested to find out whether the first saccade into a ROI was located at or near the mean fixation location, indicating an adaptation of oculomotor behaviour. To do so, mean fixation location (averaged across target location and target type) for the first, second and third saccade into a ROI was estimated separately for each session and each subject. Results are shown in figures 2.14 and 2.15. Small circles mark estimated fixation locations (white: 1st, grey: 2nd, black: 3rd), whereas the larger white circle indicates the estimated mean fixation location of the according session. As can be seen, both subject 1 and 6 tend to direct their initial saccade to the mean fixation location already in the first session, whereas the other subjects fixate neighbouring locations first. It is important to note that the mean fixation location was quite close to the centre in the first session in all subjects; thus, it is not surprising that some subjects had the tendency to direct their first saccade to the mean fixation location in this phase of the experiment. Note, however, that subject 1 directed the first saccade close to the mean fixation location in session 5, even though the mean fixation location is clearly further away from fixation than in the first session (figure 2.15). None of the other subjects showed this precision for the first saccade. However, all subjects were able to direct either the second or third saccade close to the mean fixation location.
Figure 2.14: Effect of number of fixation in a ROI (white: 1st fixation, grey: 2nd fixation, black: 3rd fixation) on estimated horizontal and vertical fixation location in session 1. Each subplot shows data for an individual subject. Small circles mark the estimated mean fixation location, the medium size white circle indicates the individual estimated fixation location for session 1. Large grey circles indicate the size of the central scotoma around each target location. The horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position.
Figure 2.15: Effect of number of fixation in a ROI (white: 1st fixation, grey: 2nd fixation, black: 3rd fixation) on estimated horizontal and vertical fixation location in session 5. Each subplot shows data for an individual subject. Small circles mark the estimated mean fixation location, the medium size white circle indicates the individual estimated fixation location for session 5. Large grey circles indicate the size of the central scotoma around each target location. The horizontal and vertical extent of the ellipse indicates the standard deviation of horizontal and vertical fixation position.
2.5 Discussion

The spontaneous development of a pseudofovea in a visual search task performed with an artificial gaze-contingent central scotoma was demonstrated in the current study. Four out of six subjects chose a parafoveal retinal location for solving the visual search task, whereas 2 subjects (5 & 6) had a tendency to bring the target to central locations despite of the presence of a central scotoma. For those subjects using parafoveal locations, two subjects (2 & 4) used a pseudofovea below fixation, one subject (1) had a pseudofovea above, and one subject (3) to the left of fixation. Furthermore, mean fixation location (and, consequently, pseudofovea location) was shifted to higher eccentricities during the course of the experiment in subjects 1-4.

At first sight, the finding that subjects 5 and 6 continuously used a pseudofovea at a rather central location despite the presence of a central scotoma seems puzzling. It is important to note that the area containing 68% of all fixations (i.e., +/- one standard deviation) spreads from the upper to the lower margin of the scotoma in subject 5 and from the left to the right margin in subject 6 (see figure 2.6). This observation indicates that both subjects were not able to prevent central fixations, whereas target identification was obviously performed with locations above and below fixation (subject 5) or to the left and right of fixation (subject 6).

The quadrant chosen for mean fixation location (above, below, left, right) did not vary as a function of target location or target type (T1, T2). However, within quadrants, there were slight variations of mean fixation location with respect to these two factors.

A further aim of this study was to explore whether the development of a pseudofovea was accompanied by an adaptation of the ability to direct saccades immediately to the pseudofovea instead of performing a foveating saccade first. Remarkably, subject 1 showed this behaviour consistently already after five hours of training. None of the other subjects, developed this ability within this time. It can be speculated that further training sessions results in an adaptation of the oculomotor reference system in the other subjects as well.
The observation that subject 1 was able to perform saccades that bring objects directly to the mean fixation location is impressive since the development of this ability takes several years in patients with macular degeneration (White & Bedell, 1990). Furthermore, whereas the patients described by White and Bedell (1990) and Whittaker et al. (1988) had to use their parafoveal and peripheral retina outside the experimental setting as well due to physical destruction of the central visual field, this was clearly not the case for the subjects in the current study. On the other hand, an adaptation of the oculomotor reference system was observed within weeks to months in monkeys with bilateral retinal lesions (Heinen & Skavenski, 1992), indicating that this specific mechanism does not necessarily require years to develop.

There are, however, several reasons why adaptation of the oculomotor reference system requires more time in patients with macular degeneration as compared to the study of Heinen and Skavenski (1992) and subject 1 in the current study:

(1) The artificial scotoma used in the current study had a circular shape, with a rather circumscribed margin, whereas naturally occurring scotoma typically have a less regular shape, with small protrusions here and there, in addition to islands of residual vision in a number of cases. Accordingly, it was easier to place an object to a particular location relatively to the margin of the artificial scotoma.

(2) As macular degeneration is a progressive disease, the size of the scotoma can increase substantially within years. Accordingly, patients have to shift their pseudofovea even further away from the fovea once the scotoma has enlarged.

(3) In later stages of the disease, scotoma in macular degeneration can have diameters of 10° and more, whereas an artificial scotoma of 2.41° was used in the current study, comparable to a very early stage of the disease. As the use of a pseudofovea becomes less precise in terms of fixation stability and dispersion of saccadic endpoints with higher eccentricities (White & Bedell, 1990), it can be assumed that it was easier to develop a pseudofovea for the subjects of the current study as compared to patients with substantially larger central scotoma.

(4) Monkeys in the study of Heinen & Skavenski (1992) as well as the subjects in the current study intensively practised to bring objects of the same size and
shape at specific locations in the visual field to their pseudofovea. In contrast, patients in the studies of White and Bedell (1990) and Whittaker et al. (1988) used their pseudofovea in natural viewing conditions for years, with targets that vary in size, shape and location. Accordingly, patients have to adapt to a much more variable situation, possibly requiring substantially more time for the oculomotor reference system to adapt.

This last point requires some further comments. Assuming that a rather variable environment causes a substantial amount of time for the adaptation of the oculomotor reference system, training to use a particular pseudofovea location could be beneficial for these patients. If such training begins already at an early time since onset of the disease, patients might need less effort to develop a pseudofovea. Accordingly, an adaptation to the progression of the disease by shifting the pseudofovea further away from the fovea might be easier if the use of a pseudofovea is trained intensively already under easier conditions, i.e., closer to the fovea. Further research will be needed to prove whether such a specific form of training accelerates the process of adaptation, and whether it is accompanied by performance improvement in tasks like reading or visual search.
3. Reading without foveal vision: the effect of pseudofovea location on reading performance

3.1 Summary

In this study I explored how reading performance depends on pseudofovea location. Participants had to read single lines of text while pseudofovea location was varied blockwise (experiment 1: to the left of vs. below fixation/ experiment 2: to the left of vs. to the right of fixation). Reading performance was worst when the pseudofovea location was below fixation and intermediate with a pseudofovea to the left of fixation. Best performance was obtained when the pseudofovea was to the right of fixation. Eye movement patterns demonstrated that the eyes had a tendency to move in the direction of the pseudofovea instead in the direction of the text in a large number of cases. This pattern of results suggest that the eyes are automatically attracted by the pseudofovea. Accordingly, a pseudofovea below or to the left of fixation complicates reading from left to right since it skews the eyes away from the text (i.e., downwards or to the left). In contrast, a pseudofovea to the right of fixation attracts the eyes in the required direction already, thus causing no conflict. The data indicate that best reading performance is achieved when gaze direction and the direction of shifts of attention induced by the pseudofovea are congruent (i.e., reading from left to right, pseudofovea to the right of fixation), while impaired performance is to be expected in incongruent conditions (i.e., pseudofovea to the left of fixation/below fixation while reading from left to right).
3.2 Introduction

To explore visual objects, as in reading, we typically perform foveating saccades: by directly fixating objects, relevant visual information is projected to the fovea, the retinal region with highest receptor density and best acuity. During a fixation, letters are identified from a relatively small region termed word identification span or visual span, extending no more than seven to eight letter spaces to the right of fixation (Rayner, Well, Pollatsek, & Bertera, 1982). To program an upcoming saccade, attention is covertly allocated to that region (e.g. Hoffman & Subramaniam, 1995). Consequently, word length information can be obtained from a region called perceptual span, extending 3-4 letters to the left of fixation to about 14-15 letters to the right of fixation (Rayner, Well, & Pollatsek, 1980). The parafoveal preview benefit describes the phenomenon that parafoveal processing facilitates reading (Rayner et al., 1980; Starr & Rayner, 2001). Likewise, masking parafoveal information severely interrupts reading, especially if information to the right of fixation is withdrawn (Rayner et al., 1982).

Gaze behaviour changes when the central retina is damaged, as in macular degeneration. MD patients suffer from a central visual scotoma, that is, a circumscribed region in the visual field within which vision is blurred or fully absent. To overcome loss of reading abilities, patients typically develop compensating gaze strategies: instead of directly fixating and object (e.g. a letter), they fixate a neighbouring location while attending the specific object. In other words, patients use a parafoveal or peripheral part of their retina, which takes over the function of the degenerated fovea. It is therefore called preferred retinal location (Timberlake et al., 1986) or pseudofovea (Guez et al., 1993). For ease of communication, the location of this pseudofovea will be reported in visual field coordinates throughout this article.

Projecting stimuli directly onto the retina by a scanning laser ophthalmoscope (SLO), several patient studies have observed a preference for a pseudofovea to the left of fixation (Fletcher, Schuchard, & Watson, 1999; Guez et al., 1993; Sunness et al., 1996). Less often, patients develop a pseudofovea
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below fixation, which is still more frequent than a pseudofovea right or above fixation.

