

Visual Attention and Memory under Central Vision Loss

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Abstract

Efficient goal-directed interaction with our environment depends on attentional selection. In normal viewing attentive stimulus processing is carried out with high-resolution foveal vision and attentional selection is closely tied to eye movements. Does the loss of central vision impair higher-level visual memory functions that depend on the efficient deployment of attention? This research question is highly relevant to patients with age-related macular degeneration (AMD) who are forced to rely on extrafoveal vision for all processes typically carried out in foveal vision. The experiments presented in this thesis were designed to examine whether encoding of objects into visual long-term memory (VLTm) or efficient attentional guidance by acquired contextual memory suffers when central vision is impaired. Experiments were performed by patients with AMD and normal-sighted younger observers under scotoma simulation. Patients were tested monocularly with their worse eye and under binocular vision. Recording of eye movements allowed for the additional analysis of exploration behavior. Performance and gaze parameters were compared to respectively matched unimpaired control groups.

The first set of experiments examined encoding of natural objects into visual long-term memory, a process that crucially depends on attentive foveation. Change detection sensitivity was measured after free scene exploration. A highly salient cue capturing attention to a non-target location in half of the trials ensured that change detection relied on memory. In Experiment 1, patients' monocular and binocular change detection sensitivity was preserved, not significantly correlated with visual impairment, and went along with normal fixation parameters. A simulated gaze-contingent central scotoma in Experiment 2 complicated visual exploration and impaired memory performance in unexperienced observers. Attentive encoding of objects into VLTm thus depends on attentive foveal vision as long as saccadic rereferencing to an extrafoveal retinal location as a focus of attention has not yet developed.

The second set of experiments investigated incidental visual learning of repeated distractor configurations during visual search. Contextual cueing leads to faster detection of the target and more efficient exploration in repeated search displays. In Experiment 3, search with a simulated central scotoma eliminated contextual cueing and scan paths became less efficient. In Experiment 4 AMD patients showed reduced contextual cueing with binocular vision. The effect diminished with their worse eye and was correlated with visual acuity. Experiment 5 demonstrates that a simulated central scotoma leads specifically to impaired guidance of attention by learned contexts. When the scotoma was removed after an initial learning phase, contextual cueing reinstated. A simulated annular peripheral scotoma on the other hand, prevented contextual learning by interfering with the integration of invariant local configurations with the global display layout.

The experiments presented in this thesis provide evidence that loss of central vision can affect higher-level visual memory processes that depend on attentive foveation in normal vision in different ways. While encoding of objects into VLTm can be compensated when eye movements are efficiently rereferenced to an extrafoveal retinal location as a focus of attention, automatic guidance of attention in familiar environments remains impaired. Rereferencing may require more top-down controlled visual exploration and compete for visuospatial working memory capacity. These results may contribute to improve training regimes that help patients to better cope with their visual deficits in everyday life.

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1 General Introduction

Crossing a busy street safely or buying a package of coffee at the well-stocked grocery store – we are required to act efficiently within complex settings every day. At every instance of such situations, we are faced with a vast amount of information, including objects that are rich in detail, embedded in different surroundings, and related to other objects within the scene. And yet, it takes usually little effort to achieve our goals. A crucial mechanism to overcome complexity and enable goal-directed interaction with our environment is attentional selection. Attentional selection helps us to prioritize one location, object or thought while unattended stimuli or options may become attenuated (James, 1890; Pashler, Johnston, & Ruthruff, 2001; Treisman & Gelade, 1980). In this way, we can focus on relevant parts of the street that we want to cross, and we will spend little time inspecting the buildings nearby that carry much less valuable information for this task. Salient events such as a flashing traffic light, on the other hand, will capture our attention automatically and we will usually immediately look at them (Theeuwes, Kramer, Hahn, & Irwin, 1998). Eye movements are closely tied to attentional selection in the visual domain. This is because the human retina provides high-acuity vision only for a relatively small region at its center that is called the fovea. Processing of more peripheral stimuli becomes gradually reduced in detail, and we therefore need to move our eyes to bring attended stimuli into foveal vision (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995).

When we want to locate a specific package of coffee in the supermarket shelf, we may fixate one item after the other until we find the package we were looking for. Sequential attentive processing of individual objects thus seems sufficient to achieve our goals. However, attentive selection interacts with cognitive mechanisms that facilitate goal-directed behavior further. Although filled with an exhaustive amount of information, the visual world is inherently structured and stable over time. Our cognitive system makes use of these invariant relationships by generating and utilizing internal representations. Attentive stimulus processing will lead to memory encoding (Hollingworth, 2006) and accumulated representations of past experience will guide attention when similar situations are encountered in the future (Chun & Jiang, 1998). Recourse to visual memory will help us to find the package of coffee more efficiently. We may remember its color and we can use this information to reject packages of any other color more quickly. Furthermore, spatial context memory can guide our attention more efficiently to the particular supermarket shelf when we visit the same supermarket frequently. In all these cases, attentional selection and subsequent foveation act in concert in normal vision.

What happens to attentional selection when foveal vision is no longer available? This question is highly relevant for patients that suffer from impaired foveal vision due to age-related macular degeneration (AMD). In AMD, central vision becomes severely compromised and may eventually diminish completely (Lindblad et al., 2009). Patients are thus forced to carry out all visual processing, including attentive selection of objects, with their remaining peripheral vision. Adaptation to eccentric viewing is not without issues, however. In particular, efficient rereferencing of eye movements to a location that is different from the fovea as our normal center of gaze (White & Bedell, 1990; Whittaker, Cummings, & Swieson, 1991) and stabilizing the eye on an attended stimulus pose severe problems (Crossland,

Culham, & Rubin, 2004; Kumar & Chung, 2014). The immediate consequences of central vision loss on basic psychophysical function, such as visual acuity, have been thoroughly investigated (for review, see Neelam, Nolan, Chakravarthy, & Beatty, 2009). Deficits in higher-level cognitive function have been demonstrated in the field of reading research (for review, see Chung, 2010), face and object recognition (Bullimore, Bailey, & Wacker, 1991; Henderson, McClure, Pierce, & Schrock, 1997), and visual search (Cornelissen, Bruin, & Kooijman, 2005; Van der Stigchel et al., 2013) and suggest that the efficient allocation of attention might also suffer when central vision is compromised.

The five experiments presented in this thesis were set out to examine the consequences of central vision loss on higher-level visual memory function that depends on efficient attentional selection and foveation in normal vision. To this end, explicit visual memory for every-day objects and the efficiency of attentional guidance based on acquired spatial contextual memory in visual search were probed in patients suffering from AMD as well as in healthy young observers under central scotoma simulation. Performance was compared to matched unimpaired control groups and gaze data were analyzed to characterize visual exploration behavior. In the remainder of this introduction, I will first provide a more extensive summary on attentional selection and its interaction with visual memory and search guidance in normal vision. In a second part, I will provide more background on the nature of central vision loss in AMD and review empirical results on consequences on eye movement control and higher-level visual function. Finally, I will summarize the questions addressed by this thesis and provide an outline of the experiments. In Chapter 2, I will detail the methodological aspects that are common to the experiments reported in chapters 3 to 7. In Chapter 8, I will summarize the results and discuss their implications.

1.1. Attention and memory in normal vision

Cognitive vision is a complex topic. Perception is based on the information sampled with the retina, but efficient visual behavior is highly dependent on attentional selection and memory for associations between stimuli. In the following sections, I will briefly introduce the physiological properties of our visual system and I will review the interactions between efficient attentional selection and memory in normal vision. This will serve as the background to understand the potential consequences of central vision impairment on higher-level visual memory function. The review of the literature will be limited to the experimental paradigms that were used in this thesis. Excellent introductory books that cover visual cognition and visual memory more comprehensively are provided by Findlay and Gilchrist (2003) and Luck and Hollingworth (2008), respectively.

1.1.1. Foveal vision and attentive processing

Vision is mediated by photoreceptor cells that convert light into electrical signals in the retina. High-resolution and color perception is provided by the cones that are active under well-lit conditions (photopic vision). Rods are sensitive to dim light (scotopic vision) and are poor at discriminating fine details and colors. The human visual field spans approximately 180 degrees of arc horizontally and 130° vertically (Henson, 1993). However, the photoreceptors are not distributed homogeneously on the retina and high-acuity vision is available only at the center of the visual field.

Most photoreceptors are located within the macula lutea, an oval-shaped pigmented region with a diameter of approximately 5.5 mm (see Figure 1.1 A). Cones are concentrated at the center of the macula whereas in peripheral regions, vision is mainly mediated by rods. The concentration of cones approaches its maximum in the fovea, a shallow pit of the retina at the center of the macula (diameter 1.5 mm, 5.2 degrees of arc; Remington, 2012; Wandell, 1995). The highest visual resolution is achieved by the foveola, a small region within the fovea (0.35 mm, 1°) that is tightly packed with cones and free of rods and capillaries. Foveola and fovea are surrounded by the annular parafovea and perifovea (width

0.5 mm and 1.5 mm, respectively). The high resolution of the visual signal captured within the foveola is preserved by a very low convergence of photoreceptors onto retinal ganglion cells (Curcio & Allen, 1990; Drasdo, Millican, Katholi, & Curcio, 2007; Sjöstrand, Olsson, Popovic, & Conradi, 1999). The signal then follows the visual pathway along the lateral geniculate nucleus of the thalamus to the primary area V1 of the visual cortex. Because this pathway is organized in a retinotopic way, the central visual field is highly over-represented in V1 compared to more peripheral regions (cortical magnification factor; Daniel & Whitteridge, 1961; Horton & Hoyt, 1991). In addition, a portion of the signal from the retina is sent to the superior colliculus that is involved in eye movement control and attentive selection (for reviews, see Gandhi & Katnani, 2011; Krauzlis, Lovejoy, & Zénon, 2013). Functionally, the regions of the visual field are defined as fovea (1° eccentricity), parafovea (1 to 5°), and periphery (beyond 5°) in vision research (Findlay & Gilchrist, 2003; Larson & Loschky, 2009).

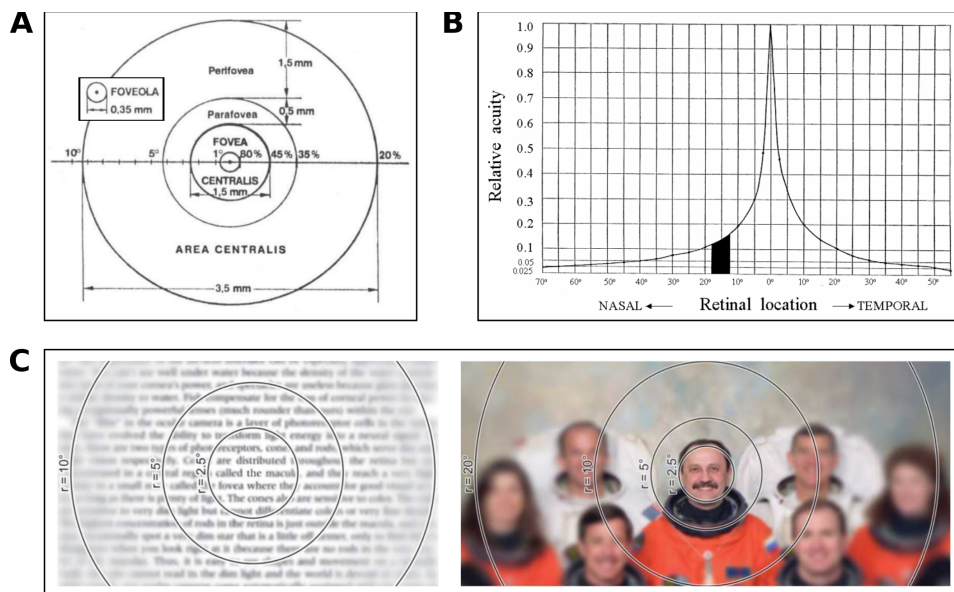


Figure 1.1.: Characteristics and limits of central vision. **A.** Regions of the macula lutea, adapted from Gralla (2007). **B.** Grating acuity at different retinal eccentricities, the black area represents the blind spot, from Findlay and Gilchrist (2003) based on Wertheim (1894). **C.** Page of print and view of people at a distance of 2.7 m with peripheral blur simulating visual resolution, from Marmor and Marmor (2010).

