

# (Un-) Coupling gaze and attention outside central vision

**Angelika Lingnau**

Center for Mind/Brain Sciences, Trento University, Italy, &  
Department of Psychology, Technical University of  
Braunschweig, Germany



**Jens Schwarzbach**

Center for Mind/Brain Sciences and Department of Cognitive  
Science and Education, Trento University, Italy



**Dirk Vorberg**

Department of Psychology, University of Münster, Germany, &  
Department of Psychology, Technical University of  
Braunschweig, Germany



In normal vision, shifts of attention and gaze are tightly coupled. Here we ask if this coupling affects performance also when central vision is not available. To this aim, we trained normal-sighted participants to perform a visual search task while vision was restricted to a gaze-contingent viewing window (“forced field location”) either in the left, right, upper, or lower visual field. Gaze direction was manipulated within a continuous visual search task that required leftward, rightward, upward, or downward eye movements. We found no general performance advantage for a particular part of the visual field or for a specific gaze direction. Rather, performance depended on the coordination of visual attention and eye movements, with impaired performance when sustained attention and gaze have to be moved in opposite directions. Our results suggest that during early stages of central visual field loss, the optimal location for the substitution of foveal vision does not depend on the particular retinal location alone, as has previously been thought, but also on the gaze direction required by the task the patient wishes to perform.

**Keywords:** eye movements, attention, low vision, central visual field loss, macular degeneration, preferred retinal location

**Citation:** Lingnau, A., Schwarzbach, J., & Vorberg, D. (2010). (Un-) Coupling gaze and attention outside central vision. *Journal of Vision*, 10(11):13, 1–13, <http://www.journalofvision.org/content/10/11/13>, doi:10.1167/10.11.13.

## Introduction

During visual exploration of a scene, we move our eyes 4–5 times per second. Typically, the control of saccadic eye movements and visual attention are tightly linked, i.e., eye movements to a position in space are preceded by shifts of transient attention to the same location (e.g., Henderson, 1993). Behavioral studies have shown that it is almost impossible to dissociate attended and saccade target locations (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995). In line with this view, a growing body of evidence suggests common neural substrates for attention and eye movements (Awh, Armstrong, & Moore, 2006; Corbetta et al., 1998; Moore & Fallah, 2001; Rizzolatti, Riggio, Dascola, & Umiltà, 1987).

Two distinct modes of visual attention have been suggested (Corbetta & Shulman, 2002; Nakayama & Mackeben, 1989): *transient* attention refers to a temporal improvement of performance that peaks at a cue-lead time of approximately 80 to 100 ms and rapidly decays with longer cue-lead times, whereas *sustained* attention refers to an enhancement of performance over longer time periods that builds up more slowly. Typically, sustained attention is assumed to be under voluntary control and to

be directable even to blank parts of the screen, whereas transient attention is usually assumed to be automatically driven.

Outside the laboratory, we need to uncouple sustained attention from gaze in situations that involve several tasks in parallel such as driving a car and attending pedestrians that are about to cross the street, or talking to a person while reaching for a glass of water. A particular need to dissociate sustained attention from gaze exists for patients with macular degeneration (MD) who suffer from central visual field loss due to irreversible damage to photoreceptors in the central part of the retina (for reviews, see Cheung & Legge, 2005; Rattner & Nathans, 2006). As a result, these patients have to learn not to directly fixate visual targets. Instead, they have to produce non-foveating saccades that project the target to a peripheral location on the retina not affected by the disease, usually called *pseudofovea* or *preferred retinal location* (Fletcher, Schuchard, & Watson, 1999; Timberlake et al., 1986; Timberlake, Peli, Essock, & Augliere, 1987; see Figure 1). Patients who suffer from central visual field loss typically have severely reduced reading rates (Fletcher et al., 1999; Legge, Rubin, Pelli, & Schleske, 1985), and this impairment increases with the size of the central scotoma (Cummings, Whittaker, Watson, & Budd, 1985; Sunness, Applegate, Haselwood, & Rubin, 1996).

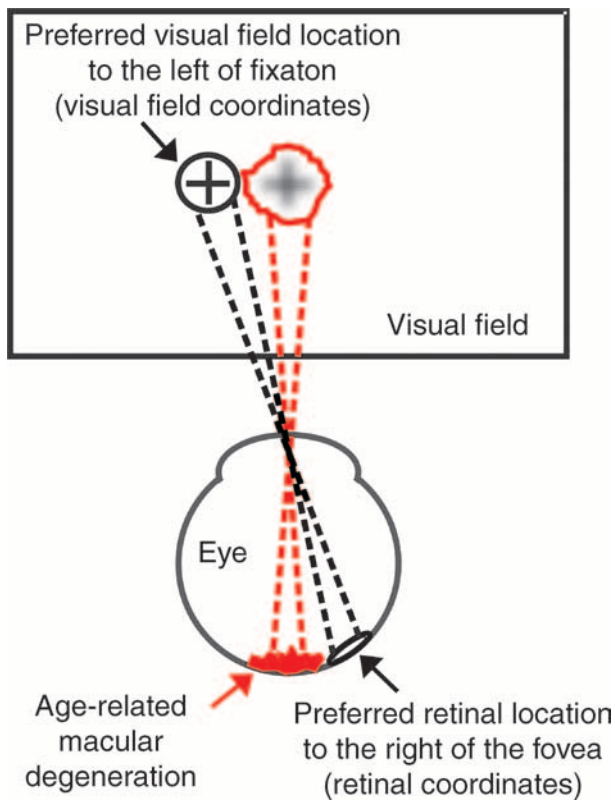


Figure 1. Patients suffering from age-related macular degeneration experience stimuli presented foveally as strongly blurred or even absent. As a result, they are forced to substitute foveal vision by using off-foveal locations called pseudofovea or “preferred retinal location” (PRL).

It is generally reported that an idiosyncratic PRL develops in about 80% of all eyes affected by a macular scotoma (Fletcher & Schuchard, 1997; Fletcher et al., 1999; Trauzettel-Klosinski & Tornow, 1996). There seems to exist no simple rule regarding the choice of a PRL. In those eyes that developed a PRL, it corresponds to the left visual field in 11–63%, to the right visual field in 15–20%, to the upper visual field in 5–19%, and to the lower visual field in 19–49% of the cases (Fletcher & Schuchard, 1997; Fletcher et al., 1999; Sunness et al., 1996; Trauzettel-Klosinski & Tornow, 1996). It is unclear, however, whether preferred retinal locations that develop in individual patients are optimal for daily life activities, such as reading or scene perception.

There is an ongoing debate as to which part of the visual field is best suited for the substitution of foveal vision. Anatomical studies have shown an overrepresentation of the horizontal versus the vertical meridian (Curcio & Allen, 1990), suggesting that a PRL to the left or right of central fixation might be best. Reading performance has been found to be impaired when the right in comparison to the left visual field is withheld from the reader (Lingnau, Schwarzbach, & Vorberg, 2008; Rayner, Well, Pollatsek, & Bertera, 1982; Trauzettel-Klosinski & Brendler, 1998).