Several factors seem to determine the location chosen for the pseudofovea, among them location and size of the scotoma (Sunness et al., 1996), area of best residual visual acuity, as well as topographic variations in sustained attention (Altpeter et al., 2000; Mackeben, 1999).

Improved performance in reading with a pseudofovea has been demonstrated in patients after intensive training (Nilsson, Frennesson, & Nilsson, 2003; Nilsson et al., 1998). There is, however, substantial controversy on how pseudofovea location affects reading performance.

There is ample evidence that both spatial and attentional resolution is better in the lower than in the upper visual field (Ellison & Walsh, 2000; He, Cavanagh, & Intriligator, 1996), which suggests that a pseudofovea below fixation is best. This location is also recommended by Peli (1986), who argues that controlling peripheral eye movements towards locations orthogonal to the direction of target motion (e.g., above/below fixation for left-to-right reading) should be easier than towards radial locations (i.e., to the left/right of fixation).

Retinal ganglion cell density is higher on the horizontal as compared to the vertical meridian (Curcio & Allen, 1990). Consequently, a pseudofovea to the left or right of fixation might benefit from higher resolution. Guez et al. (1993) stress the importance of information to the left of fixation for return sweeps and monitoring previous fixation locations, and conclude that a pseudofovea to the left of fixation must lead to superior performance. On the other hand, the parafoveal preview benefit (Rayner et al., 1980) suggests that a pseudofovea to the right of fixation is more useful. In support of this assumption, Trauzettel-Klosinski and Brendler (1998) and Fine and Rubin (1999) showed that reading rate decreases more if information to the right is not available as compared to information to the left.

The lack of agreement in the outcomes of the recommendations of these studies is not surprising given the methodological problems of studying the relationship between pseudofovea location and reading performance in pa-
tients: besides pseudofovea location, patients may differ in age, size/ location of the scotoma, time since disease onset, remaining visual acuity, etc. For example, Fletcher et al. (1999) studied reading performance in MD patients, assessing pseudofovea location by SLO. When patients where classified by pseudofovea location, no clear group differences in reading rate were found. However, reading rate varied substantially within each group, which makes it hard to evaluate these results.

An alternative approach is to study pseudofovea location effects on reading performance in normal-sighted subjects rather than in patients. For this purpose, we developed a gaze-contingent paradigm that makes it possible to blur all visual information except at a small circular area (see Appendix for a description of the technical details). The location of the simulated pseudofovea is fixed with respect to the fovea. As the eyes move, the pseudofovea moves correspondingly, momentarily unblurring the text here, whereas the text at its previous location is blurred again. Note that the aim is not to simulate a central visual scotoma. Rather, by eliminating detailed vision everywhere except at the pseudofovea, we force subjects to use a particular location in the visual field for reading. This allows to compare reading at different pseudofovea locations, with each subject serving as his or her own control. In the following, we refer to the location of the simulated pseudofovea by the abbreviation PF indexed by a letter, e.g. PF-L for “pseudofovea to the left of fixation”.

The goals of the present experiments were (a) to study how reading performance depends on pseudofovea location, and (b) to provide empirically based explanations of performance advantages and disadvantages at different pseudofovea locations.

3.3 Experiment 1: PF-L vs. PF-B

As pointed out above, it is unclear how reading performance depends on pseudofovea location, and which perceptual and attentional mechanisms are involved. Because most MD patients spontaneously develop a pseudofovea either to the left or below fixation, we compared reading performance in normal readers when usable visual information is confined to either of these locations, that is, when the artificial pseudofovea is to the left of or below fixation.
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We contrasted performance under these conditions with reading when the pseudofovea is centered at fixation.

3.3.1 Materials and methods

Subjects. Six students (five female, mean age 28.5 years) from Technical University of Braunschweig were tested in five one-hour sessions. All subjects had normal or corrected-to-normal visual acuity. Subjects either received €7.50 per hour or credit points for course requirements.

Apparatus. Eye movements were recorded by a video-based eye tracking system (EyeLink I; see Appendix for further details). Stimuli were presented on an Iiyama Vision Master 451 monitor (18”), with screen resolution of 800x600 pixel and refresh rate of 85 Hz. The monitor was positioned 76 cm from the subject, the diameter of the pseudofovea was 2.41°. Gaze-contingent stimulus presentation and randomization was programmed in C, using the MS Visual C++ 6.0 platform. For eye movement recording and online saccade detection, standard EyeLink software was used.

Subjects wore a headband with cameras attached. At the start of each trial block, a gaze calibration task was performed, which required fixating targets appearing randomly on a 3 by 3 grid and was followed by a validation.

Design. Pseudofovea location was the main independent variable, with conditions pseudofovea left (PF-L), pseudofovea below (PF-B), and pseudofovea central (PF-C). The conditions were defined by the PF centre coordinates relative to fixation; they were -2.41°/0°, 0°/2.41°, 0°/0° visual angle, respectively. PF location was constant within, but varied randomly between blocks of trials.

Task. Subjects read single lines of text presented by the gaze-contingent display procedure. Reading was silent because overt reading risks slippage of the eye-tracker headband due to head movements. After each block, text understanding was tested by questions on content of the material.

Material. Stimulus text were excerpts from the novel “Der Ruinenbaumeister” by Herbert Rosendorfer (2000). The text to be read was presented in single lines, extending 10.6° on average. To simulate normal reading, the text line was presented with an additional line of pseudo-text 2.1° above and below, which consisted of word-like letter strings, randomly arranged from text lines.
from other session. The text to be read was presented in single lines, extending 10.6° on average. To simulate normal reading, the text line was presented with an additional line of pseudo-text 2.1° above and below, which consisted of word-like letter strings, randomly arranged from text lines from other sessions. Text was written in Arial 24 pt (vertical size of lower case letters: 0.053°), 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 as described above. Figure 3.1 shows an example stimulus, in its unblurred version.

![Figure 3.1: A typical passage of text (unblurred). Subjects had to read the middle line only, and ignore the upper and lower line made up of randomly arranged letters.](image)

**Trial procedure.** Subjects started a trial by pressing a button while fixating a dot on the centre of the screen. Coordinates of the current fixation were used as the reference point for screen centre, thereby removing electronic drift from the data. A new 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. Subjects signalled having finished reading the text by a button press. If they did not do so within 60 sec., the trial ended automatically.

**Instruction.** In the first session, subjects were informed about eye tracking, stressing the need not to move head and body during data recording. After a practice block with normal text reading, further instructions on reading with a
pseudofovea were given. Because pilot studies showed that reading under these conditions is prohibitively difficult initially, subjects were recommended to read a word by fixating a neighbouring location (e.g. to the right of a word in the PF-L condition). Before starting a block, subjects were informed about the location of the pseudofovea.

**Layout of experimental sessions.** Subjects served five one-hour sessions, with five blocks per session. The first four blocks consisted of two successive blocks of the two experimental conditions (PF-L vs. PF-B) each, with order of conditions counterbalanced across subjects and sessions. The fifth block contained the control condition (PF-C). To allow subjects to keep track of the text content, blocks terminated at the end of a logical unit 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, subjects served either 191 or 195 trials in the experimental conditions and 53 trials in the control condition. As dependent variables, we recorded reading rate (words per minute), number of fixations per text line, and fixation duration.

3.3.2 Results

3.3.2.1 Text Comprehension

Across subjects, all but one of the questions were answered correctly. This shows that reading with text comprehension was possible under these conditions.

3.3.2.2 Reading Performance

Prior to analysis, offscreen fixations were removed from the data. All reported statistics are based on these preprocessed data. Words per minute (wpm), number of fixations, and fixation duration were summarized by trimmed means per subject and condition, trimming 10% each from above and below (Wilcox, 1997). Trimmed mean reading rate, number of fixations, and fixation duration (see Table 3.1) were subjected to separate 3x5 repeated-measures ANOVAS with pseudofovea location and session as factors. Degrees of freedom were adjusted by the Huyn-Feldt procedure when appropriate (associated p-values denoted as \(p_{HF}\)).
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**Effects of practice.** There were clear overall benefits of practice effects for mean reading rate \( [F(4,20) = 16.2, p < .0001] \), number of fixations \( [F(4,20) = 8.41, p < .0001] \) and fixation duration \( [F(4,20) = 4.23, p = .012] \).

**Effects of pseudofovea location.** There was a pronounced effect of pseudofovea location on reading rate \( [F(2,10) = 89.86, p < .0001] \), number of fixations \( [F(2,10) = 36.39, p_{HF} = .001] \) and fixation duration \( [F(2,10) = 13.66, p = .001] \). Reading rate was superior at the left than the lower position \( [F(1,5) = 29.79, p = .003; \ PF-L: 36.1 \text{ wpm}, \ PF-B: 20.9 \text{ wpm}] \), but still way off from reading with central pseudofovea (67.2 wpm). The same performance advantage for PF-L compared to PF-B was found for number of fixations \( [F(1,5) = 6.92, p = .047; \ number \ of \ fixations \ PF-L: 28.1, \ PF-B: 39.0, \ PF-C: 12.7] \) and fixation duration \( [F(1,5) = 18.73, p = .008; \ fixation \ duration \ PF-L: 245.7 \text{ msec}, \ PF-B: 315.8 \text{ msec}, \ PF-C: 249.7 \text{ msec}] \).