The impressive advantage of foveal resolution is depicted in Figure 1.1 B. At an eccentricity of only 2.7°, acuity measured with the grating test has halved. It is quite remarkable that we are usually unaware of these tight limits of sharp vision. When you keep your eyes still on a random word in the text of this thesis, however, it will be extremely difficult to read the second or third word to the left or right (also see Figure 1.1 C). In order to bring a word or object into foveal vision, we therefore need to move our eyes. These ballistic and stereotyped abrupt movements of the eye are called saccades. Most of vision is suppressed during saccades, preventing the perception of jumps or blurring (Burr, Morrone, & Ross, 1994; Matin, 1974), which is why you will not see your eyes moving when you look at yourself in a mirror. Periods in which the eye remains stable to accumulate visual information are called fixations. We make three to four fixations per minute and about 90% of viewing time is spent fixating (Irwin, 2004). During fixations, micro movements such as tremor, drift, and microsaccades occur but the fixated stimulus is usually maintained within the fovea (Putnam et al., 2005). The specific characteristics of fixations and saccades, such as duration and amplitude, depend on task and stimulus properties (for

review, see Rayner, 1998). Further types of eye movements are smooth pursuit during tracking of a moving object, vergence serving the perception of depth, and optokinetic and vestibular nystagmus movements compensating for the movement of a target or the head, respectively.

When a stimulus has become our focus, we look at it. However, attention can also be shifted covertly without moving the eyes. In his seminal work, Posner (1980) asked participants to respond to peripheral target stimuli after the presentation of an attentional cue. Critically, observers were asked to maintain central fixation throughout the experiment. When the cued target location was valid, the peripheral target was detected more efficiently compared to invalid cues that slowed target detection. The Posner cueing task has since established a widely-used tool to study the beneficial effects of attention on stimulus perception in vision research (for review, see Carrasco, 2011). Artificially separating the locus of attention from the fovea, however, is somewhat effortful and it has been questioned whether results from such experiments apply to natural viewing as well (Findlay, 2004). In normal viewing, the tendency to foveate a stimulus that captured attention is so strong that reflexive saccades need to be actively inhibited (Munoz & Everling, 2004). When observers are asked to make a saccade in the opposite direction of a flashed peripheral stimulus, these anti-saccades go along with increased response times and error rates (Hallett, 1978), especially when stimuli are highly relevant to behavior (Morand, Grosbras, Caldara, & Harvey, 2010). Conversely, the locus of spatial attention and the goal of saccades are closely tied (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995). Deubel and Schneider (1996) asked participants to perform voluntary saccades to a peripheral location that was symbolically cued. During saccade preparation, a discrimination target was presented briefly. Detection of this target was only reliable when its location overlapped immediately with the saccade goal. Even when participants knew the location of the discrimination target beforehand, attentional selection and saccade planning could not be decoupled voluntarily. The same pattern of results was replicated with peripheral cues, capturing attention in a more stimulus-driven way (Peterson, Kramer, & Irwin, 2004; Schneider & Deubel, 2002). Furthermore, while the planning of saccades enhances attentional processing at the saccade target location, active inhibition of saccades goes along with attentional costs at the same location (Dhawan, Deubel, & Jonikaitis, 2013). In line with these behavioral results, cortical networks for covert attention shifts and overt saccadic eye movements show a large overlap, suggesting that both processes draw on a common set of neural substrates. These include frontal and parietal regions such as the frontal eye field and the supplementary eye field, temporal regions, and the superior colliculus (Awh, Armstrong, & Moore, 2006; Corbetta et al., 1998; Corbetta & Shulman, 1998; Nobre, Gitelman, Dias, & Mesulam, 2000).

In our visual field, stimuli or objects rarely occur in isolation. To investigate which features guide attention to a particular stimulus, the visual search task has been one of the key paradigms used in the lab. In visual search, efficiency is measured as the time required to find a target within an array of distractor stimuli. A number of factors that make search more or less efficient have been identified in this way. For example, search becomes more efficient when color or orientation facilitate distinguishing the target from the distractors (for review, see Wolfe & Horowitz, 2004). The way in which attention can be guided to such features has been categorized into bottom-up and top-down driven mechanisms in most theories of selective attention (for example, Corbetta & Shulman, 1998; Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Itti & Koch, 2000; Kastner & Ungerleider, 2000; Posner, 1980; Posner & Petersen, 1990; Theeuwes, 2010; Wolfe, Cave, & Franzel, 1989; but see Awh, Belopolsky, & Theeuwes, 2012). Bottom-up (exogenous) attention is the automatic, involuntary allocation of attention to a particularly salient stimulus or feature, for example to a pedestrian that suddenly appears when we are driving a car. Top-down (endogenous) attention is the voluntary control of the allocation of attention to a certain spatial location or feature, for example to the color red when we search for an apple at the supermarket. Importantly, visual exploration is an active process and in order to determine where the eyes will fixate next, knowledge and memory representations from past experience will interact with the deployment of attention (for review, see Chun & Nakayama, 2000).

1.1.2. Visual memory and visual learning

Visual input that has been sampled with the retina is first maintained in sensory or iconic memory (Coltheart, 1980). Iconic memory comprises visible persistence, a sensory "snapshot" of the physical image arising from neural persistence, and non-visible informational persistence, the coded information or knowledge about image properties. The duration of sensory memory is very brief (Di Lollo, 1980; Irwin & Yeomans, 1986) and information will be overwritten by new sensory input. Only items that have been attended will be consolidated into more stable visual short-term memory in an abstract, object-based format (VSTM, Averbach & Coriell, 1961; Sperling, 1960). Whereas VSTM is only involved in information maintenance, visual working memory (WM) refers to a framework of structures and processes involved in maintaining and manipulating of information (for example, Baddeley, 1986, 2012; Baddeley & Hitch, 1974; Cowan, 2008; Diamond, 2013). VSTM has a limited capacity of 3-4 objects (Irwin, 1992; Luck & Vogel, 1997, 2013). Representations in VSTM persists against backward masking (Pashler, 1988; Phillips, 1974), that is they can be maintained across saccades (Irwin, 1992). Representations in VSTM can be transferred to visual long-term memory (VLTM) which has a massive storage capacity and persists over long periods (Brady, Konkle, Alvarez, & Oliva, 2008; Hollingworth, 2004, 2005; Standing, 1973; Voss, 2009).

Visual long-term memory for natural objects

The exact nature of visual memory representations has been extensively debated. Early theories proposed that high-resolution foveal information is integrated to an internal composite representation that closely resembles the visual world (Breitmeyer, Kropfl, & Julesz, 1982; Davidson, Fox, & Dick, 1973; Jonides, Irwin, & Yantis, 1982; McConkie & Rayner, 1975). However, empirical evidence suggests that such fusion of low-level sensory input from fixated regions is not supported by the visual system (Henderson & Hollingworth, 2003; Irwin, Yantis, & Jonides, 1983; O'Regan & Lévy-Schoen, 1983; Rayner & Pollatsek, 1983). In the late 1990s, the phenomenon of change blindness has led to a radically different view. In change blindness experiments, participants perform very poor at detecting even substantial modifications to objects. For instance, Rensink, O'Regan, and Clark (1997) presented two scenes that were identical except for one object that could be edited out or modified, such as a tree or a jet engine of a plane. When both images were presented in a continuous loop, separated by a brief blank (flicker paradigm), changes often went unnoticed for long viewing periods. These results have been replicated by changing objects during saccades (Grimes, 1996; Henderson & Hollingworth, 2003, 1999), or by using a physical object to occlude a change in real-world settings (Simons & Levin, 1998). Poor performance in change detection has led to the conclusion that as soon as focused attention is withdrawn, the representation of a previously encoded object in VSTM is overwritten by new visual input (Rensink et al., 1997; Simons, 2000). In this view, only very little information such as the gist or spatial layout of the scene can be retained from one view to the next whereas coherent representations only persist for a currently attended object (Becker & Pashler, 2002; Rensink, 2000, 2002; Simons & Levin, 1997; Wheeler & Treisman, 2002). Even more, O'Regan and colleagues (Noë, Pessoa, & Thompson, 2000; O'Regan, 1992; O'Regan & Noë, 2001) have proposed that there is no need for detailed visual representations of scenes or objects at all because the outside world itself can serve as a memory that can be probed with eye movements.

There is, however, a more intuitive explanation to the surprising failure to detect even large object modifications in the change blindness task. In order to compare original and changed object from one scene to the next, both instances have to be attentively encoded into visual memory. Since selective attention is closely tied to foveation (Deubel & Schneider, 1996), change detection should thus improve significantly if the changed object has been fixated. This notion is supported by studies that have monitored eye movements during change detection tasks. Nelson and Loftus (1980) asked participants to memorize photographs of natural scenes. In a subsequent test phase, these photographs had to be

discriminated from a distractor image that contained a change to a single object. Previous fixation of this critical object, within a distance smaller than 1.8° of visual angle, was necessary for accurate discrimination. Similar results were found by Hollingworth, Schrock, and Henderson (2001). Detection of changes using Rensink's flicker paradigm (Rensink et al., 1997) critically depended on foveation. Furthermore, change detection was delayed and more error-prone when observers had to maintain central fixation during the task. There are two important conclusions that can be drawn from these results. First, encoding of objects into visual memory critically depends on foveation in normal vision. Second, attentive encoding of objects can also be carried out with peripheral vision. However, encoding that requires the voluntarily allocation of attention away from the fovea is more effortful and goes along with costs in memory quality.

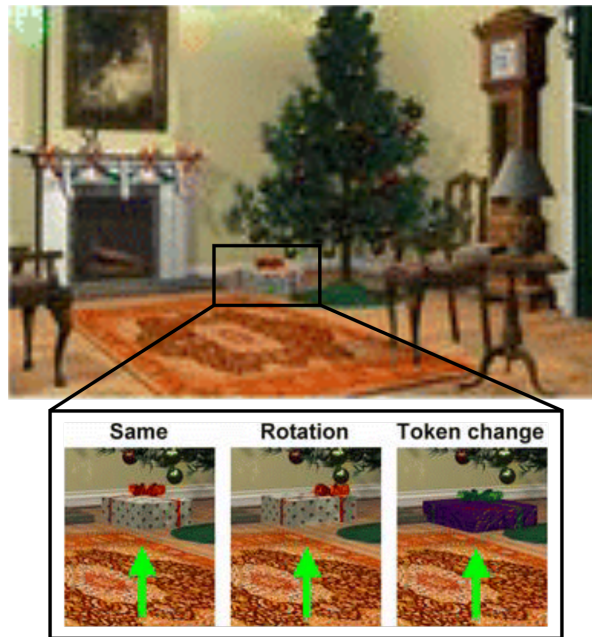


Figure 1.2.: Typical stimuli used in the change detection experiments by Hollingworth (Hollingworth, 2006). During an exploration phase, participants encoded objects within a natural scene into visual memory. A target object within this scene that was subsequently probed could either be the original object, a different object from the same semantic category (token change) or a rotated version of the original object (rotation change). The example scene is from Hollingworth (2003).

The studies reported above suggest that detailed object representations are encoded into visual memory when the objects have been selectively attended. Because observers' exploration behavior was not controlled systematically, however, the results are inconclusive about the exact contributions of VSTM and VLTm. It remains thus a possibility that detailed object representations are limited to VSTM and may be lost as soon as its capacity limit is reached (Irwin & Zelinsky, 2002). Hollingworth and colleagues carried out a series of experiments to investigate this questions (for review, see Hollingworth, 2006). These experiments involved an initial exploration phase in which participants were asked to encode objects embedded within natural scenes. Visual memory was then probed with a separate test scene that could contain either the original target, an object from the same semantic category (token change), or the original object that was rotated in space (rotation change, see Figure 1.2). The task was to indicate whether the target object had changed in the test scene compared to the initially ex-

plored scene. Crucially, the allocation of attention during initial scene exploration was controlled in several ways, for example via on-line gaze data analysis or salient onset cues, allowing to separate performance that primarily reflected VSTM from VLTm performance. As a general result, fixation time on the target and change detection performance were positively correlated, demonstrating the benefits of attentive foveation on the quality of memory representations. Furthermore, visual memory was very good both for token and rotation changes, even when more than nine intervening objects had been fixated before memory test. The most striking results were obtained using a follow-the-dot paradigm that manipulated the exact number of intervening objects between target encoding and memory test (Hollingworth, 2004). Change detection performance was enhanced for the last two attended objects, indicating a specific contribution of VSTM (Zelinsky & Loschky, 2005). When the target was encoded earlier within the sequence, such that the contribution of limited-capacity VSTM could be excluded, memory performance was well above chance and did not show any further decay. In the same study, memory test for a subset of the scenes was delayed until the end of the experiment. Memory performance for token changes was still remarkably accurate, even after more than 400 intervening objects had been attended between target encoding and test. Hollingworth's experiments thus clearly demonstrated that a large number of quite detailed object representations can be encoded into VLTm once they have been attentively foveated.