In contrast, reading speed in rapid serial visual presentation (RSVP) tasks (which eliminate eye movements) has been reported to be higher in the lower visual field, as compared to the left or right visual field (Fine & Rubin, 1999; Petre, Hazel, Fine, & Rubin, 2000). In line with these findings, better performance in tasks like target detection and localization has been reported in the inferior as compared to the superior visual field (Carrasco, Talgar, & Cameron, 2001; He, Cavanagh, & Intriligator, 1996; Mackeben, 1999), which seems to suggest that patients can benefit more from a PRL below central fixation. In the light of these conflicting results, it is not surprising that there is little consensus on which preferred retinal location is optimal (Fletcher et al., 1999; Nilsson, Frennesson, & Nilsson, 2003; Petre et al., 2000; Stelmack, Massof, & Stelmack, 2004; Trauzettel-Klosinski & Brendler, 1998).

As pointed out above, to process information available at an off-foveal location, patients have to shift sustained attention away from the fovea toward this location (Altpeter, Mackeben, & Trauzettel-Klosinski, 2000; Lingnau et al., 2008). At the same time, to be able to move the eyes to a specific location, attention is transiently shifted toward the upcoming saccadic landing position. It is unclear whether and how the coupling between transient attention and the control of saccadic eye movements, on the one hand, and the need to dissociate sustained attention from gaze, on the other hand, affects performance in non-foveal vision, but such knowledge seems crucial for the design of efficient training procedures.

In a previous study (Lingnau et al., 2008), we have examined which part of the visual field is best suited to substitute foveal vision when normal-sighted participants are forced to read text via a small gaze-contingent viewing window (“Forced Field Location,” FFL) to the left, right, or below fixation (note that we use visual field coordinates throughout). We observed that reading rates were highest when an FFL to the right of fixation was used, and lowest with an FFL below fixation. We explained this finding by the coordination of attentional shifts with the programming of subsequent saccades: To extract information at the FFL, participants must covertly shift sustained attention to that location. For reading, they must move the eyes from one word to the next (i.e., from left to right, at least in the western culture), with each eye movement presumably preceded by a transient shift of attention toward the upcoming saccadic landing position. With a forced field location to the right of fixation, shifts of sustained attention and eye movements are in spatial register, which in turn leads to superior performance in that condition, whereas performance is impaired when sustained attention and gaze must be shifted in opposite or orthogonal directions.

In our previous study, overall gaze direction was fixed (from left to right, due to the natural arrangement of text). Therefore, it was not possible to rule out an alternative explanation: reading with an FFL to the right of fixation might simply be better because of general preferences for

stimuli presented right of fixation, irrespective of gaze direction, e.g., due to visual field asymmetries or hemispheric differences in language processing. The aim of the current study was to distinguish between this alternative explanation and the assumption that perception via an off-foveal location depends on the dynamic coordination of attention and gaze direction. To this aim, we adopted a continuous visual search task (Hooge & Erkelens, 1998; Trukenbrod & Engbert, 2007) in combination with our gaze-contingent display technique (Lingnau et al., 2008) that forces participants to use a distinct non-foveal location. The visual search task required finding the path in a maze, from a central start position to an unknown goal position (Figure 2). Each path involved leftward, rightward, upward, and downward eye movements, which were assigned to regions of interest (ROIs; see Figure 2) for the analysis. The relative position of the FFL ( $2.41^\circ$  to the left, right, above, or below fixation) was varied blockwise as a within-subject factor. Performance level was operationalized by the number of fixations required to move through a particular region of interest, as a function of FFL position and current search direction. If performance depends on the coordination of shifts of attention and gaze direction, we predict interactions between search direction and FFL, with impaired



Figure 2. Sample maze (unblurred version; see Figure A1 for a blurred version of the same maze). The task is to follow a path through the maze, indicated by the direction of the arrows and the location of the gaps within the Landolt rings, and to indicate by button press the orientation of a target consisting of a straight line oriented either horizontal or vertical (example shown: vertical, with the target location marked by the dashed white circle, which was not shown in the experiment). The start position is indicated by a red Landolt ring. In this example, the participant has to move two elements downward from the start position, then to continue toward the left, etc. For analysis, mazes were divided into regions of interest that require straight leftward, rightward, upward, or downward eye movements, here indicated by the red, green, blue, and yellow rectangles superimposed onto the maze. Rectangles were not shown during the experiment.

performance whenever sustained attention and gaze must be shifted in different directions.

To anticipate our findings, performance is severely impaired when sustained attention and gaze have to be shifted in opposite directions, as compared to moving the eyes in the same or an orthogonal direction relative to the FFL. However, performance is unaffected by search direction or the position of the FFL alone. These results strongly argue against a general advantage for stimuli presented at a particular visual field location, e.g., to the right of fixation. Rather, our data suggest that performance in non-foveal vision depends on the *coordination* of attention and eye movements, with impaired performance when sustained attention and eyes have to be moved in opposite directions.

## Methods

### Participants

Six female participants from Technical University of Braunschweig, Germany, aged between 22 and 34, participated in the experiment, either as a course requirement or for a pay of €7.50 per session. All participants had normal or corrected-to-normal vision.

### Apparatus

Eye movements from both eyes were recorded by a high-speed (250 Hz) video-based eye tracking system (EyeLink I). Stimuli were presented on an Iiyama Vision Master 451 monitor (18"), with screen resolution of  $800 \times 600$  pixels and refresh rate of 85 Hz. The monitor was positioned 76 cm from the participant; the diameter of the FFL was  $2.41^\circ$ . Gaze-contingent stimulus presentation and randomization was programmed in C, using the MS Visual C++ 6.0 platform. For eye movement recording, standard libraries supplied with EyeLink were used.

Participants 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. For technical details of the gaze-contingent window procedure, see Lingnau et al. (2008) and Appendix A.

### Task

Participants were instructed to find the path through a maze from a given start position to the goal position that contains the target (Figure 2). In each trial, a maze was presented, which consisted of an  $8 \times 8$  array of Landolt rings. The start position (one of the four central squares)

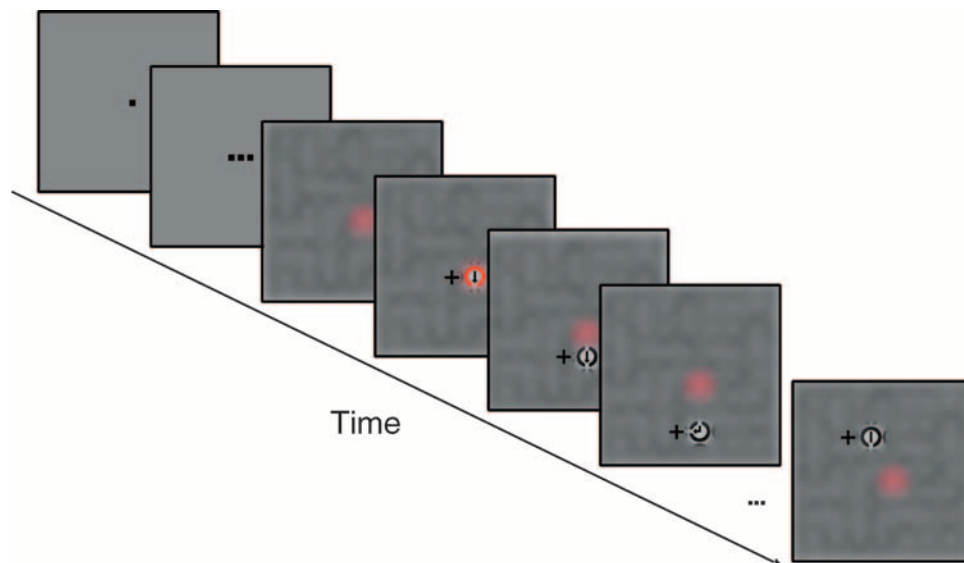


Figure 3. Illustration of trial scheme. Example shown: FFL to the right of fixation. Black cross (not shown during the experiment) illustrates hypothetical fixation position.