There was no significant interaction between training session and pseudofovea location [reading rate: \( F(8,40) = 1.53, p = .176 \); number of fixations: \( F(8,40) = 2.65, p_{HF} = .087 \); fixation duration: \( F(8,40) = 2.22, p = .046 \)].

**3.3.2.3 Eye movement patterns**

Figure 3.2 (right panel) shows a typical eye trajectory for reading with PF-C: the horizontal saccade component describes a staircase pattern similar to normal reading, with no variability in the vertical saccade component. That is, subjects slowly moved along the text line from left to right.

In contrast, PF-L produced zig-zag patterns for the horizontal saccade component (left panel), with little variability in the vertical component, i.e., subjects slowly progressed along the line, continuously moving forwards and backwards. This strongly contrasts with the pattern observed for PF-B (middle panel): instead of a zig-zag pattern for the horizontal saccade component, there was substantial variability in the vertical saccade component (i.e., subjects slowly moved forwards along the line, while making alternating downwards and upwards movements).
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Figure 3.2: Horizontal (black) and vertical (grey) fixation locations of single typical trials vs. time, for PF-L (left panel), PF-B (middle panel) and PF-C (right panel). PF-L typically results in a zig-zag pattern of horizontal saccades. Instead of this pattern, subjects make additional downwards and upwards movements with PF-B. For PF-C, the typical staircase pattern of the horizontal saccade amplitude is observed. Upper row: subject 2 (best subject in terms of mean reading rate), lower row: subject 1 (worst subject).
Figure 3.3 gives a closer look on the effect of pseudofovea location on saccade amplitudes: each subplot consists of a plot of vertical against horizontal saccade component of a single subject (pooled across the whole experiment) and the corresponding marginal distributions. For PF-C (right panel), there is a narrow unimodal distribution of the vertical saccade component and a bimodal distribution for the horizontal saccade component. Note that the distribution for forward saccades is narrower and contains more cases than the backward saccade distribution, i.e. most saccades were made forwards and had roughly equal amplitudes, whereas backward saccades occurred less often, presumably representing return sweeps.
Figure 3.3: Horizontal and vertical saccade amplitudes for PF-L (left panel), PF-B (middle panel) and PF-C (right panel), pooled across experimental sessions. Upper row: subject 2 (best subject), lower row: subject 1 (worst subject). In addition to a 2-dimensional plot of vertical against horizontal saccade amplitude, histograms of the marginal distributions are shown separately for horizontal and vertical saccade amplitude. As can be seen, horizontal saccade amplitudes for PF-L result in a bimodal distribution, representing forward and backward saccades, whereas there is a single sharp distribution for the vertical saccade component. Much more variability is obtained for vertical saccades for PF-B.
As can be seen in the left panel, there is a bimodal distribution of the horizontal saccade component and a sharp unimodal distribution of the vertical saccade component, i.e. saccades where either made forwards or backwards, whereas upwards or downwards saccades occurred seldom. In contrast, a large number of upward and downward saccades where observed for PF-B, as the distribution of vertical saccade amplitudes is much broader (middle panel)\(^2\). The distribution of the horizontal saccade amplitude is unimodal. In other words, whereas for PF-L, saccades of roughly the same amplitude where made either forwards or backwards, both horizontal and vertical saccade amplitude where much more variable for PF-B, with a larger number of vertical saccades than for PF-L.

3.3.3 Discussion

With practice, subjects improved reading performance under all conditions: they required less time to read a line of text, which was a consequence both of less fixations and of reduced time per fixation.

Our results are clear-cut with respect to the pseudofovea location optimal for reading: In normal-sighted readers, there was a clear advantage for PF-L, which yielded a higher reading rate, less fixations and shorter fixation durations than PF-B.

During the first trials, subjects were hardly able to read a single word. Even though informed about how to direct gaze to a desired location (e.g. to the right of a word when the pseudofovea is to the left), they were obviously unable to do so initially, and complained to have “no control” of their eye movements. Rather, they often reported that the pseudofovea seemed to dictate where to move the eyes, which is in line with the observed eye movement patterns. Even though performance clearly improved with practise, subjects where far from reaching perfect control of the pseudofovea within five sessions, as

\(^{2}\) Note that for subject 2 (upper row), the distribution of vertical saccade amplitudes is bimodal (indicating that upward and downward saccades had a distinct amplitude), whereas the corresponding distribution for subject 1 (lower row) is unimodal (indicating saccades of varying amplitudes). The bimodal distribution was observed for the two best subject only, whereas it was clearly unimodal for the others.
indicated by the eye movement patterns untypical for reading (figures 3.2 and 3.3) even in the last session.

Subjects reach higher reading rates and need less fixations when the pseudofovea is to the left of fixation rather than below. We surmise that these performance differences depend on the relation between the gaze direction required globally (reading from left to right) and the local shift of the pseudofovea (left vs. below fixation). Because information can only be picked up at the location of the pseudofovea, subjects need to attend to this location. As this region is the sole part of the visual space that contains salient information, it is likely to act as a peripheral cue, automatically attracting attention (Jonides, 1981; Posner, 1980; Theeuwes, Kramer, Hahn, & Irwin, 1998). Eye movement patterns indicate that subjects, instead of covertly attending the pseudofovea location, typically perform saccades to that region. In other words, the pseudofovea seems to attract gaze, a tendency that is difficult to prevent. This effect could explain why subjects execute such a large number of saccades towards the pseudofovea location even after five hours of training.

How could the “attraction effect” of the pseudofovea explain the performance advantage for PF-L? When the pseudofovea is to the left of fixation, subjects have to direct attention to the left to identify information available at the pseudofovea location only, while planning and executing saccades to the right to enable information access in the desired order. As described above, attending the pseudofovea location results in a large number of overt attention shifts. Given the close coupling between attention and eye movements (Corbetta et al., 1998; Deubel & Schneider, 1996; Rizzolatti, Riggio, & Sheliga, 1994), conflicts are likely between attending to the pseudofovea location and moving the eyes in the opposite direction. As a result, eyes move across the text in a zig-zag pattern. With pseudofovea below fixation, however, a completely different situation arises. Again, to be able to read, saccades have to be planned and executed to the right. To identify letters at the pseudofovea location, however, attention must be directed downwards. As eye movement patterns show, this conflict leads to many downward saccades, typically followed by upward saccades of equal amplitude to compensate for the slip from the line. As a result, instead of moving from left to right, the typical movement
sequence is right, down, up, right, down, up, etc. as seen in figures 3.2 and 3.3 (middle panel).

If the assumed relationship of required gaze direction and pseudofovea location holds, a strong prediction follows: For pseudofovea right, no conflict should arise between attending to the pseudofovea location and moving the eyes in text direction, as the required pseudofovea movement coincides with the required global gaze direction. Consequently, performance should be best and less backward saccades should occur in this condition. Experiment 2 was performed to test this prediction.

### 3.4 Experiment 2: PF-L vs. PF-R

As pointed out above, performance differences between pseudofovea locations observed in experiment 1 might be due to the location of the pseudofovea relatively to the required gaze direction. If this assumption is accurate, better reading performance, in combination with fewer backward saccades, should result when the pseudofovea is located to the right of fixation. To test this idea, we compared reading performance and eye movement patterns for PF-L and PF-R.

#### 3.4.1 Materials and methods

Details were as in experiment 1, except for the following changes.

**Subjects.** Six new female students (mean age: 26.3 years) from Technical University Braunschweig participated in the study, all with normal or corrected-to-normal visual acuity.

**Design.** PF-location (left/right/control) was varied blockwise as a repeated-measures factor.

#### 3.4.2 Results

**3.4.2.1 Text Comprehension**

Across the experiment, a single error was made by one subject in answering a question, indicating that subjects understood the content of the text.
3.4.2.2 Reading Performance

As in experiment 1, trimmed mean reading rate, number of fixations, and fixation duration (see Table 3.2) were subjected to separate 3 x 5 repeated-measures ANOVAS with PF-location and session as factors. Degrees of freedom were adjusted by the Huyn-Feldt procedure when appropriate (associated p-values denoted as $p_{HF}$).

Effects of Practice. Reading performance improved substantially during the experiment, affecting reading rate $[F(4,20) = 25.32, p < .0001]$, number of fixations $[F(4,20) = .695, p_{HF}=.038]$, as well as fixation duration $[F(4,20) = 5.01, p_{HF} = .024]$.  

Effects of pseudofovea location. There was a pronounced effect of pseudofovea location on reading rate $[F(2,10) = 24.22, p < .0001]$, mean number of fixations $[F(2,10) = 21.33, p < .0001]$ and fixation duration $[F(2,10) = 1.44, p = .283]$. A higher reading rate was achieved in the PF right condition compared to the PF left condition $[F(1,5) = 18.21, p = .888; \text{reading rate left: 28.8 wpm, right: 52.7 wpm}]$, with PF right almost reaching the performance of PF control (61.3 wpm). Less fixations were made for PF right compared to PF left $[F(1,5) = 25.47, p = .004; \text{number of fixations left : 34.4, right: 23.7, control: 13.0}]$, whereas fixation duration did not differ significantly $[F(1,5) = 2.44, p = .179; \text{fixation duration left: 272.6 msec., right: 252.5 msec., control: 275.8 msec.}]$. The effect of practice and pseudofovea location did not interact $[\text{reading rate: } F(8, 40) = .777, p = .625; \text{number of fixations: } F(8,40) = 1.78, p_{HF} = .225; \text{fixation duration: } F(8,40) = .902, p = .524]$. 