Excellent VLTm for a very high number of objects has also been demonstrated by Brady et al. (2008). Participants studied pictures of 2500 isolated objects and later had to discriminate the study objects from test objects. Test objects comprised objects of a novel or the same semantic category or the study object that was now presented in a different pose or state (for example, the same piece of furniture once with a closed and once with an open door). Discrimination performance was remarkable, reaching more than 87% correct even when study and test objects differed only in state (for a review on visual memory capacity see Brady, Konkle, & Alvarez, 2011). Detailed object representations can also be encoded incidentally if objects have been selectively attended. Williams, Henderson, and Zacks (2005) asked participants to search for a specific target within an array of twelve natural objects. Distractor objects either shared the same semantic category, color, or neither of these properties with the target. In an unexpected delayed memory test, objects viewed during search had to be discriminated from novel objects of the same semantic category. VLTm was most accurate for target objects but performance was above chance for all types of distractors as well. Furthermore, VLTm performance was positively correlated with the number of fixations and fixation time, replicating the results reported by Hollingworth (2006).

Taken together, these results indicate that objects that have been attended can be stored as abstract representations in VSTM and are then consolidated into VLTm. Representations in VLTm accumulate with previously encoded object representations across saccades and become more rich and robust with increasing exploration time (Hollingworth, 2004, 2005).

Incidental visual long-term memory in visual search

In our natural environment, objects rarely occur in isolation. To identify a target, such as a familiar face in the crowd, we often have to search for them. During most of complex searches, attention and gaze are allocated serially (Woodman & Luck, 2003) and visual memory is involved in multiple ways. To decide whether a currently inspected item is the target, a search template needs to be maintained in visual memory (Duncan & Humphreys, 1989; Malcolm & Henderson, 2009; Vickery, King, & Jiang, 2005; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Recent evidence suggests that such search templates are actively maintained in visual WM and bias attentive selection (Olivers, Peters, Houtkamp, & Roelfsema, 2011), including subsequent overt allocation of gaze (Hollingworth, Matsukura, & Luck, 2013; Hollingworth, Richard, & Luck, 2008). In addition, visual WM may be involved in preventing revisiting recently inspected locations (for example, B. S. Gibson, Li, Skow, Brown, & Cooke, 2000; R. M. Klein, 1988; Kristjánsson, 2000; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000). Both of

these mechanisms reflect the need to be selective because we cannot process all the information provided by our environment at once. However, context can also make search more efficient. Objects and events are usually surrounded by other objects and visual information in a meaningful way (Biederman, 1972; Chun, 2000). For example, in the supermarket you may find a package of coffee more efficiently because your attention will be guided by the arrangement of similar products close by. Because our environment is relatively stable over time, learning of these associations can help us to deploy attention more efficiently. This effect has been termed contextual cueing (Chun & Jiang, 1998).

The spatial contextual cueing paradigm In every-day life, semantic knowledge and expectations will contribute substantially to contextual learning. Contextual learning effects, however, can also be observed in simplified and much more abstract environments. In the contextual cueing paradigm (Chun & Jiang, 1998), participants are asked to search for a tilted T-shape target under several rotated L-shape distractor stimuli and indicate the target orientation with a button press. Unbeknownst to the participants, half of the displays will be repeated throughout the experiment whereas for the other half a target location is always presented with a random distractor configuration (see Figure 1.3). The repeated distractor configurations thus define invariant contexts that are predictive for the target location while no such relation exists for the random distractor configurations. Over time, participants get faster at locating the target, representing a general practice effect. Crucially, search in the repeated configurations is marked by an additional search time benefit; the contextual cueing effect.

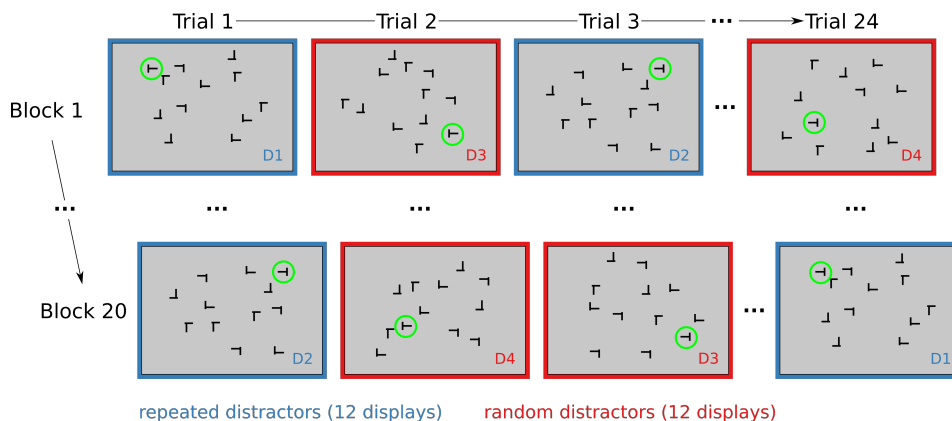


Figure 1.3.: Exemplar stimuli used in the spatial contextual cueing paradigm. Participants have to search for a target T-shape (encircled) under L-shape distractors. For half of the search displays, the distractor configurations are repeated across blocks (D1 and D2, blue frames). For the other half, random distractor configurations are created for each block (D3 and D4, red frames). The order of search displays within blocks as well as the identity of the target is randomized.

Learning of predictive context is a rather universal mechanism. Contextual cueing has been demonstrated across the lifespan in humans (Dixon, Zelazo, & De Rosa, 2010; Howard, Howard, Dennis, Yankovich, & Vaidya, 2004; Merrill, Connors, Roskos, Klinger, & Klinger, 2013), in non-human primates (baboons, Goujon & Fagot, 2013), and even pigeons are profiting from invariant context information when searching for arbitrary T-shapes (B. M. Gibson, Leber, & Mehlman, 2015). The spatial search paradigm has been used most frequently, but contextual cueing also operates on other dimensions such as covarying objects (Chun & Jiang, 1999; van Asselen, Sampaio, Pina, & Castelo-Branco, 2011), dynamic motion trajectories (multiple object tracking Chun & Jiang, 1999; Ogawa, Watanabe, & Yagi, 2009), sequential temporal structures (Olson & Chun, 2001), or semantic relations and categories (Gou-

jon, Didierjean, & Marmèche, 2007, 2009). When repeated information is redundant, for instance when both the spatial layout and object identity are predictive, learning is selective for the spatial information (Endo & Takeda, 2004). This is perhaps not surprising because many objects are bound to relatively invariant locations in our environment, making learning of spatial regularities particularly important.

Associative and incidental learning in contextual cueing Contextual cueing is a form of associative learning (Chun & Jiang, 1998). When an invariant display is encountered repeatedly, the target location becomes associated with distractor locations and a representation of the display is encoded into memory. In this way, as soon as the visual information sampled during later searches can be matched with the acquired memory representation, attention will be guided to the associated target location, making search more efficient. Experiments that monitored eye movements support this idea. Learned displays are usually not recognized immediately within the first fixation but contextual cueing rather exerts its effects on scan path efficiency (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004). Specifically, an ineffective early search phase is reduced in repeated displays, supporting the notion of an interaction between acquired memory representations and allocation of attention (Manginelli & Pollmann, 2009; Tseng & Li, 2004). The associative learning hypothesis is further supported by experiments that manipulated target location after initial learning (Makovski & Jiang, 2010; Manginelli & Pollmann, 2009; Yang & Merrill, 2015; Zellin, von Mühlengen, Müller, & Conci, 2013). If contextual cueing was due to learning of repeated distractor layouts, target detection should remain facilitated when its position is later changed in repeated displays. This is, however, not the case. The elimination of search benefits and a bias of eye movements towards the initially learned target location (Manginelli & Pollmann, 2009) suggest that specifically learning of the association between distractors and the target location is at the core of contextual cueing. In addition to attentional guidance, response selection may be also enhanced in repeated displays (Geyer, Zehetleitner, & Müller, 2010; Kunar, Flusberg, & Wolfe, 2008, 2006; Kunar, Flusberg, Horowitz, & Wolfe, 2007; Schankin & Schubö, 2009, 2010; Zhao et al., 2012).

Learning in contextual cueing is incidental (Chun & Jiang, 1998, 1999, 2003). This notion has not been without discussion. For example, the hippocampus that is usually associated with conscious forms of learning and memory, is involved in contextual cueing (Chun & Phelps, 1999; Geyer, Baumgartner, Müller, & Pollmann, 2012; Greene, Gross, Elsinger, & Rao, 2007). Other authors have argued that the power of explicit recognition tests typically conducted after the experiment may be too weak to detect awareness (Schlagbauer, Müller, Zehetleitner, & Geyer, 2012; Smyth & Shanks, 2008; Vadillo, Konstantinidis, & Shanks, 2016). In these recognition tests, observers are usually presented with the twelve repeated contexts that they encountered during search and twelve newly generated random contexts and they have to indicate whether they have seen the display before or not. Furthermore, observers show awareness especially when natural or semantically meaningful scenes are used as stimuli (Brockmole, Hambrick, Windisch, & Henderson, 2008; Brockmole & Henderson, 2006). On the other hand, explicit instruction to encode the visual context is uncorrelated with the magnitude of contextual cueing (Chun & Jiang, 2003) and the effect has been reliable in unaware observers probed with more powerful recognition tests (Smyth & Shanks, 2008). Initial learning may therefore be implicit but memory for contextual cues can eventually result in explicit knowledge (Colagiuri & Livesey, 2016; for review, see Goujon, Didierjean, & Thorpe, 2015).

Robustness of contextual memory Although our environment remains relatively stable over time, the size, shape, and exact position of objects can change from one view to the next. It would thus be beneficial if contextual memory generalized across similar contexts because in this way, recourse to previously learned contextual cues would make behavior more efficient. Several findings support this idea. Contextual cueing is unsusceptible to local uncertainty introduced by jittering search items (Chun & Jiang, 1998) or rescaling, displacing or perceptually re-grouping contextual configurations (Jiang &

Wagner, 2004), and transfers to items that are perceptually different than items that have been used during learning (Chun & Jiang, 1998; Jiang & Song, 2005). Jiang, Song, and Rigas (2005) had observers learn 60 repeated configurations embedded within 1800 random configurations over a period of five days. Even after a retention period of one week, repeated displays learned during the first sessions lead to comparable contextual cueing as those learned in the last session, demonstrating the robustness and high capacity of contextual memory.

Constraints on contextual learning Learning in contextual cueing is highly constrained to the region immediately adjacent to the target. As long as the distractors surrounding the target are predictive, contextual cues can be learned efficiently, even when longer-range distractors are random (Endo & Takeda, 2005; Olson & Chun, 2002). Using a connectionist model to simulate contextual cueing, Brady and Chun (2007) have therefore proposed a snapshot-theory of contextual learning. Distractors spatially adjacent to the target become associated when the target is detected at the end of the trial. Interfering random distractors in this critical region can abolish contextual cueing (Olson & Chun, 2002; Song & Jiang, 2005) and when a target switches location within a previously learned context, new learning is more efficient when the target is spatially close to the originally associated location (Conci, Sun, & Müller, 2011; Makovski & Jiang, 2010; Zellin, Conci, von Mühlenen, & Müller, 2011). Contextual learning therefore enhances target detection in a circumscribed region of the search display. Brady and Chun (2007) also proposed that learning in contextual cueing is based on individual, pairwise associations between the target and individual distractors but not on relations between distractor patterns (see also Jiang & Wagner, 2004; for an alternative account Beesley, Vadillo, Pearson, & Shanks, 2016). Rescaling or shifting the global layout does therefore not impair contextual cueing. Moving the local context within the global configuration, however, will impair contextual cueing because it would be too costly to calculate all possible translations and match them with contextual memory.