was marked in red. Each ring contained an arrow that indicated where to move next, as well as an entry and an exit gap. The target consisted of a ring that contained a horizontal or vertical line, rather than an arrow. Mazes contained just one connected path from start to target; there were no blind alleys leaving the path (see [Material](#) section for further details). Since mazes were strongly blurred everywhere except around the element projecting on the FFL ([Figure 3](#)), participants had to position the FFL on each single Landolt ring in order to know where to move next.

## Trial procedure

Participants started a trial by pressing a button while fixating a dot on the center of the screen. Trials continued with the presentation of three single dots on a horizontal line for 6 s, followed by the presentation of the blurred version of the maze, which changed contingent on eye fixation ([Figure 3](#)). The start position was always on one of the four central squares that neighbored the fixation dot presented before the trial started. When they had found the target location, participants had to indicate the target's orientation (vertical vs. horizontal) by pressing the corresponding response key on the keyboard. The time to key-press defined the response time. Trials were terminated either by a response or if no response was made within 60 s.

## Instruction

At the beginning of the first session, participants received written instructions about the task. They were informed that

they had lost track of the main path if the arrows did not form a connected part. Our previous experiments (Lingnau et al., 2008) had shown that vision via an FFL is extremely demanding; therefore, participants were informed that centering the FFL on a given stimulus can be achieved by fixating the appropriate neighboring location (e.g., to the left of the current target if the FFL is right of fixation, as in the example shown in [Figure 3](#)).

Participants were instructed to move their head and body as little as possible during data recording. Before each experimental block, participants were informed about the current position of the FFL.

## Design

FFL position and search direction were treated as independent within-subject variables. The experimental conditions FFL left (FFL-L), right (FFL-R), above (FFL-A), and below (FFL-B) fixation were defined by the FFL center coordinates relative to fixation, given by  $(-2.41^\circ, 0^\circ)$ ,  $(2.41^\circ, 0^\circ)$ ,  $(0^\circ, 2.41^\circ)$ , and  $(0^\circ, -2.41^\circ)$  visual angles, respectively. Each session started with a warm-up block containing central FFL-0 ( $0^\circ, 0^\circ$ ) trials only, which was excluded from data analysis. Within each maze, each search direction occurred at least once (see [Material](#) section for further details). FFL position was held constant within blocks but varied randomly between blocks of 10 trials.

## Material

Mazes consisted of 64 Landolt rings, placed on an invisible  $8 \times 8$  grid subtending  $10.5 \times 10.5^\circ$  visual angle. For each maze, a blurred version was created by applying a

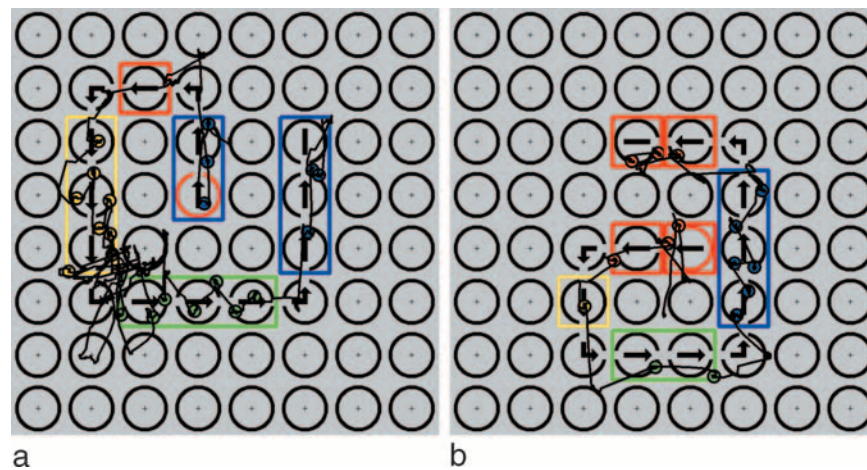


Figure 4. Sample eye traces (participant 1, session 5) for (a) FFL-A and (b) FFL-B. Colored circles indicate the landing positions of the FFL in ROIs for leftward (red), rightward (green), upward (blue), and downward (yellow) eye movements.

Gaussian filter (full width at half maximum: 36 pixels, equal to  $1.09^\circ$ ) to the original image (Figure A1). The filter blurred bitmaps strongly enough to delete almost all information regarding the arrow directions and the gaps within the Landolt rings but left the start position clearly visible due to its red color.

Distance between the centers of adjacent rings was  $1.51^\circ$ , and the diameter of each ring was  $1.21^\circ$  (see also Figure A2). The start position was marked by a red ring, and all other rings were black. The rings at the start and end positions contained one gap only ( $0.13^\circ$ ), and all other rings contained two gaps. The path to follow was indicated both by the arrow (size of straight arrow:  $0.84 \times 0.12^\circ$ ) within each ring and by the gap locations on the ring.

Mazes were constructed with the following restrictions: (a) the start position was on one of the four central positions on the  $8 \times 8$  grid, (b) the target location was never adjacent to the start position, (c) each of the four directions occurred at least once on the path and with equal probability, (d) a given direction was maintained for 3 to 5 successive steps, (e) paths consisted of 12 to 16 steps from start to target location, and (f) did not leave the central  $6 \times 6$  grid from start to target location. Directions of arrows in rings off the path from start to target position were assigned randomly. To prevent contextual learning effects, 225 different mazes were constructed, which were shown once only to each participant.

## Layout of experimental sessions

Each participant performed five 1-h sessions, which consisted of four blocks each, preceded by a warm-up block. Warm-up blocks at the beginning of each session contained five trials with FFL-0. There were four types of experimental blocks, defined by the relative position of the FFL. Blocks consisted of 10 trials each; order of conditions was randomized within and between sessions. The first

session served to familiarize participants with the task and used all four FFL positions with half the eccentricity of that used in the following sessions; data from this session were excluded from data analysis. Altogether, 40 replications per condition and participant entered the data analyses.