Figure 3.4: Horizontal (black) and vertical (grey) fixation locations of single typical trials against time for PF-L (left panel), PF-R (middle panel) and PF-C (right panel). Upper row: subject 3 (best), lower row: subject 5 (worst). As in experiment 1, a zig-zag pattern of horizontal saccades occurs for PF-L. In contrast, PF-R results in several large-amplitude forward saccades, followed by a large or several smaller return sweeps occasionally. The staircase pattern typical for reading is observed for PF-C.
3.4.2.3 Eye movement patterns

A typical eye trajectory for reading with PF-R is shown in Figure 3.4 (middle panel). The pattern of the horizontal saccade component is quite different from that characteristic for PF-L (Figure 3.4, left panel): Typically, there is a sequence of several large-amplitude forward saccades, followed by a large or several smaller return sweeps occasionally.

As for PF-L and PF-C, there is little variability in the vertical saccade component, i.e., subjects are able to keep their eyes on the text line. Figure 3.5 (middle panel) presents the corresponding distributional information for PF-R. The marginal distribution of the vertical saccade component is tightly centered around zero. Note that dispersion of the horizontal saccade component is larger for backward saccades and smaller for forward saccades for PF-R, whereas the opposite holds for PF-L (figures 3.3 and 3.5, left panel). This means that subjects produce rather precise forward saccades for PF-R, whereas backwards saccade amplitudes show much more variability, just the reverse of the pattern for PF-L.

To corroborate these impressions, we analysed how the amplitude of forward and backward horizontal saccades depends on pseudofovea location. Assuming that horizontal saccade amplitudes consist of a mixture of three gaussian distributions, we estimated mean, standard deviation and weight for each distribution separately for each subject using an adapted version of the gaussmix-function contained in the VOICEBOX toolbox available for MATLAB 5.3. Figure 3.6 shows estimated gaussian mixture distributions plotted on the observed horizontal saccade amplitudes for PF-L and PF-R (Experiment 2). Figure 3.7 gives a summary of this analysis, plotting estimated weights against estimated mean separately for each distribution. For PF-L (left panel), highest weights were estimated for the distribution corresponding to backward saccades (i.e. in pseudofovea direction). For PF-R (right panel), the opposite pattern holds, with highest weights for the distribution underlying forward saccades. For PF-C, highest weights were estimated for the distribution representing forward saccades, i.e. subjects made saccades in text direction in this condition most of the time. In conclusion, horizontal saccades have a high prob-
ability to be directed to the pseudofovea, with amplitudes roughly corresponding to the distance between pseudofovea and fixation.
Figure 3.5: Horizontal and vertical saccade amplitude for PF-L (left panel), PF-R (middle panel) and PF-C (right panel), pooled across experimental sessions. Upper row: subject 3 (best), lower row: subject 5 (worst). In addition to a 2-dimensional plot of vertical against horizontal saccade amplitude, histograms of the marginal distributions are shown separately for horizontal and vertical saccade amplitude.
Figure 3.6: Histograms of horizontal saccade amplitudes observed in experiment 2, and estimated gaussian mixture distributions (marked by grey line overlaid on the histograms). **Left panel**: PF-L, **right panel**: PF-R. Subjects are ordered according to reading rate (subject 3: best, subject 5: worst).
Figure 3.7: Summary of the estimated gaussian mixture distributions, separately for each subject. **Upper row:** Experiment 1, **lower row:** Experiment 2. **Left panel:** PF-L, **middle panel:** PF-C, **right panel:** PF-R. According to this analysis, most saccades were made in the direction of the pseudofovea, i.e. highest weights were obtained for those distributions corresponding to saccades directed to the pseudofovea.
3.4.3 Discussion

Performance improved across training sessions, with an increase in reading rate and a decrease in the number of fixations. As expected, reading is facilitated when the pseudofovea is to the right of fixation, as indicated by a higher reading rate, less fixations and less saccades to the pseudofovea location.

Superior reading performance with PF-R, and a reduced number of backward saccades in this condition supports the assumption discussed before: What is crucial is the location of the pseudofovea with respect to the predominant gaze direction required by the task. Whereas the eyes are drawn in opposite text direction for PF-L and downwards for PF-B, they are attracted in text direction for PF-R, clearly facilitating reading.

Interestingly, subjects reported that the pseudofovea often seemed to move faster than intended. In other words, the pseudofovea induced the eyes to make larger steps than useful. As can be seen in figures 3.5 and 3.6, forward saccades were larger for PF-R than for PF-C [mean forward PF-R: 2.09°, mean forward PF-C: 1.44°]. As a result, unconnected parts of the text where fixated for PF-R, while roughly neighbouring locations where fixated with PF-C, allowing to put together the single pieces of information, whereas with PF-R. According to this view, return sweeps in this condition can be explained by the necessity to relate current information to pieces of text read before.

3.5 General Discussion

We presented a new technique for studying gaze behaviour following central visual field loss in normal sighted subjects. With this technique, we were able to directly explore the relationship between pseudofovea location and reading performance as well as the underlying mechanisms.

We were able to show that normal gaze behaviour can be changed such that a distinct peripheral location is used for information uptake. We assume that the observed compensatory gaze behaviour requires allocation of attention away from fixation. Due to high salience at the pseudofovea location, covert allocation of attention is not possible. Instead, saccades to the pseudofovea are elicited which are difficult to inhibit. If attention has to be allocated to the same
part of text used for programming an upcoming saccade (pseudofovea right), reading is enhanced as the eyes are drawn in the desired direction. Allocating attention to another pseudofovea location (left, below), however, severely disrupts reading performance, continuously drawing the eyes into another direction.

These findings clearly contradict Peli (1986) and Nilsson et al. (2003), who predicted performance advantages for the lower visual field. The present observations are also in contrast to Guez et al. (1993), assuming a superiority of a pseudofovea to the left of fixation. On the other hand, the current data are consistent with the finding that reading performance is superior if text to the right is available as compared to text to the left (e.g. Rayner et al., 1980).

Our technique allows to investigate a number of important theoretical issues. For example, could the worse performance of a pseudofovea below fixation be a result of the lower resolution of the vertical meridian (Curcio & Allen, 1990)? A further issue concerns the role of text direction for the present results: How can we rule out that the observed superiority for a pseudofovea right is based on the fact that we have excessive practice in left-to-right reading in our culture? In fact, we speculate that for Hebrew readers, used to read right-to-left mostly, will show best performance with a pseudofovea to the left, while Japanese readers (top-to-bottom) should perform best with a pseudofovea below fixation. Furthermore, according to the assumed conflict between attending the pseudofovea location and executing saccades, Hebrew readers should show better performance with a pseudofovea below fixation if the task requires eye movements from top to bottom, whereas Japanese readers should perform best with pseudofovea to the right of fixation if they have to move their eyes from left to right (see chapter 4 for this issue).

What is the relevance of the present results for applied work? Do MD patients benefit from knowing which pseudofovea location is best for a specific task? The finding that MD patients are capable to develop more than one pseudofovea at the same time (Duret, Issenhuth, & Safran, 1999) indicates that it is possible to adapt gaze behaviour to the current task requirements. In support of this view, our subjects learned to use a pseudofovea at two different locations.
As pointed out before, the aim of this research was neither to realistically simulate a central scotoma nor the pseudofovea as found in MD patients. Instead, the gaze-contingent window technique was developed as an experimental tool that aids normal-sighted subjects in acquiring attentional control over off-foveal regions on the retina. We plan to use this technique also to train MD patients to establish a pseudofovea at particular locations. Rather than instructing and training patients which region of their visual field to use, training could focus on learning how to steer the pseudofovea. An additional advantage of this method is the possibility to train patients with progressively larger distances between pseudofovea and fixation. This allows to adapt task difficulty to the individual performance of the patient. Current experiments investigate the applicability of such approaches.
4. Continuous visual search without foveal vision

4.1 Summary

In this study, I further investigated the claim that the congruence between pseudofovea location and direction of eye movements required by the task determines task performance. To rule out that the superiority of a pseudofovea to the right of fixation is specific to the task of reading text from left to right, a visual search task was used that required eye movements in either of four directions (up, down, left, right), while none of them has been subject to intense training in this task before (as is the case in reading). Best performance was observed whenever the pseudofovea location was congruent with the direction required by the task (e.g., pseudofovea left from fixation, task direction: right-to-left), whereas performance did not differ between pseudofovea locations. Consequently, hard-wired properties as well as intensive pre-training in performing the task in a specific direction can be ruled out as the underlying mechanism. Instead, the data imply that the pseudofovea in fact has an attentional effect, i.e. performance is superior whenever attention is drawn in the direction that is also required by the task.
4.2 Introduction

Under natural viewing conditions, we move the eyes such that important features of the environment are projected to the fovea, i.e. the central part of the retina with highest cone density and, therefore, best visual acuity. In macular degeneration, a degenerative disease of the retina, foveal and parafoveal retina is impaired by photoreceptor degeneration. To compensate the progressive loss of vision, patients typically begin to fixate aside objects instead of directly fixating it, thereby bringing objects to a peripheral part of the retina not affected by the disease. This location is typically termed preferred retinal location (1986) or pseudofovea (Guez et al., 1993).

The most serious restriction in daily life reported by MD patients is the growing loss of reading abilities. Accordingly, an increasing number of studies are concerned with the effects of a central scotoma on reading abilities. As an example, it has been demonstrated that reading rates drop to a few words per minute in the presence of a central scotoma (Legge et al., 1985; Rayner & Bertera, 1979). McMahon, Hansen, and Viana (1991) demonstrated lower reading rates in MD patients, accompanied by higher saccadic frequencies. Furthermore, shorter saccade amplitudes and more frequent regressions occur (Bullimore & Bailey, 1995). Legge, Ahn, Klitz, and Luebker (1997) argued that a reduced visual span (i.e. the area to the left and right of fixation within which characters can be identified) could account for the need for more eye movements in MD patients.