Incidental learning of contextual cues does not require selective attention to the items that define the invariant context. Jiang and Leung (2005) had observers search through contexts that were composed of two differently colored distractor subsets. The subset sharing its color with the target was attended while the other subset could be ignored during search. In one condition, only the ignored set was kept invariant while items of the attended set were random. In a later test phase, colors were switched such that the previously ignored set now became attended. Robust contextual cueing was measured in the test phase, showing that observers had learned the invariant contexts latently, without allocating selective attention to the items. Similar conclusions can be drawn from dual-task manipulations. In these experiments, observers are asked to maintain a set of items that are unrelated to the search display in visual WM while performing visual search. Holding the locations of dot patterns in visuospatial WM, in particular, should interfere with spatial attention deployment because both processes are assumed to draw on the same set of attentional resources (Woodman & Luck, 2004). Secondary WM load by colors, dot patterns or dot locations, however, does not impair learning of contextual cues (Annac et al., 2013; Manginelli, Langer, Klose, & Pollmann, 2013; Vickery, Sussman, & Jiang, 2010; but see Travis, Mattingley, & Dux, 2013).

Constraints on attentional guidance by contextual memory In contrast with contextual learning, the use of contextual cues critically depends on attentional selection and visuospatial WM. In the study by Jiang and Leung (2005), another condition was used to test whether previously attended, predictive distractors can guide attention when they become ignored after sufficient learning. The finding was that contextual cueing was completely abolished in this condition, indicating that the successful use of contextual cues does crucially depend on selective attention to these items (also see, Jiang & Chun, 2001). Secondary visuospatial WM load also selectively impairs efficient attentional guidance (Annac et al., 2013; Manginelli, Geringswald, & Pollmann, 2012; Manginelli, Langer, et al., 2013; for review, see Pollmann, 2019) and this effect depends on the magnitude of memory load (Zhang, Zhang, Huang,

Kong, & Wang, 2011). Converging support comes from a functional imaging study by Manginelli and colleagues (Manginelli, Baumgartner, & Pollmann, 2013). The authors had observers perform a visuospatial WM task in the scanner and investigated brain regions that were modulated by WM load. Two of these regions, one located in the posterior parietal cortex and another one in the temporo-parietal junction area, were specifically modulated by contextual cueing. These activations were only found during late phases of contextual cueing but not during early learning, suggesting that specifically attentional guidance by learned contextual cues is mediated by visuospatial WM. Search strategies may also interfere with the use of contextual cues. Lleras and Von Mühlenen (2004) found that contextual cueing was absent when observers were instructed to use an active, effortful search strategy compared with intact contextual cueing when a passive, intuitive search strategy was used. The authors suggested that a more top-down controlled search may block automatic, stimulus-driven guidance of attention by learned displays.

1.1.3. Summary and conclusion

High-acuity vision is only provided by the fovea and is thus restricted to a rather small portion of the human visual field. As a consequence, we constantly move our eyes to stimuli that are relevant to behavior. Shifts of spatial attention precede saccadic eye movements and both mechanisms closely tied. Attention can be decoupled from the fovea when the eye remains static, but this decoupling may go along with attentional costs. When eye movements become necessary for exploration, focal attention can not be separated from the goal of saccades in normal viewing.

Visual memory for natural objects critically depends on previous attentive selection that goes along with foveation. In a series of experiments, Hollingworth and colleagues have demonstrated that attentive encoding is crucial for visual memory. Abstracted representations of objects that have been attended accumulate in VSTM and are consolidated into VLTm, forming robust memory traces. Furthermore, the quality of VLTm correlates with the amount of attentive processing devoted to the object and objects that have not been attended lead to chance performance in subsequent memory tests. Hollingworth and colleagues were able to replicate these results across multiple samples and under various manipulations of the observers' attentional focus. Their paradigm seems thus very suitable to test attentive encoding of objects into VLTm and was adapted in the experiments presented in Chapter 3 and 4. Because the follow-the-dot version might be too difficult to be performed by the patients, we opted for a simplified version that uses valid and invalid onset cues to guide attention towards or away from the target object before memory test.

Objects are usually embedded within meaningful contexts that are relatively stable over time. Learning of these contextual covariations is therefore highly adaptive. Attentional guidance by learned contexts can be measured with the contextual cueing paradigm. Robust incidental memory representations are encoded for repeatedly presented search displays and this contextual memory facilitates attentional guidance to the target location. The spatial contextual cueing paradigm has received the most attention and has reliably been replicated numerous times. Because attentional guidance in learned contexts is also reflected in more efficient exploration behavior, eye movement analysis can provide additional measures to characterize contextual search facilitation or lack thereof. Contextual memory is robust and insusceptible to local uncertainty or the perceptual appearance of search items, as might be experienced by patients with central vision deficits. On the other hand, contextual cueing is sensitive to distractors adjacent to the target, requires selective attention to the search items, depends on visuospatial WM and to the search mode used. The spatial contextual cueing paradigm is therefore a well-suited paradigm to investigate attentional guidance by contextual memory under central vision loss and was adapted in the experiments in Section 5, 6, and 7.

1.2. Loss of central vision in Age-related macular degeneration

Age-related macular degeneration (AMD) is a multifactorial neurodegenerative disease of the eye that usually affects people over age 50 (Hawkins, Bird, Klein, & West, 1999). In Europe, 3.32% of people over age 65 suffer from advanced AMD, representing a total of 2.5 million Europeans, and 15.41% are at risk for developing advanced AMD (EUREYE; Augood et al., 2006). Because of the rapidly aging population, AMD becomes an increasingly important condition world wide (W. L. Wong et al., 2014). While peripheral vision is usually retained, damage to the photoreceptors, in the macula in particular, leads to progressive and irreversible impairment of central vision. At late disease stages, complete loss of central vision may result in legal blindness (S. L. Fine, Berger, Maguire, & Ho, 2000; Stone, Sheffield, & Hageman, 2001). Patients thus have to carry out all visual processing with their remaining peripheral vision. In the following sections, I will provide an overview of the pathology of the disease and review its consequences on gaze control and performance in higher-level visual tasks.

1.2.1. Disease pathology

The metabolic rate of the retina is outstandingly high; it consumes about 50% more oxygen than the brain when normalized for its weight (Warburg, 1928). This metabolic support is provided by retinal pigment epithelium (RPE) cells in the outermost layer of the retina that are in heavy exchange with the choroid, a rich network of blood vessels (see Figure 1.4 A). Over the years, the function of the RPE cells becomes impaired due to oxidative and photo-oxidative damage (S. Beatty, Koh, Phil, Henson, & Boulton, 2000; Young, 1988), parainflammatory dysregulation, and vascular sclerosis that go along with normal aging. Toxic debris is deposited intracellular (lipofuscin) or extracellular, forming so-called drusen (J. Ambati, Ambati, Yoo, Ianchulev, & Adamis, 2003; J. Ambati & Fowler, 2012; Evans, 2001). Few small drusen are common in healthy aging (Ferris et al., 2013; Gass, 1973; R. Klein, Klein, & Linton, 1992). Drusen clusters (R. Klein et al., 2015; Sarks, 1982; Sarks, Arnold, Killingsworth, & Sarks, 1999) or multiple large, confluent, or soft drusen in the central retina in combination with other pigmentary changes of the RPE such as hyper- or hypopigmentation, however, define the condition of early AMD (Bird et al., 1995; Bressler, Bressler, West, Fine, & Taylor, 1989; Ferris et al., 2005; Ferris et al., 2013; R. Klein, Klein, Jensen, & Meuer, 1997). There is currently no effective treatment to stop disease progression. "Dry" and "wet" morphological subtypes of late AMD (Bird et al., 1995) may subsequently develop in the same patient or same eye (Sunness, Gonzalez-Baron, Bressler, Hawkins, & Applegate, 1999), causing severe loss of central vision (see Figure 1.4 B).

Dry AMD, also called geographic atrophy or non-exudative AMD progresses rather slowly and is assumed to be the default pathway of the disease (J. Ambati, Atkinson, & Gelfand, 2013; Bird, 2010). It results from the regression of large drusen and subsequent RPE cell death in most cases, leading to the degeneration of overlying photoreceptors (M. L. Klein et al., 2008). Treatment is largely limited to nutritional supplementation with antioxidants and zinc to slow down disease progression (AREDS, 2001; AREDS2, 2013; for critical discussion see Abramson & Abramson, 2002, J. Ambati & Ambati, 2002, Seigel, 2002) but central vision may eventually diminish completely. Wet AMD is also called neovascular or exudative AMD and has been reported to occur about twice as often as dry AMD (Augood et al., 2006; R. Klein et al., 1992; Vingerling et al., 1995). It is assumed that injury to RPE cells stimulates choroidal blood vessels to grow to sustain metabolic function of the retina (D'Amore, 1994; de Jong, 2006; Kliffen, Sharma, Mooy, Kerkvliet, & de Jong, 1997). Unfortunately, this reactive choroidal neovascularization causes more damage than the original degenerative process. These new, immature blood vessels may leak blood and fluid or lipids into the retina, causing a detachment of the RPE and eventually result in disciform scar. Wet AMD can lead to acute deterioration of central vision and visual acuity may reduce by half after one year (T. Y. Wong et al., 2008). Treatment with anti-vascular endothelial growth factor agents (ranibizumab, bevacizumab) via monthly intravitreal injection is highly effective to limit this damage (Brown et al., 2006; Martin et al., 2011; Rosenfeld et al., 2006).

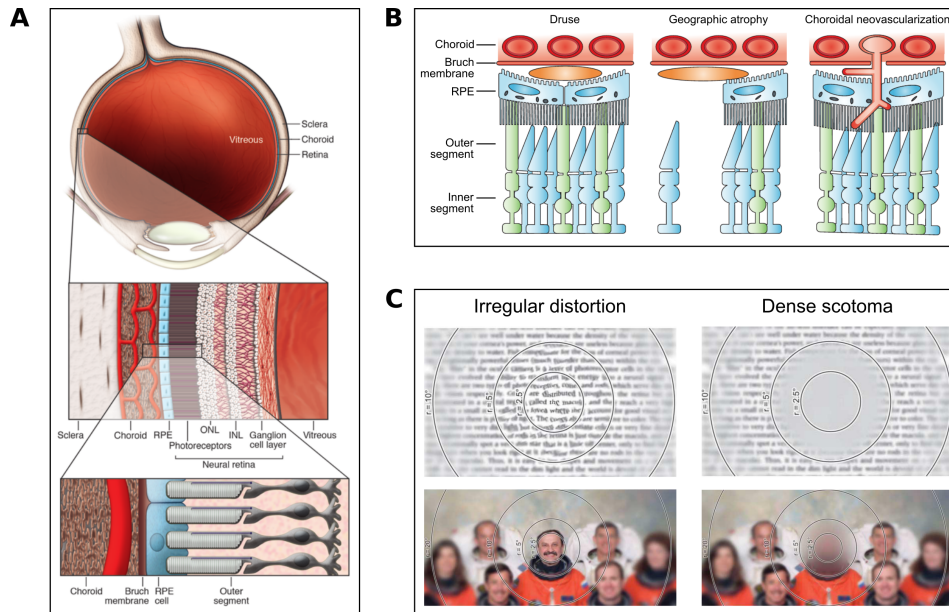


Figure 1.4.: Retinal pathology in age-related macular degeneration and disease symptoms. **A.** Cross-sections of the eye and the healthy retina. RPE, retinal pigment epithelium; INL, inner nuclear layer; ONL, outer nuclear layer. From Bird (2010). **B.** Schematic depiction of retinal pathology in AMD. Formation of drusen between RPE and Bruch’s membrane in early AMD (left), geographic atrophy of the RPE and subsequent loss of photoreceptor cells in dry AMD (middle) and choroidal neovascularization with new blood vessels originating from the choroid, breaking through the Bruch’s membrane and growing into the retinal space in wet AMD (right). From Rattner and Nathans (2006). **C.** Page of print and view of people at a distance of 2.7 m with peripheral blur with irregular distortions (metamorphosia) simulating vision during earlier stages of the disease (left) and dense central scotomata simulating vision during late AMD (right). From Marmor and Marmor (2010).