## Data analysis

Data analysis was based on the data from the left eye. For detection of saccades and fixations, standard libraries supplied with EyeLink were used. Eye movements were identified as saccades when velocity exceeded  $30^\circ/\text{s}$  or acceleration exceeded  $8000^\circ/\text{s}^2$ . Trials in which participants gave the wrong or no response within the given time window (11.8%) were excluded from the analysis. Off-screen fixations were removed from the data. Regions of interest (ROIs) were determined by the search direction for each segment on the path from start to target position (Figure 2) in the given maze. Fixations falling on elements with arrows indicating a directional change were not included in the ROI-based analysis; thus, adjacent ROIs were separated by one or two fixations at least. FFL coordinates, rather than those of central fixation, were used for the analysis. In Figure 4, center coordinates of the FFL detected in a specific ROI are colored accordingly. Note that in the remainder of this paper, we refer to the landing positions of the center coordinates of the FFL as *fixations*, whereas we use the term *central fixation* when we refer to the coordinates corresponding to the fovea.

For each trial and path segment, we computed how often the center of the FFL landed within an ROI as a function of search direction (leftward, rightward, upward, downward; see Figures 2 and 4 for illustrations of corresponding regions of interest) and FFL position (FFL-L, FFL-R, FFL-A, FFL-B).

Number of fixations and fixation durations were summarized by trimmed means per participant and condition,

trimming 10% each from above and below (Wilcox, 1997). Since the ROIs differed in size (see [Material](#) section for further details), numbers of fixations per ROI were normalized by dividing by the number of elements (Landolt rings) per ROI. Trimmed mean number of fixations and fixation durations were subjected to separate  $4 \times 4 \times 4$  repeated-measures ANOVAs, with *FFL position*, *Search Direction*, and *Session Number* as factors.

## Results

### Number of fixations per element: Main effects

Participants fixated each maze element 2.2 times on average. Number of fixations per element within a region of interest was unaffected by search direction [ $F(3,15) = 0.679$ ,  $p = 0.578$ ] ([Figure 5a](#)) and by FFL position [ $F(3,15) = 0.686$ ,  $p = 0.574$ ] ([Figure 5b](#)). Across experimental sessions, participants required fewer fixations to follow the path through the maze [ $F(3, 15) = 5.264$ ,  $p = 0.04$ ] ([Figure 5c](#)).

Average fixation duration (462 ms) was affected neither by search direction [ $F(3, 15) = 2.438$ ;  $p = 0.105$ ] nor by FFL position [ $F(3, 15) = 1.585$ ;  $p = 0.235$ ]. Fixation duration did not change with experimental sessions [ $F(3,15) = 1.291$ ;  $p = 0.314$ ].

### Number of fixations per element: Interactive effects

Crucially, gaze behavior was strongly affected by the conjunction of current search direction and FFL position [ $F(9,45) = 16.408$ ,  $p < 0.0001$ ] ([Figure 6a](#)): Participants required about the same number of fixations per element, whether search direction and FFL position were the same

or orthogonal to each other. However, almost twice as many fixations per element were needed to follow path segments pointing in a direction opposite to the current FFL position.

Neither search direction [ $F(4, 45) = 0.471$ ,  $p = 0.886$ ] nor FFL position [ $F(9, 45) = 0.569$ ,  $p = 0.815$ ] interacted with experimental session. The interaction of search direction and FFL position changed little with practice [interaction FFL position  $\times$  search direction  $\times$  session:  $F(27, 135) = 1.45$ ,  $p = 0.088$ ].

To highlight the interaction of search direction and FFL position, we collapsed experimental conditions according to the search direction relative to the FFL position, classifying them as same (e.g., FFL-L, search direction leftward), opposite (e.g., FFL-L, search direction rightward), or orthogonal (e.g., FFL-L, search direction upward/downward). [Figure 6b](#) shows that most fixations were needed for search in a direction opposite to that of the FFL position, compared to when search direction and FFL position were either the same [ $F(1,5) = 97.29$ ,  $p < 0.0001$ ] or orthogonal [ $F(1,5) = 53.64$ ,  $p = 0.001$ ]. Number of fixations did not differ for same and orthogonal directions [ $F(1,5) = 0.237$ ,  $p = 0.647$ ].

In contrast to number of fixations, fixation durations showed no interaction of search direction and FFL position [ $F(9,45) = 1.24$ ;  $p = 0.295$ ].

## Discussion

We investigated how gaze direction and attention are coupled if central vision is prevented by a gaze-contingent display technique that restricts vision to a small off-foveal viewing window. We demonstrated that performance strongly depends on the relation between search direction and FFL position relative to the fovea. When participants must move their eyes in a direction opposite to the part of the visual field they are currently forced to use,

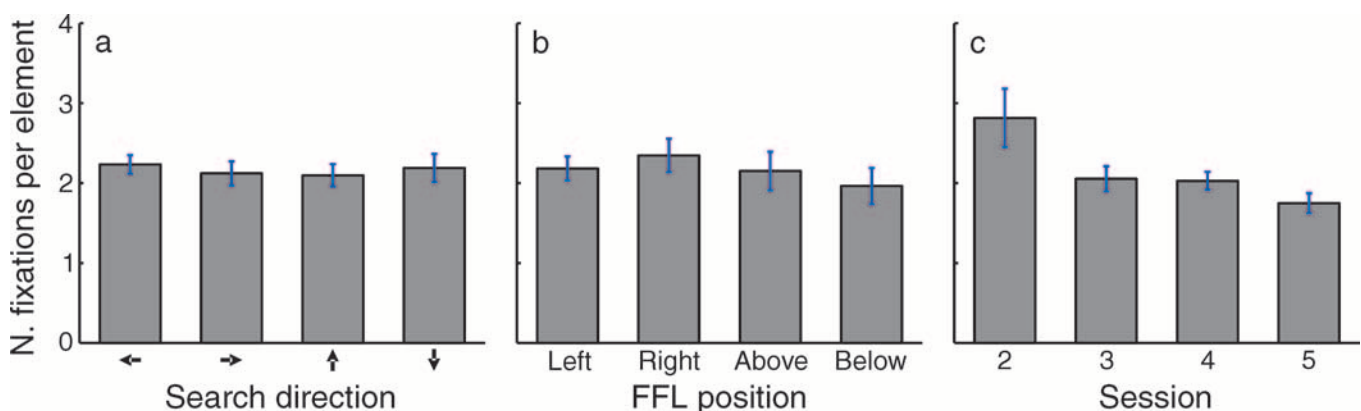


Figure 5. Effects of (a) search direction (leftward, rightward, upward, downward), (b) FFL position, and (c) experimental session on number of fixations per element. Error bars show standard errors of the mean (SEM).