Investigating eye movements directly in MD patients is problematic as patients typically differ in several properties of their scotoma, e.g. size, shape, location (Fine & Rubin, 1999). Consequently, it seems more promising to study the effects of a central scotoma in normal sighted subjects by means of an artificial gaze-contingent scotoma. In line with results of a naturally occurring central scotoma, a severe disruption of reading performance was reported if 10-12 central letters were masked (Rayner & Bertera, 1979). Likewise, Bertera (1988) reported a doubling in search time and a 15 % increase in fixation duration in healthy subjects performing a visual search task with a 20 min arc artificial scotoma.
Continuous visual search without foveal vision

Reading becomes more difficult if parafoveal information is masked, especially if information to the right of fixation is withdrawn (Rayner et al., 1982). This finding is consistent with the claim that attention has to be covertly allocated to the target region of an upcoming saccade (e.g. Hoffman & Subramaniam, 1995).

The relationship between spatial attention and saccadic eye movements has been strongly debated, with a growing number of studies suggesting a close relationship. An influential idea came from Posner (1980), who stated that peripheral stimuli attract both covert attention and eye movements. A related approach was described in the oculomotor readiness theory (Klein, 1980; Klein, Kingstone, & Pontefract, 1992). According to this view, an eye movement to a particular location is prepared whenever attention has to be shifted, facilitating processing of stimuli at that specific location. An even closer coupling of attention and eye movements is assumed in the premotor theory of attention (Rizzolatti, Riggio, Dascola, & Umilta, 1987), stating that attention shifts are the outcomes of saccadic programming.

So far, little is known about the exact relationship between poor control of saccadic eye movements in MD patients and reading abilities. A related question concerns the relationship between pseudofovea location and reading performance: Are there particular locations in the visual field suited better for tasks like reading than others? If such a relationship exists, does it depend on the specific task? As long as such questions are not solved, it is difficult to decide whether the adaptations patients intuitively develop are the most efficient ones (McMahon et al., 1991). Likewise, it is important to know which location is suited best for a specific task for the development of an appropriate training program (Hall & Ciuffreda, 2001; Nilsson et al., 2003; Safran & Landis, 1996).

As mentioned above, it is problematic to investigate the relationship between pseudofovea location and reading performance in MD patients. Accordingly, there is potential disagreement between studies with respect to the potential “best” pseudofovea location (Fine & Rubin, 1999; Guez et al., 1993; Trauzettel-Klosinski & Brendler, 1998).
To study this question under more controlled conditions, a gaze-contingent display technique (see Appendix) is used: depending on current gaze position, only a small circular window is available for viewing, whereas the rest of the visual field is blurred. Varying the location of the circular window (i.e., the simulated pseudofovea) relatively to current gaze position allows to study the effect of pseudofovea location on performance in tasks like reading and visual search. In reading (see chapter 3), a strong performance advantage was found for pseudofovea to the right of fixation (in visual field coordinates) and a clear disadvantage for pseudofovea below fixation, with intermediate performance for pseudofovea left. Eye movement patterns indicated that information provided at the pseudofovea location attracted attention, and, consequently, gaze position. According to this view, information provided at the pseudofovea location serves as a peripheral cue that automatically attracts attention and, consequently, gaze. If the pseudofovea is to the right of fixation, this exogenous attention shift is congruent with the required gaze direction for reading text (from left to right). As a consequence, the eyes are pulled in the desired direction. In contrast, if the pseudofovea is to the left of fixation, attraction of both attention and gaze has to be overcome, which in turn leads to a conflict between performing saccades in direction of the pseudofovea vs. performing saccades in text direction. In line with this view, Klein et al. (1992) reported that in a task that requires both exogenous and endogenous attention shifts, “exogenous orienting overrides endogenous orienting”.

It is unclear whether these findings are restricted to reading, a task that requires successive eye movements from left to right. As we are used to read from left to right since childhood in our culture, we are well trained for shifts of both attention and eye movements to the right, whereas other directions (e.g. from top to bottom) might require more effort. In support of this view, Freeman (1980) observed better visual acuity for letters in rows than in columns. Such a dependence was neither found for young children that were able to identify letters but could not read, nor for a group of bilingual Chinese subjects. Likewise, Carrasco, Talgar, and Cameron (2001) reported a horizontal-vertical anisotropy, i.e. better performance on the horizontal as compared to the vertical meridian in tasks that require orientation discrimination, detection and localization. A parallel to this findings can be found in physiology: in the ret-
ina, a higher density of retinal ganglion cells exists on the horizontal as compared to the vertical meridian (Curcio & Allen, 1990), arguing for an inherent property of the visual system rather than a learned mechanism.

A possible way to explore whether a specific form of training or a horizontal-vertical asymmetry caused the above mentioned findings is to use a task that require several possible directions (from right to left/ top to bottom etc.). Therefore, a continuous visual search task was used in the present study. Subjects had to move their eyes from the start to the end position of a maze (see figure 4.1). In each single maze, four directions (left, right, up, down) occurred. By varying pseudofovea location, I investigated whether fewer fixations were required if pseudofovea location was congruent with the local maze direction (e.g. pseudofovea to the left of fixation, maze direction left). If the performance advantage for pseudofovea right observed in reading (chapter 3) is based on the fact that attention was attracted by the pseudofovea, facilitating eye movements in the same direction, superior performance should be found whenever the pseudofovea location is congruent with the required gaze direction. If such a congruency effect can be found both for horizontal (left, right) and vertical (up, down) directions, an inherent property of the visual system as well as a learned strategy due to reading from left to right can be ruled out. Instead, such a finding would indicate that the performance of the pseudofovea depends on the congruency between the direction of attention shifts elicited by the pseudofovea location and the required direction of eye movements induced by the task.

4.3 Materials and methods

**Subjects.** Six female subjects aged between 22 and 34 participated in the experiment, either as a course requirement or for a pay of € 7,50 per session. All subjects had normal or corrected to normal vision.

**Apparatus.** Eye movements were recorded by a video-based eye tracking system (Eyelink I; see Appendix for further details). Stimuli were presented on an Iiyama Vision Master 451 monitor (18’’), with screen resolution of 800x600 pixel and refresh rate of 85 Hz. The monitor was positioned 76 cm from the subject, the diameter of the pseudofovea was 2.41°. Gaze-contingent stimulus presentation and randomization was programmed in C, using the MS Visual
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C++ 6.0 platform. For eye movement recording and online saccade detection, standard libraries supplied with EyeLink were used.

Subjects wore a headband with cameras attached. At the beginning of a session, gaze calibration was performed by fixating targets appearing randomly on a 3 by 3 grid, followed by a validation.

**Task.** Subjects had to find the way through a maze consisting of landolt stimuli (see figure 4.1) similar to the task introduced by Hooge and Erkelens (1998). To be able to identify the gaps of the landolt stimuli, subjects had to locate the pseudofovea on it. The task was solved as soon as the target stimulus was identified, consisting of a straight line (instead of an arrow), surrounded by a landolt stimulus containing a single gap rather than two (see figure 4.3). Subjects had to indicate the direction specified by the target line ("left", "right", "up", "down") by pressing either of four buttons.

**Design.** Pseudofovea location and maze direction were treated as main independent variable. The conditions pseudofovea left (PF-L), right (PF-R), above (PF-A), and below (PF-B) were defined by its centre coordinates relative to fixation, given by $-2.41^\circ/0^\circ$, $+2.41^\circ/0^\circ$, $0^\circ/+2.41^\circ$, $0^\circ/-2.41^\circ$ visual angle, respectively. In each stimulus, maze direction was defined by stimuli on the way from the start to the target location indicating a specific direction (left, right, up, down; see figure 4.2). Note that after each directional change, a stimulus consisting of a corner arrow had to be passed, so at least one or two fixations were made between adjacent directions. PF-location was constant within blocks, but varied randomly between blocks of trials. In each stimulus, each maze direction occurred at least once (see material for further details).
Figure 4.1: Example maze. **Upper panel:** clear version, **lower panel:** blurred version. The red circle indicates the start position.
Figure 4.2: In every maze, each of the directions left (blue), right (orange), up (yellow) and down (green) occurs (note that coloured regions are shown here for illustrative purposes only).

Figure 4.3: Example targets, marking the goal of the maze. **Left panel:** line points to the right (right button press required). **Right panel:** line points upwards (upper button press required).
**Material.** Each maze contained 64 circles, placed on an invisible 8x8 grid subtending 10.53 x 10.53° visual angle. For each maze, a blurred version was created using a gaussian blur function (CorelDraw 10) with a radius of 17 pixel. Figure 4.1 shows an example stimulus, both in its original (upper panel) and blurred (lower panel) version.

Distance between the centres of adjacent circles was 1.51°, the diameter of each circle was 1.21°. The start position was marked by a red circle, all other circles were black. The circles at the start and end position contained a single gap (0.13°), all other circles contained two gaps. The way from the start to the end position was indicated both by arrows (size of straight arrows: 0.84 x 0.12°) contained in each circle and the location of the gaps. Mazes were constructed such that the following conditions were fulfilled: a) the start position had to be on either of four possible central positions on the 8x8 grid, b) the target must not occur on locations adjacent to the start position, c) each of the four directions had to occur at least once in each maze, with all four directions occurring with equal probability, d) a particular direction had to consist of 3-5 stimuli, e) 12-16 stimuli had to be passed from the start to the target location, f) only the inner 6x6 grid was used for the way from the start to the target location. Directions of the arrows outside the way from start to end position were assigned randomly. To prevent potential contextual learning effects, 225 different mazes were constructed such that each maze was only shown once to each subject.