The major risk factor for developing AMD is older age. Prevalence and risk of late AMD increase from less than 0.5 % and 4 % between 40 and 59 years to more than 1.5 % and 10 % between 70 and 79 years and more than 11 % and 23 % at 80 years and older, respectively (Augood et al., 2006; Friedman et al., 2004). However, the development of AMD is influenced by complex interactions of genetic and environmental factors as well. Early and especially late AMD are strongly associated with genetic factors (Holliday et al., 2013) and a number of genetic loci associated with heritability have been identified lately (Black & Clark, 2016; Fritsche et al., 2016). Cigarette smoking is the most important and confirmed environmental risk factor (for reviews, see Thornton et al., 2005; Velilla et al., 2013). Other potential, but unconfirmed, risk factors include unhealthy diet and life style, metabolic and vascular parameters, eye specific condition, lifetime exposure to sunlight, female gender and ethnicity (for reviews, see Chakravarthy et al., 2010; Evans, 2001; Lim, Mitchell, Seddon, Holz, & Wong, 2012).

1.2.2. Consequences on visual function and quality of life

In early AMD, visual acuity often remains intact but drusen can disturb the fine arrangement of photoreceptors, leading to deficits in reading and distortion of objects (metamorphosia, Bressler, Bressler, & Fine, 1988; Midena & Vujosevic, 2015; see Figure 1.4 C). Early AMD can also impair recovery

after light adaptation, central field sensitivity, or orientation and shape discrimination (for reviews, see Hogg & Chakravarthy, 2006; Neelam et al., 2009). During disease progression, death of photoreceptors in the central macula results in dysfunctional patches on the retina, causing relative or absolute light insensitivity (scotoma, Fletcher & Schuchard, 1997) that severely impairs visual acuity and contrast sensitivity (Bellmann, Unnebrink, Rubin, Miller, & Holz, 2003; Doris et al., 2001; R. Klein, Wang, Klein, Moss, & Meuer, 1995; Kleiner, Enger, Alexander, & Fine, 1988; Monés & Rubin, 2005; Sunness, Gonzalez-Baron, Applegate, et al., 1999). Many patients are not aware of their scotomata, potentially due to perceptual filling-in (Pratt, Ohara, Woo, & Bedell, 2014; Ramachandran & Gregory, 1991; Zur & Ullman, 2003). In a study by Fletcher, Schuchard, and Renninger (2012), more than half of AMD patients were completely unaware, even when dense scotomata covered large parts of their visual field. Patients may instead perceive objects as suddenly (dis-)appearing, being stretched, blurry or overlaid by dark fog (Fletcher et al., 2012; Schuchard, 2005; personal communication with patients).

Patients with late AMD often have to rely on visual aids or the help of others for many daily tasks affecting near vision (reading, sewing, handicraft work) or driving ability and may eventually give up on these activities. When visual acuity deteriorates severely in both eyes, self-reported quality of life scores drop substantially and risk for clinical depression increases (for review, see Mitchell & Bradley, 2006). Recent research on retinal prostheses, for example microphotodiode arrays that are implanted in the damaged retina (Dowling, 2009; Humayun et al., 2012; Luo & da Cruz, 2014), are promising accounts to restore vision. However, these implants are not suitable for all patients and more research is necessary to improve image quality but also the efficient use of these systems by the patients. Current rehabilitation methods seek to improve the use of the remaining peripheral vision, supported by visual aids such as magnification, specifically developed fonts for reading (Bernard, Aguilar, & Castet, 2016) or methods that enhance image recognition (Peli, Goldstein, Young, Trempe, & Buzney, 1991).

1.2.3. Adaptation to eccentric viewing

Impairment of basic visual function is not the only issue for AMD patients. The automatic process of foveating an attended stimulus quickly becomes a disadvantage since the object would become severely distorted or disappear in the scotoma. Most patients with absolute central scotomata thus develop a preferred retinal locus (PRL) in a discrete area of the undamaged peripheral retina within six months (Crossland, Culham, Kabanarou, & Rubin, 2005; Fletcher & Schuchard, 1997) that is used to fixate objects eccentrically (Cummings, Whittaker, Watson, & Budd, 1985; Timberlake et al., 1986; von Noorden & Mackensensen, 1962; Whittaker, Budd, & Cummings, 1988).

Establishing this PRL as a new oculomotor reference for efficient saccade execution to an attended object, however, is not without problems. Even patients with long-standing vision loss who efficiently position targets within their PRL show abnormal eye movement patterns. Saccades take longer to initiate, are less accurate and have a higher frequency than in healthy controls (McMahon, Hansen, & Viana, 1991; White & Bedell, 1990; Whittaker et al., 1991). White and Bedell (1990) reported that patients with a longer disease history were overall more normal in oculomotor behavior. Saccadic latencies were reduced and targets were shifted towards the fovea less frequently during refixations. However, only 7 out of 21 patients indicated a complete shift of the oculomotor reference and 6 of these patients had the juvenile form of macular degeneration. The progressive nature of the disease may contribute to difficulties in maintaining efficient oculomotor rereferencing because a previously established PRL can gradually become compromised. Furthermore, fixations with a PRL show an increased spatial variability (Bellmann, Feely, Crossland, Kabanarou, & Rubin, 2004; Fletcher & Schuchard, 1997; Kumar & Chung, 2014; Schuchard, Naseer, & de Castro, 1999). Fixation instability increases with eccentricity of the PRL (Timberlake et al., 2005; Whittaker et al., 1988) and may thus additionally hamper efficient use of a PRL when the disease progresses.

There are many open questions concerning the development and characteristics of an extrafoveal PRL. In most patients, the PRL is located adjacent to the scotoma in the lower or left visual field (Fletcher &

Schuchard, 1997; Guez, Le Gargasson, Rigaudiere, & O'Regan, 1993; Sunness, Applegate, Haselwood, & Rubin, 1996; Timberlake, Peli, Essock, & Augliere, 1987; White & Bedell, 1990). However, this location is very unfavorable for reading from left to right because saccades have to be made into the scotomatous area. It has been suggested that the location of a PRL may be influenced by individual attentional performance in specific regions of the visual field (Altpeter, Mackeben, & Trauzettel-Klosinski, 2000) or by properties of the visual task (Lingnau, Albrecht, Schwarzbach, & Vorberg, 2014; Lingnau, Schwarzbach, & Vorberg, 2008, 2010). In line with this proposal, the use of different PRLs has been reported under unequal light conditions or for high-acuity local letter discrimination versus global word identification (Déruez, Whatham, Mermoud, & Safran, 2002; Duret, Issenhuth, & Safran, 1999; Nilsson, Frennesson, & Nilsson, 2003). Switching between multiple PRLs has also been observed, especially in the presence of large central scotomata (Whittaker et al., 1988). Furthermore, the location of a PRL can differ between on monocular and binocular vision. When monocular PRL locations do not correspond, long-standing AMD patients may shift their gaze position from binocular to monocular vision (Kabanarou et al., 2006). Large interocular differences may also lead to binocular inhibition in some AMD patients (Faubert & Overbury, 2000; Quillen, 2001; Valberg & Fosse, 2002). Given this observed high variability, it may therefore not be surprising that neither function-, performance-, nor retinotopy-driven accounts can currently provide a satisfactory explanation for the location of spontaneously developed PRLs (for review, see Cheung & Legge, 2005).

1.2.4. Performance in higher-level visual tasks

Processing of visual stimuli becomes complicated by reduced visual resolution, impaired control of eye movements, and by crowding. Crowding occurs when spatial interactions between neighboring objects constrain recognition, and increases with eccentricity (Bouma, 1970; for a review see Whitney & Levi, 2011). Loss of central vision thus affects performance in a range of higher-level visual tasks.

Reading

The consequences of central vision loss on higher-level visual function have been most thoroughly investigated in reading research. The ability to read requires high acuity to recognize letters and precise control of eye movements. Reading ability therefore becomes affected at relatively early stages of the disease and about 70 % of AMD patients have trouble reading regular print (Mangione et al., 1998). Under artificial gaze-contingent scotoma simulation, relatively small scotomata (2° , approximately 10 characters) substantially impair reading, and increased fixation numbers and durations reflect the high demand on extrafoveal processing (Rayner & Bertera, 1979).

Slowed reading in peripheral vision can not be fully compensated by increasing print size (Bullimore & Bailey, 1995; Chung, Mansfield, & Legge, 1998; Latham & Whitaker, 1996) or by reducing crowding (Chung, 2002, 2007, 2012). It has thus been proposed that reading speed in AMD patients is limited by a reduced size of the visual span (Cheong, Legge, Lawrence, Cheung, & Ruff, 2008; Legge et al., 2007). The visual span is a bottom-up sensory bottleneck that is defined by the number of letters that can be recognized within a single fixation (Legge, Mansfield, & Chung, 2001; O'Regan, Lévy-Schoen, & Jacobs, 1983; Pelli et al., 2007). In support of this hypothesis, training-induced enlargement of the visual span improves reading speed in peripheral vision (Bernard, Arunkumar, & Chung, 2012; Chung, Legge, & Cheung, 2004; Yu, Cheung, Legge, & Chung, 2010). Most of these experiments were carried out by serially presenting words at the same location (rapid serial visual presentation, RSVP). When presentation time in RSVP reading is increased, word recognition improves (Cheong et al., 2008; Chung et al., 2004; Lee, Legge, & Ortiz, 2003). Falkenberg and colleagues (2007) proposed that prolonged word recognition may thus be due to the necessity to shift attention several times within the word. The finding of a reduced size of the perceptual span in AMD patients during page-mode reading (Bullimore & Bailey, 1995; Crossland & Rubin, 2006) may support this hypothesis.

The perceptual span encompasses all characters that are attended within a fixation and influences the planning of eye movements (McConkie & Rayner, 1976; Rayner, 1975). Crucially, the perceptual span is limited by attentional and other cognitive factors, but not by visual acuity (Miellet, O'Donnell, & Sereno, 2009). Page-mode reading is also complicated by eye movement control. Simulated fixation instability in healthy observers reduced peripheral reading speed, even when acuity and crowding were accounted for (Falkenberg, Rubin, & Bex, 2007). Conversely, substantially enhanced reading in AMD patients has been reported after improvement of PRL fixation stability (Crossland et al., 2004; Nilsson, Frennesson, & Nilsson, 1998, 2003; Tarita-Nistor, González, Markowitz, & Steinbach, 2009; see Déruaz et al., 2004 for a critical discussion) and improvement of saccadic accuracy (Seiple, Szlyk, McMahon, Pulido, & Fishman, 2005).

Face and object recognition

AMD patients have severe difficulties in recognizing faces and facial expressions (Bullimore et al., 1991; Tejeria, Harper, Artes, & Dickinson, 2002). Bullimore and colleagues (1991) reported that healthy controls recognized faces at a distance ten times farther than AMD patients. Face recognition performance was correlated with word reading acuity, suggesting that loss of central vision goes along with a deficit in integrating individual features. This notion is supported by the observation that more severely impaired patients performed worse at face identity discrimination compared to expression recognition. Face identity discrimination requires the integration of several facial features whereas expression recognition can be based on distinct features such as the mouth. Similar deficits in integrating facial features have been reported in an emotion versus expression categorization (Boucart et al., 2008) and a face matching task (Barnes, De L'Aune, & Schuchard, 2011) and may be linked with abnormal fixation patterns in AMD patients during visual exploration of facial stimuli (Bernard & Chung, 2016; Seiple, Rosen, & Garcia, 2013). Bernard and colleagues (2016) found that AMD patients frequently fixated external features such as hair, chin, and face outline and that this bias also influenced responses in a face recognition task. The authors hypothesized that crowding may impair perception of internal features. In analogy to word recognition, a shrinkage of the peripheral visual span has also been discussed as a limiting factor in face recognition (He et al., 2015).

Object recognition has been investigated under simulated foveal vision loss in healthy observers (Henderson et al., 1997). Participants explored an array of four line drawing objects and recognition was tested at the end of each trial. When the eye approached an object, the object was removed from the array, simulating a comparatively small scotoma of approximately 1.65° of visual angle. Recognition performance was high but good accuracy had to be compensated with longer fixation times and eye movement patterns were disrupted, reflecting increased processing demands.