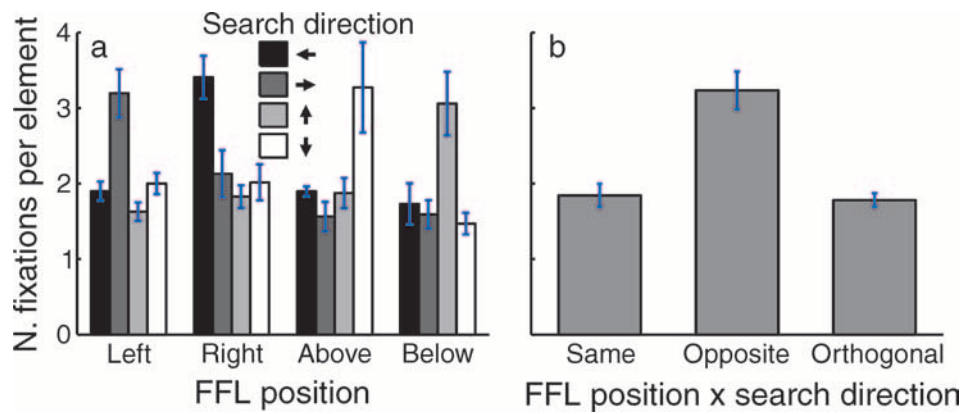


Figure 6. (a) The effect of FFL position and search direction on number of fixations per element. Black: search direction leftward, dark gray: search direction rightward, bright gray: search direction upward, white: search direction downward. (b) The effect of congruency between FFL position and search direction (“same,” “opposite,” “orthogonal”; see text for details) on number of fixations. Error bars indicate standard errors of the mean (*SEM*).

performance severely deteriorates, in comparison to when sustained attention and gaze direction are in register.

Our findings can be best explained on the basis of the known coupling between covert attention shifts and saccadic eye movements (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Klein, 1980; Klein, Kingstone, & Pontefract, 1992; Rizzolatti et al., 1987). We assume that processing information available just at the FFL requires that sustained attention is directed toward the FFL. At the same time, participants have to move their eyes in the direction indicated by each single element of the maze, which requires transient attention shifts toward the upcoming saccade landing position (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Klein, 1980; Klein et al., 1992; Rizzolatti et al., 1987).

Figure 7 illustrates the sequences of eye and attention movements likely to be involved in traversing a path from one position to the next, for an FFL left of fixation. At time  $t_0$ , the eye fixates a location such that sustained attention (symbolized by the gray and black circle) is centered on the FFL left of fixation (symbolized by the white disk), which allows recognition of the direction to be followed next, as indicated by the arrows in Figures 7a–7c.

If the current information indicates that a leftward step is required next ( $t_0$ ), the eye simply moves to the current focus of attention ( $t_1$ ), after which sustained attention is shifted left ( $t_2$ ), which allows extracting the next piece of direction information (Figure 7a). Thus, following a leftward arrow minimally involves a sequence of one attention shift and one eye movement ( $a + e$ ).

The situation is slightly more complex for steps in an orthogonal direction (Figure 7b). First, attention must be transiently moved in a diagonal direction ( $t_1$ ), which is followed by a saccade to this location ( $t_2$ ), which, after a move of sustained attention to the left ( $t_3$ ), allows decoding the next direction cue. Altogether, such a sequence

requires one eye movement plus two attention shifts ( $a_{\text{diag}} + e + a$ ).

For moves in the opposite direction, transient attention must be shifted by a double-sized step following the decoding of the instruction at  $t_0$ , such that it lands to the right of the current eye position ( $t_1$ ) before the eye can also be moved there at  $t_2$  (Figure 7c). To extract the next piece of directional information, sustained attention must be decoupled again from eye position, shifting left at  $t_3$ . In summary, sequences that require shifts of attention and gaze in opposite directions require one double-sized step of attention, one eye movement, and one single-sized step of attention ( $a_2 + e + a$ ).

### Impaired performance when attention and gaze are shifted in opposite direction

According to the processes illustrated in Figure 7, one would expect impaired performance both when participants have to shift attention and gaze in orthogonal as well as in opposite directions. Instead, we found impaired performance for opposite directions only. In line with these findings, Hooge and Frens (2000) observed that participants required more time to generate saccades toward previously fixated locations, requiring a reversal of the saccade direction. Hooge and Frens (2000) termed this phenomenon *Inhibition of Saccade Return* and suggested that it takes place at the level of the planning stage of saccades. This observation is compatible with the idea that during the generation of saccades in a particular direction, neurons that encode the opposite direction are inhibited. Assuming that there is a certain overlap in the neuronal resources involved in planning and executing saccades and shifting attention, such an inhibitory mechanism could impair performance when attention and gaze must be shifted in opposite directions: either by increasing the time

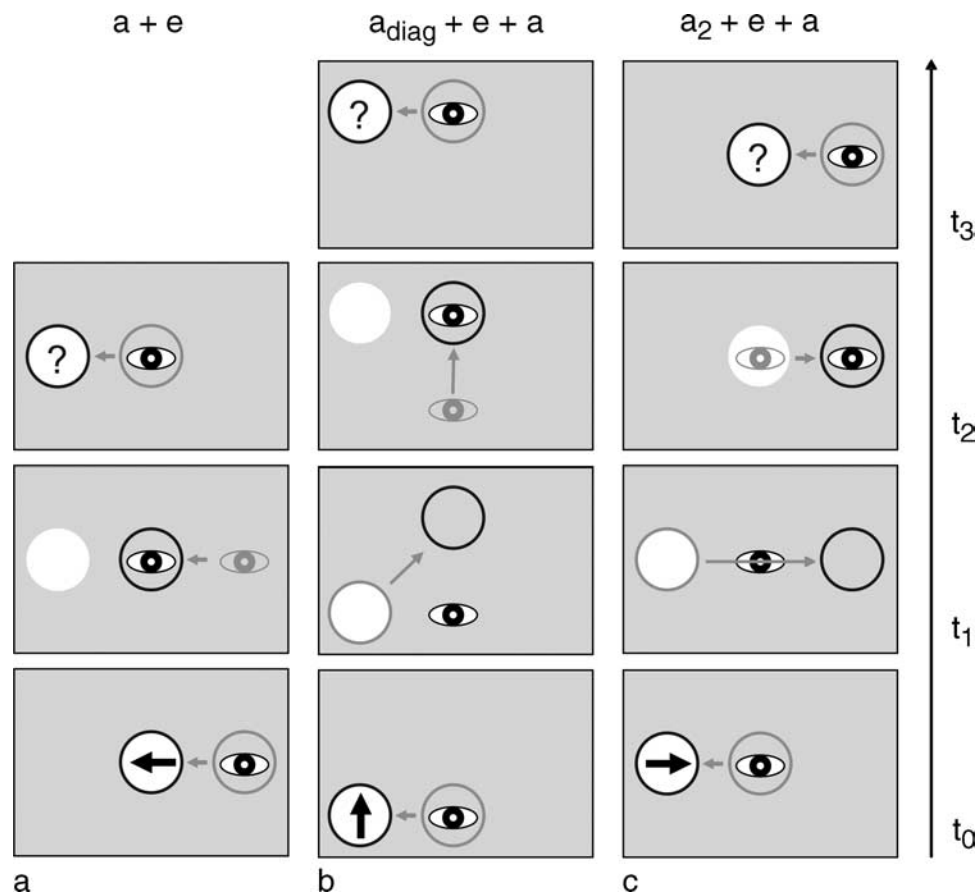


Figure 7. Sequences of eye and attention movements that are needed for traversing a path from one position to the next, when attention and eyes are to be moved in the (a) same, (b) orthogonal, or (c) opposite directions. In the examples, FFL position is left relative to fixation. Expressions provided in the top panel indicate predicted durations. Symbols: Black eye: current fixation position; gray eye: fixation position at  $t_{-1}$ ; black circle: currently attended position; gray circle: position attended in  $t_{-1}$ ; white disk: FFL, large black arrow: required eye movement direction, small gray arrow: required shift of attention. See text for details.

required to generate a saccade, or by missing the saccadic target positions, which in turn increases the number of fixations required to solve the task.