**Trial procedure.** Subjects started a trial by pressing a button while fixating a dot on the centre of the screen. Trials continued with presentation of three single dots on a horizontal line for 6 seconds, followed by the presentation of the blurred version of the maze. As soon as the target was located, subjects had to press one of four possible buttons indicating its direction (left/ right/ up/ down; see figure 4.3). The trial terminated if subjects pressed a response button or if no response was made within 60 seconds.

**Instruction.** Subjects received general information about eye tracking in the first session, stressing the need to move head and body as little as possible during data recording. Each session started with a warm-up block, consisting of
the same task, but with pseudofovea location identical to fixation location (PF-0). In the first session, subjects were informed that to be able to perceive information at the pseudofovea location, they had to fixate neighbouring locations of a particular object. Before each block, subjects were informed about the location of the pseudofovea.

**Layout of experimental sessions.** Table 4.1 in the Appendix gives an overview of the design. Subjects performed 5 sessions consisting of 5 blocks each. Each session consisted of 4 blocks, preceded by a warm-up block (excluded from data analysis). The warm-up block consisted of 5 trials with PF-0, followed by four experimental blocks consisting of 10 trials each. Experimental blocks within a session were randomized. The first session served to make subjects familiar with the task, with half of the distance between pseudofovea and fixation only. This session was excluded from data analysis. Altogether, there were 40 replications per condition and subject used for analysis.

### 4.4 Results

For each maze, regions of interest (ROI) as indicated in figure 4.2 were defined, indicating either of four possible directions on the way from the start to the end position. Next, individual fixation locations were calculated for each single subject and each single stimulus, using a procedure programmed in MATLAB. Note that instead of gaze position, the current position of the pseudofovea was used (e.g. +2.41° if the pseudofovea was to the right of fixation). In other words, the position of the pseudofovea rather than the fovea was analyzed. For each ROI, containing either of four maze directions (left, right, up, down), the number of fixations and fixation durations were computed, separately for each pseudofovea location (PF-L, PF-R, PF-A, PF-B). The results of this procedure of an example trial is visualized in figure 4.11. The scanpath of subject 6 in this individual trial is overlaid on the maze, and each fixation (i.e., the position of the pseudofovea) detected in a specific region of interest is coloured accordingly.

Mean number of fixations and fixation duration were subjected to separate 4 (pseudofovea location) x 4 (maze direction) x 4 (session) repeated-
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measures ANOVAS. Degrees of freedom were adjusted by the Huyn-Feldt procedure when appropriate (associated p-values denoted as \( p_{HF} \)).

4.4.1 Visual Search Performance

Training effects. Figure 4.4 shows that subjects improved during the experiment, as evidenced by the effect of experimental session on number of fixations \([F(3,15) = 8.912, p = .001;\) mean number of fixations session 2: 74.5, session 3: 54.2, session 4: 51.0, session 5: 45.1]. No such improvement was found, however, for fixation duration \([F(3,15) = .605, p = .622;\) mean fixation duration session 2: 420 msec, session 3: 459 msec, session 4: 441 msec, session 5: 430 msec].
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**Figure 4.4:** Effect of training session on mean number of fixations (left panel) and fixation duration (right panel). Mean number of fixations decrease across training sessions, whereas fixation duration stays stable across the experiment (error bars indicate +/- SE of the mean).

**Effects of pseudofovea location.** As can be seen in figure 4.5, number of fixations did not differ between pseudofovea locations \([F(3,15) = 1.941, p = .166;\) mean number of fixations left: 53.2, right: 63.7, above: 61.3, below: 46.7]. The same is true for fixation duration \([F(3,15) = 1.531, p = .247;\) mean fixation duration left: 407 msec, right: 471 msec, above: 412 msec, below: 459 msec].

**Figure 4.5:** Effect of pseudofovea location on number of fixations (left panel) and fixation duration (right panel). Neither number of fixations nor fixation duration differed significantly. Error bars indicate +/- SE of the mean.

**Effects of maze direction.** Figure 4.6 depicts the effect of maze direction on number of fixations \([F(3,15) = 4.564, p = .018;\) mean number of fixations left: 62.1, right: 53.5, up: 51.6, down: 57.7], with worst performance for the direction right-to-left. Fixation duration did not differ between maze directions \([F(3,15) = 1.927, p_{HF} = .221].\)
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Interaction pseudofovea location x maze direction. The basic finding of this experiment can be seen in figure 4.7: less fixations are made whenever pseudofovea location is congruent with maze direction (e.g. PF-L, maze direction left). This finding is supported by the interaction of pseudofovea location and maze direction on number of fixations \([F(9,45) = 13.307, p < .0001]\). Figure 4.8 clearly shows that no such interaction for combinations of maze direction and pseudofovea location that are perpendicular (i.e., maze direction up/ down for pseudofovea left/ right, maze direction left/ right for pseudofovea above/ below fixation).

Figure 4.6: Effect of pseudofovea location on number of fixations (left panel) and fixation duration (right panel). Most fixations were required for maze direction left-to-right. Fixation duration did not differ significantly between maze directions. Error bars indicate +/- SE of the mean.

Figure 4.7: Interaction pseudofovea location x maze direction for number of fixations (maze direction either same or opposite to pseudofovea location). Left panel: pseudofovea left/ right, right panel: pseudofovea above/ below fixation. Best performance (i.e., fewest number of fixations) was reached whenever pseudofovea location was congruent with local maze direction (PF-L & maze left, PF-R & maze right, PF-A & maze up, PF-B & maze down). Error bars indicate +/- SE of the mean.
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Figure 4.8: Interaction pseudofovea location x maze direction for number of fixations when maze direction and pseudofovea location are perpendicular. **Left panel:** pseudofovea left/ right, **right panel:** pseudofovea above/ below fixation. Error bars indicate +/- SE of the mean.

The picture is less clear for fixation duration. For pseudofovea to the left and right of fixation, the same pattern (shorter fixation durations if pseudofovea location is congruent with maze direction) is observed (figure 4.9, left panel), while no such interaction exists for pseudofovea above and below fixation (figure 4.9, right panel). Accordingly, the interaction of pseudofovea location and maze direction on fixation duration is less pronounced \[ F(9,45) = 2.243, p = .036; \text{see table 4.2 for mean number of fixations and fixation duration}. \] Note that figure 4.10 suggests an interaction between pseudofovea location and maze direction for perpendicular directions, possibly due to high variability in the data.

Figure 4.9: Interaction pseudofovea location x maze direction for fixation duration (same/ opposite maze directions). **Left panel:** pseudofovea left/ right, **right panel:** pseudofovea above/ below fixation. Error bars indicate +/- SE of the mean.
Figure 4.10: Interaction pseudofovea location x maze direction for fixation duration (perpendicular combinations). **Left panel**: pseudofovea left/ right, **right panel**: pseudofovea above/ below fixation. Error bars indicate +/- SE of the mean.

Figure 4.11: Example scanpath at the begin of the experiment (subject 6, session 2, trial 10, PF-L). Coloured circles indicate those fixations observed within a particular region of interest (e.g. red for fixations within regions of the maze requiring eye movements from left to right). The subject passes through the maze by alternately moving left and right, even in those parts that require upward or downward movements.
Continuous visual search without foveal vision

Figure 4.12: Example scanpath at the end of the experiment (subject 6, session 5, trial 5, PF-L). Left- and rightward movements are clearly less pronounced than at the beginning of the experiment (see figure 4.11 for comparison).
4.3.2 Eye movement patterns

Figure 4.11 depicts a typical eye trajectory in the second session of the experiment (subject 6, PF-L). As can be seen, the subject passes through the maze by alternately moving left and right, even in those parts that require upward or downward movements. This pattern is less pronounced at the end of the training (see figure 4.12 for an example trial of the same subject under the same condition in the last session), indicating that this inefficient eye movement behaviour can be overcome with substantial practise.
Continuous visual search without foveal vision

Figure 4.13: Horizontal and vertical saccade amplitudes for PF-L (left panel) and PF-R (right panel), pooled across experimental sessions. **Upper row**: subject 3 (best subject in terms of number of fixations), **lower row**: subject 4 (worst subject) In addition to a 2-dimensional plot of vertical against horizontal saccade amplitude, histograms of the marginal distributions are shown separately for horizontal and vertical saccade amplitude. As can be seen, horizontal saccade amplitudes result in bimodal distributions, representing forward and backward saccades, whereas there is a single sharp distribution for the vertical saccade component.
To summarize the effect of pseudofovea location on eye movement patterns, horizontal and vertical saccade amplitudes are pooled in figures 4.13 and 4.14 for the best and worst subject. As can be seen in figure 4.13, there is little variability in the vertical saccade component for PF-L and PF-R for both the best (upper row) and the worst (lower row) subject. In other words, if the pseudofovea is located on the horizontal axis, saccades are preferentially performed in pseudofovea direction and in the opposite direction, whereas upward and downward saccades have only small amplitudes.

The opposite pattern can be found in figure 4.14, showing distributional information for PF-A and PF-B. In these conditions, variability is much smaller for the horizontal saccade component, while a much broader distribution is
found for vertical saccade components. As for PF-L and PF-R, subjects seem to prefer to execute saccades on the axis of the pseudofovea (i.e., upwards and downwards if the pseudofovea is either above or below), while saccades to the left and right have much smaller amplitudes.