Visual search

The impact of central vision loss on visual search performance depends on the difficulty of the search task and the extent of central vision impairment. In high-acuity search tasks, even small simulated central scotomata can double search times (Bertera, 1988; Murphy & Foley-Fisher, 1988). Cornelissen and colleagues (Cornelissen et al., 2005) investigated adaptation to increased search difficulty by varying scotoma sizes. Greater scotomata increased fixation durations but this compensation was insufficient, indicated by a higher amount of regressive saccades. Greater absolute scotomata also interfered with efficient control of eye movements, leading to increased saccade amplitudes and overall less regular scan paths. Van der Stigchel and colleagues (Van der Stigchel et al., 2013) reported reduced search performance and inefficient eye movement control in four patients with juvenile macular degeneration. Patients were compared with healthy controls searching either with or without simulated scotoma. Patients were slowed in easy pop-out and more difficult serial search compared with both control groups. In serial search, controls with the simulated scotoma and patients compensated increased difficulty with

longer fixation durations but patients additionally required more saccadic eye movements to find the target. In pop-out search, saccadic amplitudes were reduced in patients, suggesting a more serial search strategy. During search in natural scenes, simulated foveal scotomata are well compensated by the visual system. Scotomata encompassing parafoveal vision, however, lead to increased search times (McIlreavy, Fiser, & Bex, 2012), saccade amplitudes, and fixation durations (Nuthmann, 2014). Search targets can efficiently be localized with peripheral vision but the verification of the target identity, a process that depends on foveation in normal vision, is slowed (Mielle, Zhou, He, Rodger, & Caldara, 2010; Nuthmann, 2014).

1.2.5. Summary and conclusions

AMD is a multifactorial neurodegenerative disease of the eye that leads to progressive and irreversible impairment of central vision. The progress of AMD is highly variable between individuals and within each eye. Considerable progress in understanding the etiology of AMD has been achieved in the last decades. The pathogenesis and prevention of the disease, however, remain largely elusive. Patients thus have to learn to use their remaining peripheral vision efficiently to carry out daily tasks. The close tie between attentional selection and subsequent foveation that makes normal exploration highly efficient becomes a considerable problem for AMD patients. Most patients develop a PRL at a more eccentric region of the retina to fixate attended stimuli, but the particular location and the potential number of PRLs that a patient may resort to appears highly variable. In general, fixations with a PRL are less stable than in normal vision. The most difficult part of PRL usage, however, is the efficient rereferencing of eye movements such that attended stimuli fall within the PRL. This process can take very long, may be only partially complete and may have to be relearned as loss of central vision progresses. Inefficient PRL usage, including the need of additional eye movements to compensate for reduced resolution or correction of inaccurate saccades, may thus well go along with deficits in attentive stimulus processing. In particular, a reduced perceptual span in reading and face recognition, tasks that require the integration of individual features, and less efficient visual search in arbitrary search arrays and natural scenes, indicates that the efficient allocation of attention to a stimulus may suffer in AMD.

1.3. Questions addressed by this thesis and outline of the experiments

The efficient deployment of selective attention is crucial for adaptive behavior. In normal vision, attentive selection is tightly coupled to subsequent foveation (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995; see Section 1.1.1). To maintain adaptive behavior, patients who suffer from central vision loss (AMD) have to learn to relocate attentive processing to a PRL in peripheral vision (see Section 1.2.3). Reading research has shown that reduced visual acuity and increased crowding contribute to impaired word recognition in peripheral vision but they are not the only limiting factors (Crossland & Rubin, 2006; Legge et al., 2007). Slowed reading has been linked to impaired face recognition in AMD patients (Bullimore & Bailey, 1995), suggesting that deficient attentional deployment may impair the integration of complex features (Falkenberg et al., 2007). Other functions such as object recognition or visual search require more time, reflecting high demands on peripheral stimulus processing that may entail compromised attentive selection (Cornelissen et al., 2005; Henderson et al., 1997; Van der Stigchel et al., 2013; see Section 1.2.4). The complicated control of eye movements with a PRL (Crossland et al., 2004; White & Bedell, 1990; see Section 1.2.3) may go along with additional shifts of attention and add to deficits in attentive selection.

The experiments presented in this thesis were therefore designed to investigate whether higher-level visual memory functions that are known to depend on efficient deployment of attention may suffer in the presence of central vision loss. Answering this question is important for the patients because impairment

of adaptive visual behavior would be an additional burden of disease. The experiments were carried out in patients with AMD using their more severely impaired eye as well as under binocular vision. This allowed us to compare performance when central vision deficits should be most prominent with performance that may be compensated by the better eye in binocular vision. The same experiments were also tested with normal-sighted observers under central scotoma simulation. The simulation experiments served for two reasons. Visual defects in patients are usually very variable (see Section 1.2) which is difficult to control for within the experimental setup. Simulations in healthy observers thus allowed for a purer view of the effects of a circumscribed central scotoma. Second, patients who are more experienced with central vision loss may deploy attention more efficiently to peripheral vision. The simulation experiments in unexperienced observers allowed us to examine whether intact foveal vision is required for the paradigms we used in general. Performance of patients and under scotoma simulation were compared to respectively matched unimpaired control groups. To ensure that the implementation of gaze-contingent scotoma simulation was technically sound and efficiently blocked visual input from central vision, we developed a behavioral validation task that can be found in the appendix (see Appendix A).

In Experiments 1 (Chapter 3) and 2 (Chapter 4), we tested the impact of central vision loss on attentive encoding of every-day objects in natural scenes. The studies by Hollingworth (Hollingworth, 2006; see Section 1.1.2) have shown that objects that are selectively attended with the fovea can form rich and robust VLTm representations. We therefore adapted Hollingworth’s 2003 paradigm that tests the quality of visual memory with an object change detection task. In this paradigm, objects are embedded within a scene context and can be explored in an unrestricted fashion during an initial viewing phase. This should allow observers with central vision loss to optimize eye movement planning and closely resembles exploration of our natural environment. Experiment 1 was performed with a sample of AMD patients and memory performance was compared to age-matched healthy controls. In Experiment 2, we repeated the same change detection task in young healthy observers under gaze-contingent central scotoma simulation and contrasted change detection performance with unimpaired viewing. We utilized three different types of scotoma simulation, a fully opaque central scotoma and a more subtle warp scotoma extending across foveal and parafoveal vision, and a smaller fully opaque scotoma selectively impairing foveal vision to simulate different degrees of central vision impairment. The central question was whether attentive processing, necessary for encoding detailed object representations into VLTm, can be efficiently deployed in peripheral vision.

In Experiments 3 (Chapter 5), 4 (Chapter 6), and 5 (Chapter 7) we investigated whether the efficient deployment of attention during search in invariant spatial configurations becomes impaired under central vision loss. We used the spatial contextual cueing paradigm (Chun & Jiang, 1998). It has been shown that the standard contextual cueing paradigm is relatively robust against local spatial uncertainties of search stimuli that define the context (see Section 1.1.2). Reduced spatial resolution of peripheral vision should therefore not be a limiting factor for learning spatial contexts under central vision loss. In Experiment 3, young healthy participants performed the contextual cueing task in two sessions, once under free viewing and once with a gaze-contingent simulated central scotoma diminishing foveal and parafoveal vision. In Experiment 4, we repeated the contextual cueing task with the same AMD patients who had also taken part in Experiment 1 and compared results to age-matched healthy controls. Experiment 5 reinvestigated contextual cueing under simulated central vision impairment in healthy young observers. The paradigm was expanded by adding a test phase in which the simulated scotoma was removed. This allowed us to differentiate between the impact of central vision impairment on the learning of contextual cues versus the use of acquired contextual memory to make attentional guidance more efficient. With an additional condition, we tested the role of local versus global contexts during learning with a simulated annular peripheral scotoma. The central question of the contextual cueing experiments was whether attentional guidance that makes exploration of invariant contexts more efficient in normal vision becomes impaired when central vision is no longer available.

2 General Methods

To avoid repetitions, all methods common to the experiments presented in Chapters 3 to 7 are summarized in this chapter. Methodological aspects that were specific to each experiment are detailed in the respective methods subsections.

2.1. Participants

Contextual cueing as well as object change detection experiments were carried out in young, healthy observers from the student population as well as in patients suffering from AMD and healthy, matched controls from the general population. All procedures followed the tenets of the Declaration of Helsinki (World Medical Association, 2000) and all studies were approved by the ethics board of the Otto-von-Guericke-University Magdeburg. Participants were not informed about the purpose of the respective study until they had completed all experimental sessions. Informed written consent was obtained prior to each experiment.

2.1.1. Simulation experiments

For all simulation experiments, young healthy adults with self-reported normal or corrected-to-normal visual acuity were recruited as participants from the Otto-von-Guericke University community. Participants were compensated with course credits or received a compensation of €6/h.

2.1.2. Patient experiments

Patients

The patient sample included 17 patients (7 females, 10 males; 1 left-handed) diagnosed with AMD (for details, see Table 2.1). Patients were recruited and diagnosed at the Ophthalmic Department of the University Hospitals of the Otto-von-Guericke University.

Participants with narrow irido-corneal angle, glaucoma, ocular trauma, eye surgery (except cataract surgery), distinct cataract, diabetic retinopathy and other retinal diseases, high myopia (> 5 dpt), amblyopia, cerebral blood flow disorder, and stroke were excluded. Macular degeneration was diagnosed based on an ophthalmic examination for both eyes, including slit lamp examination by an ophthalmologist, fundus photography, and optical coherence tomography. For each participant, best corrected monocular decimal visual acuities were determined by an optician. Visual field defects were explored with standard static white-on-white perimetry (dynamic strategy; Goldmann size III; program: dG2; OCTOPUS® Perimeter 101, Haag-Streit GmbH, Wedel, Germany) complemented by fundus-controlled microperimetry with a Scanning Laser Ophthalmoscope (stimulus intensity: 0 db (71 cd/m^2) and 20 db; Goldmann size III; SLO, Rodenstock, Ottobrunn, Germany) or a micro perimeter (4-2 dB threshold-strategy; Goldmann size III; MP-1, NIDEK CO., LTD., Gamagori, Japan) to determine the locus of

fixation. Relative scotomata, that is, visual depression without a complete loss of light perception, were defined based on static white-on-white perimetry when sensitivity was decreased for at least one of the five centrally tested stimuli.

All patients except P08 were affected by AMD in both eyes. The progress of the disease was variable between patients as well as between individual eyes. One patient had dense central scotomata extending at least 11° of visual angle in both eyes. In six patients, dense macular scotomata had developed in one of their eyes with diameters ranging from 5 to $\geq 60^\circ$ of visual angle. The remaining ten patients had developed relative scotomata, showing reduced perceptual sensitivity, at least in one of their eyes.

Patients performed all experiments binocularly in the first session and were tested again monocularly within approximately two weeks. For monocular testing, we measured, when possible, the more severely affected eye in which potential effects of foveal dysfunction should be most prominent. Patients received a compensation of €10/h. Additionally, patients and their accompanying persons were compensated for travel costs to the laboratory.

Controls

Controls were recruited from the Magdeburg area via flyers, word of mouth from others who participated and data base entries from previous experiments. For each patient experiment, controls were matched to patients individually considering sex, age, and years of education. Prior to testing, a subgroup of controls were assessed in an ophthalmological examination at the Ophthalmic Department of the University Hospitals of the Otto-von-Guericke University. Only controls with normal anterior and posterior eye segments were included. Further, to ensure sufficient visual acuity at testing distance, only controls with best corrected decimal near visual acuity ≥ 0.8 were included. For all other controls, visual acuity was assessed with the Freiburg Vision Test (Bach, 1996, 2007) to ensure normal vision (decimal visual acuity ≥ 0.8). Controls received a compensation of €10/h.

2.2. Apparatus

For all experiments, stimulus presentation and response recording were controlled using the Psychtoolbox (Brainard, 1997; Pelli, 1997) and the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002) or iViewXToolbox extensions under Matlab. Eye position was recorded using an Eyelink 1000 Desktop Mount with a temporal resolution of 1000 Hz or an Eyelink II head-mounted gaze-tracking system (SR Research Ltd., Mississauga, Ontario, Canada) with a temporal resolution of 500 Hz or an iViewX Hi-Speed, Eyelink eye tracking system (SensoMotoric Instruments GmbH, Teltow, Germany) with a temporal resolution of 240 Hz.