### No impairment when attention and gaze are shifted in orthogonal directions

Note that in our previous study on reading with a forced field location (Lingnau et al., 2008), we observed the largest impairment for reading with an FFL below central fixation, i.e., orthogonally to the left-to-right reading direction. Although we chose the continuous visual search task because of its sequential nature, in analogy to reading, there are obviously differences between reading and visual search that might have caused the behavioral differences in the two paradigms.

First of all, in reading, information from a region extending to roughly 15 letter spaces to the right of central fixation (“perceptual span”) is used to determine suitable saccadic landing positions (Liversedge & Findlay, 2000; Starr & Rayner, 2001), whereas little information from

below the current line is processed (Pollatsek, Raney, Lagasse, & Rayner, 1993). Information picked up within the perceptual span thus allows the reader to adjust saccade amplitude, skipping short words and function words if possible. Saccade direction, in contrast, must be changed during return sweeps from the end of a line of text to the beginning to the next line only, or for refixations if it becomes evident that the text was not understood properly. Typically for reading in the western culture, upward or downward saccades are not required.

It has been suggested that in visual search, as in reading, information is preferentially processed from the location to be fixated next (e.g., Henderson, Pollatsek, & Rayner, 1989). In contrast to reading, however, each target element in the current paradigm indicated the position of the next one, which required either a saccade in the same direction or a directional change by  $90^\circ$ , but never in the opposite direction. Therefore, in the present study, participants may have become used to flexibly change gaze between all main directions, whereas in our reading paradigm, horizontal saccades may have been less demanding, which might have led to more impairment for an FFL below



central fixation. Taken together, we believe that the apparent differences between our current findings and our previous study are due to differences in task demands.

## Fixation durations

Fixation durations during scene perception and visual search typically range between 200 and 500 ms, depending on task demands and the type of stimuli. Thus, fixation duration around 460 ms in the current study, even when there is no conflict between attention shifts and saccades, appear rather long. We believe that this is due to (i) the demanding nature of the task, which constrained the window size available for viewing to only one item per fixation, and (ii) shifted the viewing window away from fixation, thus making saccade programming harder.

## Practical considerations

There is evidence that both macula and peri-macula in MD patients undergo considerable changes throughout the disease (Brown, Adams, Coletta, & Haegerstrom-Portnoy, 1986; Eisenbarth, Mackeben, Poggel, & Strasburger, 2008; Sunness, Massof, Johnson, Finkelstein, & Fine, 1985). Therefore, care needs to be taken when drawing conclusions from data collected from normal-sighted participants. Nevertheless, our data can help in generating hypotheses about the factors likely to be crucial and thus promising for developing and testing alternative training procedures for MD patients, as will be described in the following sections.

Peli (1986) has argued that a PRL located orthogonally to gaze direction should lead to optimal performance, since inhibiting the tendency to automatically foveate might be easier than under conditions when gaze direction and preferred retinal location are the same or lie opposite to each other. Different from this prediction, we have found no overall benefit for orthogonal directions. However, the observed similar performance levels for same and orthogonal directions may have been due to two different processes, one favoring same (congruent attention and eye movement shifts) and one favoring orthogonal directions (which prevent foveating saccades). Opposite directions profit neither from one nor the other, thus leading to worst performance.

Our current findings do not allow us to exclude that uncoupling attention from gaze might be easier for MD patients than for normal-sighted participants with an artificial scotoma. Participants in the present study succeeded in using an off-foveal visual field location and to switch back to normal vision outside the laboratory. In contrast, MD patients suffer from a permanent lack of central vision, which might lead to non-negligible changes (e.g., compensatory strategies, avoidance responses) that are hard to study in normal-sighted participants. Moreover, it

is conceivable that conflicts between shifting attention and eyes in opposite directions do not arise for MD patients, if they permanently shift attention toward the field location that corresponds to their PRL, rather than shifting back and forth between fovea and preferred visual field location. To address this point, it is helpful to distinguish between different stages that patients suffering from central visual field loss may experience (Schuchard, 2005). *Eccentric viewing* describes a behavior in which the oculomotor reference stays at fixation, and the patient has the impression of looking next to the target when using their PRL. In contrast, *eccentric fixation* describes the use of the PRL after the oculomotor reference has shifted from the fovea to the PRL. In eccentric fixation, the patient has the impression of directly looking at the target. Such a shift of the oculomotor reference has been reported in patients with bilateral macular disease (White & Bedell, 1990) but may require several years to establish. Given that our normal-sighted participants had a few hours of experience only with the use of an FFL at a relatively small eccentricity, we assume that the present experimental paradigm resembles eccentric viewing, comparable to earlier stages of macular degeneration, before the oculomotor reference (and thus the reference for shifting attention) has shifted away from the fovea toward the PRL. Very little is known about the factors that impair or facilitate such a permanent shift of the oculomotor reference toward the PRL. Based on our current results, we predict that patients might benefit from training programs that help them to establish their oculomotor reference at the PRL. Further research is required to test these predictions in clinical populations.

## Conclusions

Macular degeneration is the leading cause of blindness in developed countries, with a prevalence of 11.8% for advanced stages above the age of 80 (Friedman et al., 2004). Current medical treatment can at best slow down the progress of the disease, but the damage itself cannot be reversed (Rattner & Nathans, 2006). Therefore, restoration of visual abilities by means of efficient training procedures becomes an ever more important goal for MD patients (Elliott et al., 1997).

Whereas previous studies have concentrated on determining the optimal location for a preferred retinal location, the present study has focused on the role of task demands, i. e., the coordination of gaze direction and sustained shifts of attention toward the FFL. Our results suggest that, for small eccentricities, there is no general advantage of any particular retinal locus. Rather, performance in off-foveal vision depends on the coordination of shifts of attention and gaze direction: Performance is impaired whenever gaze and sustained attention must be directed in opposite directions.

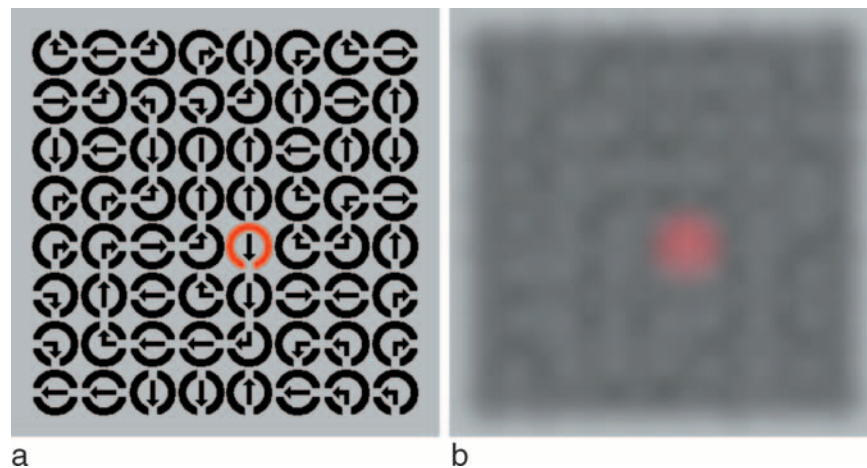


Figure A1. (a) Unblurred and (b) blurred versions of a sample maze (see text for details). In the blurred version, neither the orientation of the arrows nor the position of the target can be identified, while the start position is easily localized by its color.