4.5 Discussion

So far, only few studies have investigated the effects of MD on tasks apart from reading. The visual search paradigm is a suitable candidate to study the requirements of a pseudofovea in more complex tasks under controlled conditions. Studying visual search with a gaze-contingent display has the additional advantage to be able to control the amount of peripheral information. In the present study, I investigated the relationship between pseudofovea location and visual search performance (number of fixations, fixation duration). Superior performance (fewest and shortest fixations) was observed whenever saccades had to be performed in the direction of the pseudofovea. This finding supports the idea of the congruence between attention and eye movement shifts as the underlying mechanism.

The present data are in line with the observed relationship between pseudofovea location and reading performance (chapter 3): superior performance was found when the pseudofovea was right in those parts of the maze requiring eye movements from left to right. Moreover, the same relationship was also found for the other three directions studied. The underlying eye movement patterns as well as saccadic amplitude distributions undermined the idea that gaze is attracted by the pseudofovea location, with saccades preferentially performed on the horizontal axis if the pseudofovea is either left or right, whereas most saccades are performed upwards or downwards if the pseudofovea is either above or below fixation.

An obvious difference between the two studies should be mentioned, however: Whereas gaze was clearly attracted by the pseudofovea location in reading, the present study showed a preference for saccades on either the horizontal or vertical axis, depending on whether the pseudofovea was located on the horizontal or vertical axis. The reason why no clear preference for saccades in direction of the pseudofovea location occurred in the present study might be
Continuous visual search without foveal vision

due to the fact that – in contrast to reading a whole line of text - a particular
direction was rather short (3-5 stimuli). It is to be expected that gaze attraction
by the pseudofovea would have been more pronounced if each local direction
consisted of more stimuli. The fact that congruence between pseudofovea loca-
tion and maze direction enhanced visual search performance indicates that cov-
ert instead of overt attention shifts in direction of the pseudofovea can explain
the current results.

The fact that the observed relationship between pseudofovea location
and required gaze direction is not restricted to a task like reading, requiring eye
movements from left to right, indicates that neither an overtrained strategy to
move both attention and the eyes (Freeman, 1980) nor an anisometry of the
visual system (Carrasco et al., 2001) can explain the current findings. Rather, I
argue for a more general mechanism that leads to a performance advantage
whenever attention is drawn in a direction that is also the target of an upcoming
saccade. This assumption is in line with the predictions of the oculomotor
readiness theory (Klein, 1980; Klein et al., 1992) as well as the premotor the-
ory of attention (Rizzolatti et al., 1987).

What can be concluded from the present results for the development of
training applications? Even though the applicability of the current findings to
MD patients has to be further investigated, I speculate that – depending on the
task – the pseudofovea should be located such that it corresponds with the re-
quired gaze direction. In reading, this would be to the right of fixation, in line
with the stronger reduction in reading performance if information to the right
of fixation is not available as reported by Rayner et al. (1980).

The current study demonstrated the need to study the underlying eye
movement patterns to get a better understanding of the problems related with a
central visual field damage. Whereas I was able to explain the advantages and
disadvantages of particular pseudofovea locations, eye movement patterns have
the potential to investigate a number of related issues. For example, Safran,
Duret, Issenhuth, and Mermoud (1999) observed a large amount of pseudo
regressions and pseudo line losses in an MD patient as a result of switching
between several pseudofovea locations. Likewise, McMahon et al. (1991) ob-
served hypometric saccades and considerable square-wave jerk patterns in a
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task requiring eye movements from left to right. Taken together with the present results, I expect that patients could benefit from a training procedure that improves control over saccades directed to parafoveal and peripheral locations. The method I used to let subjects use a distinct area of their visual field for solving the visual search task has the potential to train this ability.
5. General Discussion

The present study was concerned with the control of eye movements in the absence of foveal vision. To study this issue in normal-sighted subjects, a gaze-contingent display technique was developed. With this method, the effects of a central scotoma as well as the advantages and disadvantages of particular pseudofovea locations were studied.

**Eye movements with a central scotoma.** The spontaneous development of a pseudofovea in a visual search task was investigated in chapter 2 ("Visual search with an artificial central scotoma"). Four out of six subjects developed a stable parafoveal pseudofovea location within five hours of training. By the end of the experiment, one of the subjects was able to perform saccades that bring the target directly to the pseudofovea location without the need for a fo-veating saccade. This behaviour indicates that at least a partial adaptation of the saccadic system must have taken place, with the pseudofovea as a new reference for the saccadic system. In MD patients, this ability is typically observed after several years after the onset of the disease (White & Bedell, 1990; Whittaker et al., 1988).

A standard technique to study the ability of the saccadic system to adapt to changes in the environment is to systematically shift the target location closer or further away from fixation during a saccade. As a result, the eyes do not land directly on the target, and small corrective saccades are performed. After a few trials, however, the oculomotor system adapts to the experimental manipulation by programming saccades that compensate for the induced error (Deubel, 1987). If saccadic gain has to be decreased, 30-60 trials are required for adaption, whereas gain increases take place within about 400 trials.

Heinen and Skavenski (1992) studied the effects of bilateral foveal lesions on eye movement behaviour in monkeys. Within two days, monkeys used a stable pseudofovea location for fixation. However, the development of the ability to perform non-foveating saccades lasted several weeks. Obviously, the saccadic system needs much longer to adapt than the fixation system. Furthermore, this time scale indicates that the adaptation observed as the result of a
central scotoma must be different from the adaptation following systematic gaze-contingent target displacements as described above.

**Eye movements without foveal vision in reading.** The findings reported in chapter 3 ("Reading without foveal vision") clearly contradict the prediction that a pseudofovea below fixation results in superior reading performance (Nilsson et al., 2003; Peli, 1986). Furthermore, the presented data are in contrast to Guez et al. (1993), who assume a superiority of a pseudofovea left because of the need to monitor "where the eyes have been" and the requirement to perform return sweeps. Note that return sweeps were not required in the current task as single lines of text had to be read. I therefore cannot rule out that a pseudofovea to the left of fixation would be helpful for this specific task. It is doubtful, however, whether such a benefit can overcome the general performance disadvantage of a pseudofovea left in reading.

The presented data are consistent with the observation that reading performance is superior if text to the right is available as compared to text to the left (e.g. Rayner et al., 1980). This finding is in line with the core assumptions of most current models of eye movements in reading (Engbert, Longtin, & Kliegl, 2002; Morrison, 1984; O'Regan, 1992; Reichle, Pollatsek, Fisher, & Rayner, 1998). An exception is the ideal-observer model Mr Chips (Legge, Klitz, & Tjan, 1997). One of the aims of Mr Chips is to provide explicit predictions about the effects of foveal lesions on reading performance. According to this model, a pseudofovea to the left of fixation should be best in the presence of a relative scotoma. The data presented here clearly contradict this assumption. I assume that this disagreement is due to the fact that Legge, Klitz et al. (1997) used a relative scotoma for their simulations, leaving information about letter spacing available.

It should be noted that Mr Chips predicts a high amount of regressions in the presence of a central scotoma under ideal conditions (i.e., if the subject performs as good as possible). In other words, the erratic zig-zag pattern of eye movements observed in reading could indicate a useful adaptation to the lack of foveal input instead of maladaptive saccadic behaviour. It would be interesting to further explore this idea by studying whether these untypical eye movement patterns can be overcome by prolonged training. In contrast, if "erratic"
eye movement patterns result from an adaptive process, they should be found even after long periods of training.

**Eye movements without foveal vision: The role of visuospatial attention.**
The experiment presented in chapter 3 ("Reading without foveal vision") indicated that the pseudofovea caused automatic overt shifts of attention, with a performance disadvantage if the pseudofovea is in opposite direction to the text. The experiment presented in chapter 4 ("Continuous visual search with a pseudofovea") demonstrated that the congruence effect observed in reading can be generalized to tasks that require eye movements from right to left, top to bottom, and bottom to top.

Taken together, the present data indicate that the pseudofovea location can be seen as a potential saccade target, competing with the task-relevant targets (e.g., the upcoming word or the next visual search target). Superior performance can be found whenever attention is drawn in a direction that is also the target of an upcoming saccade. In the following, some further ideas about the underlying mechanisms are described.

According to the *biased competition* model (Desimone, 1998; Desimone & Duncan, 1995), only a limited amount of information entering the visual system can be used for the control of behaviour. Consequently, it is necessary to filter out unwanted information. The biased competition approach assumes competition among stimuli in the visual field for visual processing and control of behaviour. Attention serves to resolve this competition by suppressing neuronal representations of behaviourally irrelevant stimuli.

In line with the biased competition model of attention, salience maps could serve to select saccade targets in the presence of both bottom-up and top-down influences. Findlay and Walker (1999) implemented this idea in their model of saccade generation, with the decision where to move the eyes determined by a peak on the salience map. In the presence of several potential targets, the point of highest salience is assumed to determine the saccade target.

Findlay and Walker (1999) suggest that the colliculus superior (CS) contains such a salience map, based on the fact that it is an important structure
for both orienting and saccade triggering (see Sparks, 1999, for an overview). A further region well suited for providing a salience map is the frontal eye field (FEF): in a visual search task, FEF activity increases immediately before the execution of an eye movement if the target location is within the receptive field of a neuron (Schall & Hanes, 1993).

According to the model of Findlay and Walker (1999), learning in the oculomotor system should be possible by modification of the salience map. In support of this view, Bichot, Schall and Thompson (1996) observed modulation of the properties of FEF neurons following intensive training of a visual search task.