In the scotoma simulation experiments, stimuli were viewed binocularly by all participants. In the patient experiments, the stimuli were viewed binocularly by the controls and by the patients for the binocular condition. In the patients' monocular condition, observers viewed the stimuli monocularly with their more severely impaired eye when possible. The eye position of the left eye for binocular viewing and of the respective eye tested in the monocular condition was recorded using corneal reflection and pupil tracking. Visual acuity of patients was optimally corrected for the given viewing distance using a custom-made trial-frame and a full diameter (38 mm) perimeter trial lens set. For monocular testing, we used a black occluder for the non-tested eye.

Head movements were minimized by stabilizing participants' head using a chin and forehead rest. Participants were tested individually in a dimly lit, sound-attenuated chamber.

2. General Methods

Table 2.1.: Patient Characteristics

Patient	Sex	Age (years)	Education (years)	Type of AMD		Visual Acuity (logMar/decimal)		Type of scotoma (\emptyset horizontal $^\circ$ /vertical $^\circ$)		Fixation	
				RE	LE	RE	LE	RE	LE	RE	LE
P01	M	75	19	dry	wet	0.2/0.63	0.3/0.50	r	r	c	c
P02	M	76	18	dry	dry	0.2/0.63	0.1/0.80	r	r	c	c
P03	M	73	18	wet	dry	0.6/0.25	0.0/1.00	r	—	e, t	c
P04	F	68	16	dry	dry	0.1/0.80	0.0/1.00	r	r	c	c
P05	M	70	8	wet	wet	0.8/0.16	0.2/0.63	a (7/5)	p	e, t	c
P06	M	68	11	dry	dry	0.6/0.25	0.6/0.25	a (11/11)	a (18/20)	e, t, d	e, t, v
P07	F	69	8	dry	dry	0.2/0.63	0.2/0.63	r	r	c	c
P08	M	70	18	—	dry	-0.1/1.25	0.4/0.40	—	r	c	c
P09	F	76	8	dry	wet	0.0/1.00	1.3/0.05	r	a (30/32)	c	e, t, d
P10	M	68	12	dry	dry	1.2/0.06	0.2/0.63	a (5/5) ^a	r	c	c
P11	F	75	8	dry	wet	0.1/0.80	0.7/0.20	r	r	c ^b	c ^b
P12	F	70	8	wet	dry	0.1/0.80	-0.1/1.25	r	r	c ^b	c ^b
P13	M	67	10	dry	dry	1.0/0.10	0.3/0.50	a (40/45)	r	e, t	c
P14	M	75	17	dry	wet	0.0/1.00	1.0/0.10	—	r	c	c
P15	F	74	13	wet	wet	0.6/0.25	0.0/1.00	r	r	c ^b	c ^b
P16	F	67	10	wet	wet	1.3/0.05	0.0/1.00	a (52/ \geq 60)	r	e	c
P17	M	71	8	dry	dry	0.2/0.63	1.3/0.05	—	a (5/11)	c	c

Note: AMD = age-related macular degeneration; LogMAR = logarithmic "Minimum Angle of Resolution"; RE = right eye; LE = left eye; M = male; F = female. Scotoma: a = absolute; r = relative; p = peripheral. Fixation: c = central; e = eccentric. Retinal location of fixation relative to fovea: d = dorsal; v = ventral; t = temporal.

^a The patient had developed a bilobed scotoma around the fovea.

^b The locus of fixation was determined exclusively based on non-fundus controlled microperimetry.

2.3. Stimuli

2.3.1. Change detection paradigm

48 scene images used in the main experiment and four additional practice scenes were created with the 3D Traumhaus Designer 9 Premium software (version V.489, Data Becker, 2009, <http://www.databecker.de>). Each scene depicted a typical indoor environment, for example, a kitchen or a living room, containing ten to 21 semantically consistent, everyday objects. The target objects were unique items and distributed equally across quadrants to balance target position. In a second version of these initial scenes, the target objects were replaced with a different, equally sized object from the same semantic category (token change, for example, a purple, pear-shaped coffee pot was replaced with a silver, cylindrical coffee pot, see Figure 3.1 and Figure 4.1 for examples). The scene images had a width of 22.80° and a height of 17.10° of visual angle and were centered on a gray background. The target objects were on average 2.29° wide ($SD = 0.98^\circ$) and 2.49° of visual angle long ($SD = 1.25^\circ$).

The onset cue was a green disk with a diameter of 2.01° of visual angle. In the valid cue condition, it was placed on the center of an imaginary rectangle encompassing the target object. In the invalid cue condition, the onset cue was randomly placed in one of the three quadrants not containing the target object. The post-cue was a green arrow extending 3.02° in width and 3.02° of visual angle in height, pointing unambiguously to the respective target object. Masks for each scene were created by randomizing the phase structure of the initial scenes using the Matlab code as provided by Prins (2007).

The fixation cross was composed of two black line segments with a line width of 0.63° and a length of 3.14° of visual angle. For patients, we added a horizontal and vertical line extending across the screen

and intersecting at the center of the fixation cross to facilitate its visibility. In addition, we enlarged the standard calibration targets implemented in the Eyelink Toolbox (Cornelissen et al., 2002) and added a horizontal and vertical line intersecting at the center of the disks to increase visibility and facilitate eye tracker calibration in patients.

2.3.2. Contextual cueing paradigm

Each search display contained one target (90 or 270° rotated "T") and eleven distractors (0, 90, 180 or 270° rotated "L"). Each item was colored black presented on a gray background (RGB: 127, 127, 127). The orientation of the target was randomly chosen for each trial and did, therefore, neither correlate with the specific displays nor the experimental conditions. Distractors were rotated randomly with the restriction that each rotation was not used more than three times per display. An offset was introduced at the junction of the two segments of the L-shapes to make them more similar to the target in order to increase search difficulty- Stimulus positions were randomly chosen on four imaginary concentric circles, each containing 4, 12, 20, and 28 equidistant potential item locations respectively.

In order to create repeated and novel search configurations, 24 target positions were chosen randomly from the two intermediate circles at the beginning of the experiment. For 12 of those target positions, randomly assigned distractor configurations remained constant throughout the experiment ("repeated" condition). The other 12 target positions were combined with randomly generated distractor configurations for each experimental block ("novel" condition).

The fixation stimulus for the scotoma simulation experiments was designed as a white target consisting of three concentric circles and two diagonal line segments intersecting at the center and subtending an area of $9^\circ \times 9^\circ$ of visual angle. For the patient experiments, the fixation cross was composed of two black line segments which had a line width of 0.62° and a length of 3.11° of visual angle. For the patients, we added one horizontal and one vertical line extending across the whole screen and intersecting at the center of the fixation cross in order to facilitate visibility of the fixation cross. In addition, we slightly changed the standard calibration targets implemented in the Eyelink Toolbox (Cornelissen et al., 2002) for testing the patients. We enlarged the calibration disks and added one horizontal and one vertical line intersecting at the center of the disks. This was done to increase visibility and facilitate eye tracker calibration in the patient group.

2.4. Gaze-contingent scotoma simulation

The position of the artificial scotomata was updated with the gaze coordinates retrieved from the respective eye tracking system. No other additional filter algorithms – for example, for fixation or saccade identification – were implemented. The Eyelink 1000 average end-to-end delay was 2.8 ms and the worst-case latency until the update of the gaze-contingent stimulus manipulation on the LCD monitor was two frames (16.7 ms), resulting in an estimated worst-case delay between actual gaze position and stimulus update was about 20 ms. The iViewX Hi-Speed system had an estimated delay of maximal 10 ms due to the heuristic filtering of the gaze samples and the estimated worst-case latency until the update of the display was two frames on the CRT (20 ms), adding up to a total of a maximum delay of the scotoma of 30 ms.

When no gaze samples were available – for example, due to eye blinks or signal losses – the scotoma remained on the last measured valid gaze position until a new gaze sample became available. The proper technical implementation of the gaze-contingent scotoma simulation was validated with a behavioral discrimination task (see Appendix A). In short, this procedure comprises a visual discrimination task of high-acuity targets requiring foveal resolution. Results using the iViewX Hi-Speed system can be found in Appendix A. For the Eyelink 1000 system, performance was virtually perfect when targets

could be foveated (mean 98.60 %; range 96.10 to 100 %) but dropped significantly when central vision was diminished by the scotoma (mean 32.76 %; range 14.84 to 53.13 %).

2.5. Gaze data analysis

Gaze data were analyzed with a custom-made Python script applying a velocity-based algorithm. We used the procedures described in Nyström and Holmqvist (2010) for filtering the data with the Savitzky-Golay (Savitzky & Golay, 1964) FIR smoothing filter algorithm with second-order polynomials and a filter length of 20 ms, the removal of invalid gaze samples due to eye blinks or signal losses and the calculation of adaptive velocity thresholds. We then identified saccade events by velocities that exceeded the adaptive peak velocity threshold. The saccade start was calculated as the first sample of monotonically increasing velocities trespassing the individual saccade velocity threshold before the velocity peak and the saccade end was calculated as the last sample of monotonically decreasing velocities falling below this threshold after the velocity peak. Fixations were then identified from the inter-saccadic events that exceeded a duration of 100 ms.

3 Experiment 1: Visual memory for objects following foveal vision loss

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3.1. Abstract

Allocation of visual attention is crucial for encoding items into visual long-term memory. In free vision, attention is closely linked to the center of gaze, raising the question whether foveal vision loss entails sub-optimal deployment of attention and subsequent impairment of object encoding. To investigate this question, we examined visual long-term memory for objects in patients suffering from foveal vision loss due to age-related macular degeneration. We measured patients' change detection sensitivity after a period of free scene exploration monocularly with their worse eye when possible, and under binocular vision, comparing sensitivity and eye movements to matched normal-sighted controls. A highly salient cue was used to capture attention to a non-target location before a target change occurred in half of the trials, ensuring that change detection relied on memory. Patients' monocular and binocular sensitivity to object change was comparable to controls, even after more than four intervening fixations, and not significantly correlated with visual impairment. We conclude that extrafoveal vision suffices for efficient encoding into visual long-term memory.

3.2. Introduction

Attending to an object is crucial for its encoding into visual memory. The importance of selective attention for immediate memory is impressively documented by the change-blindness phenomenon (Rensink et al., 1997). Gross modifications of a scene can go undetected for a long time when the original and changed versions of the scene are presented in alteration, only separated by a blank screen to prevent change detection by a luminance onset. However, when the part of the scene that contains the change is fixated – and thereby attended – the change becomes immediately apparent. Notably, the need to foveate the changing item in the change detection paradigm persists even when object changes are large enough to be easily detected with peripheral vision. Immediate memory has thus been attributed to the attentional processing that goes along with foveating an object.

Even more, Rensink (2002) has claimed that as soon as we withdraw attention and move our gaze to a different object, the memory of the previous object is lost. This, however, underestimates the

potential of visual long-term memory (VLTM). Hollingworth and colleagues could show that objects that were once attended – that is, fixated – could be discriminated from novel objects with high accuracy (Hollingworth, 2006). In a series of experiments, they let observers freely explore a natural scene containing a number of objects. Subsequently, a change was induced on an object that had previously been attended (fixated), while it was ensured that the change could neither be noticed as luminance change within the scene, attracting attention to the change location, nor that it happened in foveal view, allowing change detection without recourse to VLTM. In these experiments, change detection, even for subtle token or viewpoint changes, was very accurate (Hollingworth, 2006). However, VLTM for objects depended on attentional selection. Unattended – that is, not previously fixated – objects failed to establish detailed memory representations and led to chance performance in change detection (Hollingworth & Henderson, 2002; Hollingworth et al., 2001; Simons & Rensink, 2005). Objects that have been attended during exploration, however, are often remembered in astonishingly rich detail, even across multiple intervening attended objects within the same scene or many different intervening scenes (Brady et al., 2008; Hollingworth, 2004; Hollingworth & Henderson, 2002; Standing, 1973) and retention periods of at least one day (Hollingworth, 2005; Vogt & Magnussen, 2007). Moreover, the quality of VLTM is correlated with the magnitude of target foveation during exploration. The amount of time that observers fixate an object predicted later change detection (Hollingworth & Henderson, 2002) and, similarly, the number of fixations on an object predicted later memory success (Pertzov, Avidan, & Zohary, 2009; Tatler, Gilchrist, & Land, 2005).