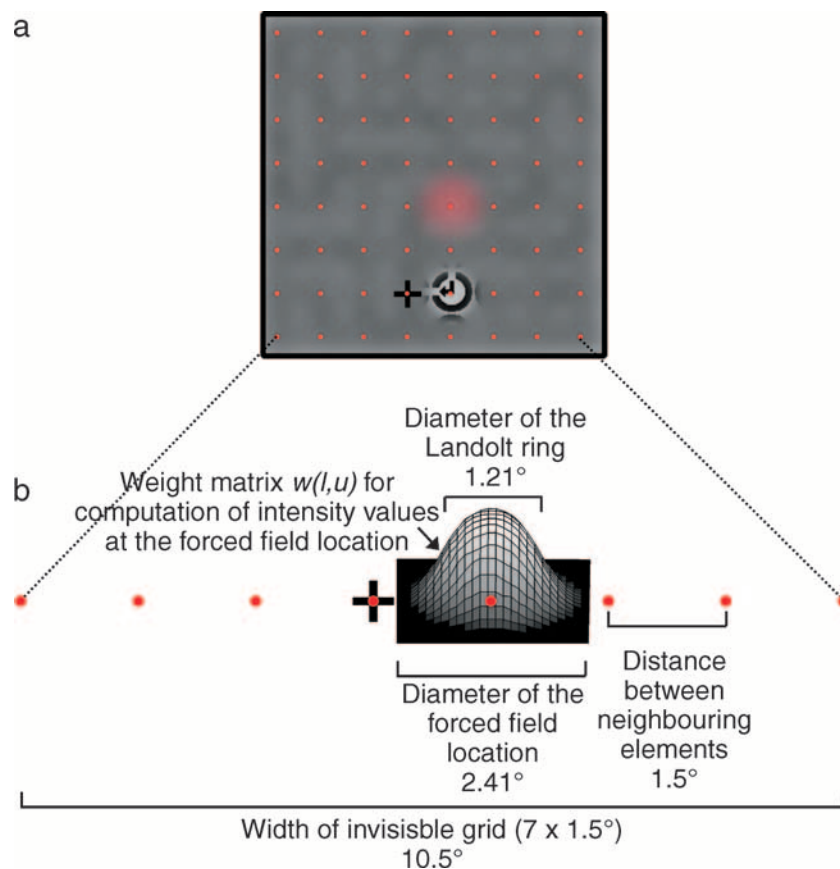


Figure A2. Illustration of the size of the forced field location (FFL) and the visual search display. (a) Blurred version of one sample maze, with hypothetical central fixation position indicated by black fixation cross (not shown during experiment; sample shown: FFL to the right of central fixation). Red dots illustrate the center coordinates of each single maze element, forming an invisible  $8 \times 8$  grid. (b) Enlarged view of one row of the  $8 \times 8$  grid, together with an illustration of weight matrix used for computation of the intensity values within the  $2.41 \times 2.41^\circ$  area ( $81 \times 81$  pixels) covered by the forced field location. Within this region, the intensity values of the unblurred and blurred versions of each bitmap (see Figure A1) are averaged and weighted by the corresponding weight matrix. The weight matrix  $w(l, u)$  defines the extent and shape of the forced field location, with smooth transitions at the (lower and upper) boundaries. The resulting matrix containing the computed intensity values at the forced field location is copied to the screen. Hypothetical central fixation position is indicated by black fixation cross. For further details, see Lingnau et al. (2008).

We think that the present findings have important implications for the development of training procedures for MD patients, as they suggest that, contrary to current thinking, the optimal preferred retinal location does not depend on its spatial location per se. Rather, it depends on which gaze direction is required by the task at hand. Furthermore, our study shows that it is possible to flexibly substitute foveal vision by different visual field locations. This suggests that it might be possible to train MD patients at an early stage of the disease to use several locations for different tasks such as reading or scene perception.

## Appendix A

Figures A1 and A2.

## Acknowledgments

A.L. was supported by a Ph.D. Fellowship from the German National Merit Foundation and by the Provincia di Autonoma di Trento and the Fondazione Cassa di Risparmio di Trento e Rovereto. We like to thank Thorsten Albrecht for help with data collection and discussions, and to the editor, Gordon Legge, for helpful comments.

Commercial relationships: none.

Corresponding author: Angelika Lingnau.

Email: angelika.lingnau@unitn.it.

Address: Corso Betti 31, Rovereto 38068, Italy.

## References

- Altpeter, E., Mackeben, M., & Trauzettel-Klosinski, S. (2000). The importance of sustained attention for patients with maculopathies. *Vision Research*, *40*, 1539–1547.
- Awh, E., Armstrong, K. M., & Moore, T. (2006). Visual and oculomotor selection: Links, causes and implications for spatial attention. *Trends in Cognitive Sciences*, *10*, 124–130.
- Brown, B., Adams, A. J., Coletta, N. J., & Haegerstrom-Portnoy, G. (1986). Dark adaptation in age-related maculopathy. *Ophthalmic Physiology Optics*, *6*, 81–84.
- Carrasco, M., Talgar, C. P., & Cameron, E. L. (2001). Characterizing visual performance fields: Effects of transient covert attention, spatial frequency, eccentricity, task and set size. *Spatial Vision*, *15*, 61–75.
- Cheung, S. H., & Legge, G. E. (2005). Functional and cortical adaptations to central vision loss. *Visual Neuroscience*, *22*, 187–201.
- Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., et al. (1998). A common network of functional areas for attention and eye movements. *Neuron*, *21*, 761–773.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*, 201–215.
- Cummings, R. W., Whittaker, S. G., Watson, G. R., & Budd, J. M. (1985). Scanning characters and reading with a central scotoma. *American Journal of Optometry and Physiological Optics*, *62*, 833–843.
- Curcio, C. A., & Allen, K. A. (1990). Topography of ganglion cells in human retina. *Journal of Comparative Neurology*, *300*, 5–25.
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*, 1827–1837.
- Eisenbarth, W., Mackeben, M., Poggel, D. A., & Strasburger, H. (2008). Characteristics of dynamic processing in the visual field of patients with age-related maculopathy. *Graefes Archive for Clinical and Experimental Ophthalmology*, *246*, 27–37.
- Elliott, D. B., Trukolo-Ilic, M., Strong, J. G., Pace, R., Plotkin, A., & Bevers, P. (1997). Demographic characteristics of the vision-disabled elderly. *Investigative Ophthalmology & Visual Science*, *38*, 2566–2575.
- Fine, E. M., & Rubin, G. S. (1999). Reading with simulated scotomas: Attending to the right is better than attending to the left. *Vision Research*, *39*, 1039–1048.
- Fletcher, D. C., & Schuchard, R. A. (1997). Preferred retinal loci relationship to macular scotomas in a low-vision population. *Ophthalmology*, *104*, 632–638.
- Fletcher, D. C., Schuchard, R. A., & Watson, G. (1999). Relative locations of macular scotomas near the PRL: Effect on low vision reading. *Journal of Rehabilitation Research and Development*, *36*, 356–364.
- Friedman, D. S., O'Colmain, B. J., Munoz, B., Tomany, S. C., McCarty, C., de Jong, P. T., et al. (2004). Prevalence of age-related macular degeneration in the United States. *Archives of Ophthalmology*, *122*, 564–572.
- He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature*, *383*, 334–337.
- Henderson, J. M. (1993). Visual attention and saccadic eye movements. In G. d'Ydewalle & J. V. Rensbergen