In line with the biased competition model of attention (Desimone, 1998; Desimone & Duncan, 1995) and the model of Findlay and Walker (1999) Godijn and Theeuwes (2003) suggest that saccadic preparation can be understood as activity peaks on a salience map. Furthermore, they assume inhibition of surrounding locations (see figure 5.1 for an illustration). In the presence of two potential saccade targets, two saccades are prepared in parallel. The location that reaches the threshold first will become the target of the saccade. If the two targets are far from each other, the two activity peaks are assumed to inhibit each other. As a result, the threshold for the execution of a saccade will be reached later. In contrast, if the two targets are close to each other, activity is assumed to add up, and the threshold is approached faster.

Parallel programming of two saccades in the presence of a pseudofovea could be responsible for the eye movement patterns observed in the present study. In congruent trials, the threshold for the execution of a saccade is reached faster as the pseudofovea is in the neighbourhood of a saccade target relevant for the current task. Consequently, it is easier to perform saccades in the intended direction, leading to superior performance. In incongruent trials, on the other hand, activation at the location that represents the pseudofovea eventually reaches threshold before a saccade to the target (i.e., the next word) can be executed, resulting in saccades in opposite direction from the text (PF-L) or downwards (PF-B), with the risk of slippage from the line (see chapter 3).
Figure 5.1: Assumed activation patterns in a saccade map (adapted from: Godijn & Theeuwes, 2003). A: Preparation of a saccade to a target location, marked by small x, results in increased activity at the region representing the corresponding visual field location, whereas neighbouring locations are inhibited. B: In the presence of two potential saccade targets, two saccades are prepared in parallel, with mutual inhibition if saccade targets are far away from each other (broken lines: activation of single targets, straight lines: combined activity). C: If two saccades have to be prepared to locations close to each other, activation eventually adds up, with a peak between the two locations.

**Practical applications.** As remarked by Legge et al. (1997), developers of training procedures for patients with visual field losses “receive little guidance from theories of reading” (p. 525). For example, one of the goals of training programs is to instruct MD patients to use a particular pseudofovea location presumably suited better for that task. Notably, patients are typically instructed to use a pseudofovea location above or below fixation for reading. (Nilsson et al., 2003; Nilsson et al., 1998). The present research provides theoretical background for the understanding of advantages and disadvantages of particular pseudofovea locations, with worst performance for a pseudofovea below fixation. Furthermore, the gaze-contingent display technique presented here is capable to train the use of a particular pseudofovea location. I hope that these findings can trigger the development of more effective training programs for the improvement of visual tasks in patients with macular degeneration.
6. References


References


Godijn, R., & Theeuwes, J. (2003). The relationship between exogenous and endogenous saccades and attention. In J. Hyönä, R. Radach & H. Deubel (Eds.), *The mind's eye: cognitive and applied aspects of eye movement research.* (pp. 3-26).


References


References


7. Appendix

Gaze-contingent display procedure

In the following, the gaze-contingent display procedure is presented. As the general mechanism is identical both for the central scotoma (chapter 2) and the pseudofovea (chapters 3-4), I start with a description for the procedure used for the pseudofovea.

The gaze-contingent display procedure blurs all visual information except at a small circular area (“pseudofovea”) at a fixed distance from the fovea (see figure 1 for an illustration). As the eyes move, the pseudofovea moves correspondingly, momentarily unblurring the text, whereas that at its previous location becomes blurred again. To do so, eye movements are continuously recorded by a video-based eye tracking system (EyeLink I, SR Research), tracking the pupil of both eyes at a sampling rate of 250 Hz. Online detection of saccades and fixations is based on a criterion that includes both saccade velocity (30°/sec.) and acceleration (8000°/sec²).
Figure 1: Illustration of the gaze-contingent display procedure. For each trial, two bitmaps of the same stimulus picture are created, called \textit{Blur (lower left)} and \textit{Sharp (lower right)}. \textit{Blur} is derived from \textit{Sharp} by smoothing with a gaussian blur function. The pseudofovea (see \textbf{top} of the figure) is generated by forming a weighted average of the corresponding pixels of \textit{Sharp} and \textit{Blur} at the desired location. Computation is restricted to a 81x81 pixel region around the current fixation, as indicated by the grid on \textit{Sharp} and \textit{Blur}. Within this region, the RGB values of \textit{Sharp} and \textit{Blur} are averaged, weighted by the corresponding weight matrix. The weight matrix $\omega(i, j)$ defines the extent and shape of the pseudofovea, with smooth transitions at the boundaries. The resulting matrix containing the computed RGB values at the pseudofovea location is copied to the screen. See text for details.
The main problem in implementing the procedure is speed. To minimize computational effort, I use the following algorithm. For a trial, two bit-maps of the same stimulus picture are created, called *Sharp* and *Blur*, respectively. *Blur* is derived from *Sharp* by smoothing with a gaussian blur function (CorelDraw 10) with a radius of 17 pixel. The pseudofovea is generated by forming a weighted average of the corresponding pixels of *Sharp* and *Blur* at the desired location; call the resulting bitmap PF. The weight matrix $\omega(i, j)$ defines the extent and shape of the pseudofovea, with smooth transitions at the boundaries. It is given by the following function:

$$
\omega(p) = \begin{cases} 
1 & p > 1 \\
1 - 2p^2 & \frac{1}{2} \leq p \leq 1 \\
2(1-p)^2 & 0 \leq p < \frac{1}{2} \\
0 & p \leq 0 
\end{cases}
$$

where $p = \frac{d - i}{o - i}$

where $d$ is the Euclidian distance of the pixel under consideration from the centre of the pseudofovea, and $o$ and $i$ give the range within the weights are different from 0 and 1 (see figure 2).

Figure 2: Illustration of the weight matrix used for computation of the RGB values within the 81x81 matrix.
I sketch the algorithm for the case when the pseudofovea is centered around the point of gaze (x, y):

1. Read in RGB values of Blur and Sharp.

2. Display Blur.

3. Determine the gaze coordinates (x, y).

4. Compute the RGB values within the (2n+1) x (2n+1) area defining PF by:

\[
RGB_{PF}(x+i, y+j) = RGB_{sharp}(x+i, y+j) \times \omega(i, j) + RGB_{blur}(x+i, y+j) \times (1 - \omega(i, j))
\]

where \(|i|, |j| \leq n\).

5. Display PF on the screen, centered at (x, y).

6. As soon as a change in gaze position is registered, display Blur.

7. Go to step 3.

The routine works identically when the pseudofovea is shifted (e.g. to the left or below fixation), except that the shift coordinates with respect to fixation (e.g. 80 pixel to the left) is added to current gaze position. For creation of the central scotoma, the routine works identically as described above. The only difference is that the roles of Blur and Sharp are reversed (i.e., Sharp is displayed to the screen in step 2 and 6).

I used the BitBlt function in step 5. BitBlt provides a fast copy of rectangular regions of a bitmap to the current screen (see Petzold, 2000). Altogether, the procedure takes 11.48 msec from detecting a change in gaze position to the end of the new BitBlt to the screen.
### Table 2.1: Individual results for the effect of training session on horizontal and vertical pseudofovea location.

<table>
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## Table 2.2: Individual results for the effect of target location on pseudofovea location. Target locations resulting in significantly different pseudofovea locations, as revealed by post hoc comparisons against the mean effect, are indicated by one or two stars (*: p<.10, **: p<.05).
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Table 2.3: Individual results for the effect of target type, together with the associated horizontal and vertical pseudofovea location (*: $p<.10$, **: $p<.05$).
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<th>fixation duration [msec]</th>
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<td>PF location below</td>
<td>control</td>
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<td>12.8 ( 2.3)</td>
<td>51.6 ( 5.2)</td>
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<td>19.8 ( 1.3)</td>
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</tbody>
</table>

Table 3.1: Mean and standard error (se) for reading rate, number of fixations and fixation duration in experiment 1.
Table 3.2: Mean and standard error (SE) for reading rate, number of fixations and fixation duration in experiment 2.
### Table 4.1: Example design matrix, indicating the ordering of warm-up, training and experimental conditions. Conditions marked grey were excluded from data analysis.
Table 4.2: Mean and standard error (SE) for number of fixations and fixation duration for all combinations of maze direction and pseudofovea location.

<table>
<thead>
<tr>
<th>maze direction</th>
<th>PF location</th>
<th>number of fixations</th>
<th>fixation duration [msec]</th>
</tr>
</thead>
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<tr>
<td></td>
<td>left</td>
<td>right</td>
<td>above</td>
</tr>
<tr>
<td>left</td>
<td>48.21</td>
<td>95.13</td>
<td>58.58</td>
</tr>
<tr>
<td></td>
<td>(4.7)</td>
<td>(12.6)</td>
<td>(5.7)</td>
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<tr>
<td>right</td>
<td>73.58</td>
<td>54.54</td>
<td>46.88</td>
</tr>
<tr>
<td></td>
<td>(6.8)</td>
<td>(7.9)</td>
<td>(4.6)</td>
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<tr>
<td>up</td>
<td>42.96</td>
<td>47.0</td>
<td>52.67</td>
</tr>
<tr>
<td></td>
<td>(4.0)</td>
<td>(5.5)</td>
<td>(3.0)</td>
</tr>
<tr>
<td>down</td>
<td>47.88</td>
<td>58.04</td>
<td>87.0</td>
</tr>
<tr>
<td></td>
<td>(4.5)</td>
<td>(8.5)</td>
<td>(11.5)</td>
</tr>
</tbody>
</table>