- (Eds.), *Perception and Cognition* (pp. 37–50). Amsterdam, The Netherlands: Elsevier.
- Henderson, J. M., Pollatsek, A., & Rayner, K. (1989). Covert visual attention and extrafoveal information use during object identification. *Perception & Psychophysics*, *45*, 196–208.
- Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception & Psychophysics*, *57*, 787–795.
- Hooge, I. T. C., & Erkelens, C. J. (1998). Adjustment of fixation duration in visual search. *Vision Research*, *38*, 1295–1302.
- Hooge, I. T. C., & Frens, M. A. (2000). Inhibition of saccade return (ISR): Spatio-temporal properties of saccade programming. *Vision Research*, *40*, 3415–3426.
- Klein, R. M. (1980). Does oculomotor readiness mediate cognitive control of visual attention? In R. Nickerson (Ed.), *Attention & performance VIII* (pp. 259–276). Hillsdale, NJ: Erlbaum.
- Klein, R. M., Kingstone, A., & Pontefract, A. (1992). Orienting of visual attention. In K. Rayner (Ed.), *Eye movements and visual cognition* (pp. 46–67). New York: Springer.
- Kowler, E., Anderson, E., Doshier, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, *35*, 1897–1916.
- Legge, G. E., Rubin, G. S., Pelli, D. G., & Schleske, M. M. (1985). Psychophysics of reading—II. Low vision. *Vision Research*, *25*, 253–266.
- Lingnau, A., Schwarzbach, J., & Vorberg, D. (2008). Adaptive strategies for reading with a forced retinal location. *Journal of Vision*, *8*(5):6, 1–18, <http://www.journalofvision.org/content/8/5/6>, doi:10.1167/8.5.6. [PubMed] [Article]
- Liversedge, S. P., & Findlay, J. M. (2000). Saccadic eye movements and cognition. *Trends in Cognitive Sciences*, *4*, 6–14.
- Mackeben, M. (1999). Sustained focal attention and peripheral letter recognition. *Spatial Vision*, *12*, 51–72.
- Moore, T., & Fallah, M. (2001). Control of eye movements and spatial attention. *Proceedings of the National Academy of Sciences of the United States of America*, *98*, 1273–1276.
- Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631–1647.
- Nilsson, U. L., Frennsson, C., & Nilsson, S. E. G. (2003). Patients with AMD and a large absolute central scotoma can be trained successfully to use eccentric viewing, as demonstrated in a scanning laser ophthalmoscope. *Vision Research*, *43*, 1777–1787.
- Peli, E. (1986). Control of eye movement with peripheral vision: Implications for training of eccentric viewing. *American Journal of Optometry and Physiological Optics*, *63*, 113–118.
- Petre, K. L., Hazel, C. A., Fine, E. M., & Rubin, G. S. (2000). Reading with eccentric fixation is faster in inferior visual field than in left visual field. *Optometry and Vision Science*, *77*, 34–39.
- Pollatsek, A., Raney, G. E., Lagasse, L., & Rayner, K. (1993). The use of information below fixation in reading and in visual search. *Canadian Journal of Experimental Psychology*, *47*, 179–200.
- Rattner, A., & Nathans, J. (2006). Macular degeneration: Recent advances and therapeutic opportunities. *Nature Reviews Neuroscience*, *7*, 860–872.
- Rayner, K., Well, A. D., Pollatsek, A., & Bertera, J. H. (1982). The availability of useful information to the right of fixation in reading. *Perception & Psychophysics*, *31*, 537–550.
- Rizzolatti, G., Riggio, L., Dascola, I., & Umiltà, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia*, *25*, 31–40.
- Schuchard, R. A. (2005). Preferred retinal loci and macular scotoma characteristics in patients with age-related macular degeneration. *Canadian Journal of Ophthalmology*, *40*, 303–312.
- Starr, M. S., & Rayner, K. (2001). Eye movements during reading: Some current controversies. *Trends in Cognitive Science*, *5*, 156–163.
- Stelmack, J. A., Massof, R. W., & Stelmack, T. R. (2004). Is there a standard of care for eccentric viewing training? *Journal of Rehabilitation Research and Development*, *41*, 729–738.
- Sunness, J. S., Applegate, C. A., Haselwood, D., & Rubin, G. S. (1996). Fixation patterns and reading rates in eyes with central scotomas from advanced atrophic age-related macular degeneration and Stargardt disease. *Ophthalmology*, *103*, 1458–1466.
- Sunness, J. S., Massof, R. W., Johnson, M. A., Finkelstein, D., & Fine, S. L. (1985). Peripheral retinal function in age-related macular degeneration. *Archives of Ophthalmology*, *103*, 811–816.
- Timberlake, G. T., Mainster, M. A., Peli, E., Augliere, R. A., Essock, E. A., & Arend, L. E. (1986). Reading with a macular scotoma. I. Retinal location of scotoma and fixation area. *Investigative Ophthalmology & Visual Science*, *27*, 1137–1147.
- Timberlake, G. T., Peli, E., Essock, E. A., & Augliere, R. A. (1987). Reading with a macular scotoma. II. Retinal locus for scanning text. *Investigative Ophthalmology and Visual Science*, *28*, 1268–1274.

- Trauzettel-Klosinski, S., & Brendler, K. (1998). Eye movements in reading with hemianopic field defects: The significance of clinical parameters. *Graefe's Archive for Clinical and Experimental Ophthalmology*, *236*, 91–102.
- Trauzettel-Klosinski, S., & Tornow, R.-P. (1996). Fixation behavior and reading ability in macular scotoma. *Neuro-Ophthalmology*, *16*, 241–253.
- Trukenbrod, H. A., & Engbert, R. (2007). Oculomotor control in a sequential search task. *Vision Research*, *47*, 2426–2443.
- White, J. M., & Bedell, H. E. (1990). The oculomotor reference in humans with bilateral macular disease. *Investigative Ophthalmology Visual Science*, *31*, 1149–1161.
- Wilcox, R. (1997). *Introduction to robust estimation and hypothesis testing*. San Diego, CA: Academic Press.