Here, we asked whether encoding of objects into VLTM is specific to foveal vision or whether accurate memory representations can also be established when foveal vision is severely impaired or lost. Attention is tightly coupled to the intended saccade target in the exploration of a scene. In normal viewing, the locus of attention shifts from its current location to the saccade target (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Lingnau et al., 2010) briefly before a saccade is executed. Conversely, salient events capturing attention are also foveated (Theeuwes et al., 1998). In this way, attended scene objects profit from the superior spatial resolution of the fovea. Typically, only in situations where eye movements are actively suppressed, attention may be shifted covertly to encode objects with extrafoveal vision (Posner, 1980). After foveal vision loss, the normal advantage of foveal attending quickly becomes a disadvantage. In age-related macular degeneration (AMD), a degenerative disease affecting specifically the macula (Arroyo, 2006; Nazemi, Fink, Lim, & Sadun, 2005), foveal vision may deteriorate from distorted vision and reduced acuity to the development of a central scotoma (Lindblad et al., 2009). For visual discrimination tasks, the patients are forced to use the surrounding parafoveal regions of the retina. Patients with foveal vision loss will quickly adapt to view the environment with their extrafoveal retina that has remained intact. The majority of patients may even select a specific preferred retinal locus (PRL) that is then used as a "pseudofovea", for viewing and fixating a target eccentrically, within the first months of the disease (Fletcher & Schuchard, 1997; Guez et al., 1993; von Noorden & Mackensensen, 1962; White & Bedell, 1990; Whittaker et al., 1988). However, it may take years until saccades become rereferenced to the PRL, that is, that saccades are programmed such that the PRL becomes the oculomotor reference instead of the fovea (von Noorden & Mackensensen, 1962; White & Bedell, 1990; Whittaker et al., 1991). Given the close correspondence of spatial attentional selection and saccade target location in normal vision (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995), this may indicate that patients with foveal vision loss must constantly shift attention covertly away from the fovea or enlarge the attentional focus in order to attend objects in visible parts of the retina. Although this may not completely eliminate VLTM encoding of visual objects, it may very well lead to encoding deficits in comparison to objects perceived with normal foveal vision.

In addition to this theoretical question – will VLTM for objects suffer when foveal vision is impaired – it is quite obviously also an important question for patients suffering from AMD. An impairment of high-level visuo-cognitive functions such as attentive encoding of objects due to foveal vision loss might be an additional burden beyond basic visual deficits that go along with the disease (for a review on psychophysical function in AMD, see Neelam et al., 2009).

The current study

We examined VLTM for objects in computer-generated real-world scenes in AMD patients and closely matched normal-sighted controls. To ensure that performance had to rely on memory, we adapted a change detection paradigm that uses salient onset cues to guide attention away from the locus of potential change (Hollingworth, 2003). Observers were asked to memorize all objects in a scene during a free exploration period of 20 s. Then, a salient onset-cue was presented at an unpredictable location within the scene. The main purpose of the cue was to capture attention and – in the case of an invalid cue – guide it away from the target location. In order to test object change detection based on VLTM, we needed to prevent participants from fixating the object immediately before a potential change, because fixating the target stimulus would have allowed to base change detection on a comparison with visual working memory content. Additionally, masking the scene immediately before the object change prevented change detection by luminance onsets.

Thus, the invalid cue condition was central for the assessment of VLTM. Eye-movement recordings were used to ensure that the capture of overt attention, on which the paradigm depends, worked in patients as well as in controls, and that the targets were indeed retrieved from VLTM.

3.3. Method

3.3.1. Participants

Patients

All 17 patients described in section 2.1.2 Patient experiments, took part in the binocular session of the experiment (for details, see Table 2.1). The average age of the patient group was 71 years, ranging from 67 to 76 years. The mean educational level of the patient group was 12 years of education, ranging from 8 to 19 years.

All patients except P13 and P17 took part in the monocular session of the experiment. We measured the more severely affected eye, in which possible effects of foveal dysfunction should be most prominent, in all but two patients who were not able to perform the task with their worse eye (P09 and P16).

Across all patients, the average logarithmic “Minimum Angle of Resolution” (LogMAR) was 0.11 (decimal visual acuity 0.77) in the better eye and 0.69 (decimal visual acuity 0.20) in the worse eye. For the eye used for monocular testing, average LogMAR was 0.45 (decimal visual acuity 0.35).

Controls

17 controls (7 females, 10 males; 1 left-handed) participated in the study. Their mean age was 68 years, ranging from 60 to 73 years. Controls were matched to patients individually considering sex, age and years of education (for details see Table 3.1). The mean educational level of the control group was 13 years of education ranging from 8 to 18 years. In eleven controls, normal visual acuity was confirmed in an ophthalmological examination prior to testing (best corrected decimal near visual acuity ≥ 0.8). The other six controls performed the Freiburg Vision Test (Bach, 1996, 2007) to ensure normal vision (decimal visual acuity ≥ 0.8 ; for more details, see section 2.1.2 Patient experiments).

3.3.2. Apparatus

We used a 22-inch Samsung SyncMaster 2233RZ LCD monitor that was 474 mm (1680 pixels) wide and 296 mm (1050 pixels) high and the vertical refresh rate was 120 Hz. Responses were recorded with a ResponsePixx Handheld five button response box (VVPixx Technologies Inc.; <http://www.vpixx.com>). The distance to the screen was kept constant at 85 cm leading to a pixel size of 0.019° of visual angle.

Table 3.1.: Sample characteristics

Table 3.1.: Sample characteristics						
Patients				Matched controls		
Patient	Sex	Age (years)	Education (years)	Sex	Age (years)	Education (years)
P01	M	75	19	M	72	17
P02	M	76	18	M	73	18
P03	M	73	18	M	71	18
P04	F	68	16	F	66	10
P05	M	70	8	M	70	8
P06	M	68	11	M	63	10
P07	F	69	8	F	66	10
P08	M	70	18	M	69	12
P09 ^a	F	76	8	F	70	10
P10	M	68	12	M	69	12
P11	F	75	8	F	70	10
P12	F	70	8	F	68	10
P13 ^b	M	67	10	M	60	18
P14	M	75	17	M	72	12
P15	F	74	13	F	70	15
P16 ^a	F	67	10	F	60	19
P17 ^b	M	71	8	M	70	17

Note: M = male; F = female.

^a Two patients could not complete the experiment with their more severely affected eye in the monocular condition and were therefore tested with the better eye.

^b Two patients did not perform the experiment monocularly.

The eye position was recorded using an Eyelink 1000 Desktop Mount (SR Research Ltd., Mississauga, Ontario, Canada) system with a temporal resolution of 1000 Hz, using corneal reflection and pupil tracking.¹

3.3.3. Stimuli

Details about the stimuli used in the experiment can be found in Section 2.3.1 Change detection paradigm and examples are depicted in Figure 3.1.

3.3.4. Procedure

Participants were asked to indicate whether a target object of a previously inspected indoor scene was the same or whether it had changed in an otherwise identical test scene with button presses of the left and right index finger respectively. They were instructed to memorize as many objects as possible during free exploration and wait until they had spotted a green post-cue arrow that unambiguously pointed to the target object until committing their response. They were instructed to press the the left button of the response box, centered in front of them, with their left index finger when the target object had remained the same and the right button with the right index finger if it had changed. By means of a printed version of a scene example not used in the experiment, participants were precisely informed about the nature of a potential token change and the corresponding button assignment before

¹ One patient (P08) was tested in the lab of Gisela Müller-Plath in Halle (Saale), Germany, in the monocular condition. In this setup, we used a 20-inch CRT monitor which was 400 mm (1600 pixels) wide and 300 mm (1200 pixels) high running at a vertical refresh rate of 85 Hz. The viewing distance was 55.1 cm leading to a pixel size of 0.026° of visual angle. We adapted all visual stimuli to match in size and eccentricity in degrees of visual angle as we had implemented in our lab. Eye position was recorded with an Eyelink II head-mounted gaze-tracking system (SR Research Ltd., Mississauga, Ontario, Canada) with a temporal resolution of 500 Hz.

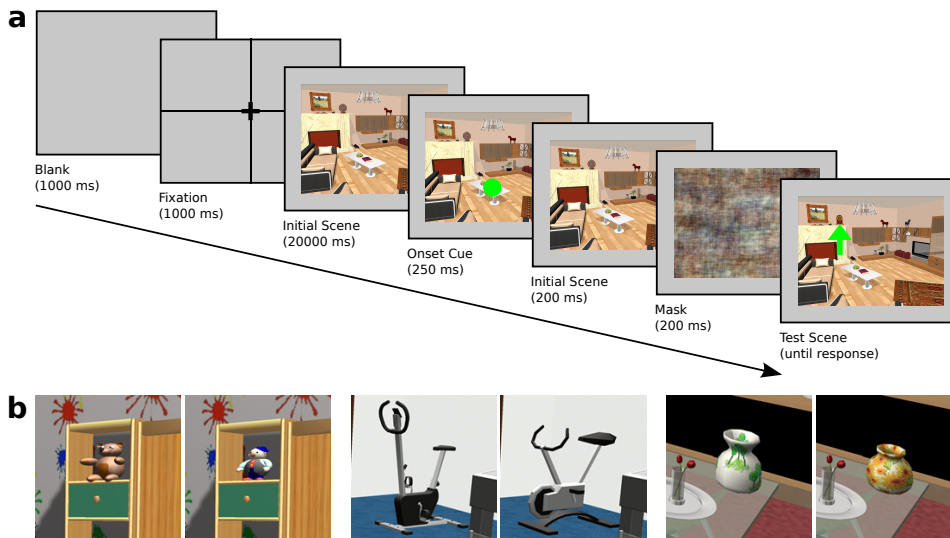


Figure 3.1.: Schematic diagram of an experimental trial and exemplary target objects. (a) Each trial consisted of a blank screen (1000 ms), followed by the fixation cross (1000 ms), the initial scene (20 s), the initial scene and the onset cue (250 ms), the initial scene (200 ms), the mask (200 ms) and the test scene with the post-cue pointing towards the target object (presented until response). In this example, the target object is the clock, the onset cue is invalid and the target object is exchanged with a different type of clock in the test scene. (b) Exemplary pairs of target objects from three different scenes with the object presented during free exploration on the left and its replacement in the change-condition on the right.

the experiment started. When necessary, participants were reminded of the button assignment including both response alternatives during the experiment, in an unaccented manner in order to not influence the participant’s decision.

Each session started with a nine-point gaze-calibration, followed by a short training including four separate practice scenes, one in each of the Cue \times Test scene conditions, to familiarize participants with the task. The actual experiment was composed of 48 unique indoor scenes, 12 in each of the four conditions. In those subsets of scenes, the target appeared in each quadrant three times. Trial sequences were randomized for each participant and the assignment of the scenes to the conditions was balanced across participants. Every trial started with the presentation of a blank for 1000 ms followed by the fixation cross for 1000 ms, the initial scene presented for 20 s, the onset cue within the scene for 250 ms, the original initial scene again for 200 ms, the mask for 200 ms and the test scene until the participant responded (Figure 3.1). Auditory feedback was provided for correct (a 2000 Hz high-pitch tone) and wrong answers (a 500 Hz low-pitch tone). After each trial, participants were allowed self-determined breaks and the experimenter proceeded with the subsequent trial when the participant was ready to continue. One session lasted approximately 60 min for controls and between 60 to 90 min for patients depending on the severity of visual impairment.

Patients performed the experiment binocularly in a first session and were tested again approximately within two weeks using only their more severely affected eye when possible. We chose to test specifically the worse eye because effects of foveal impairment on VLTm should be most prominent in this condition. For the monocular session, a black occluder was inserted into the trial frame, blocking visual input for the respective eye and patients were shown the same visual scenes but with different onset-cue and change condition assignment. Controls performed the experiment once binocularly. Patients’ visual

acuity was corrected individually by adjusting trial lenses, based on results of the optical refraction, until patients reported optimal visibility of stimuli. When necessary, for example, because of wearing progressive lenses, we applied the same procedure to controls referring to their eyeglass prescription.

3.3.5. Data Analysis

Change detection performance analysis and all statistical tests were carried out using R (version 3.0.2 R Core Team, 2013). Change detection sensitivity was measured as A' for each participant and each onset-cue condition, estimating the receiver operating characteristic (ROC) area and ranging from .5 (chance) to 1 (perfect sensitivity) using the formula reported by Snodgrass and Corwin (1988; see also Stanislaw and Todorov, 1999). The hit rate was calculated as proportion of correct responses when the target changed and the false alarm rate as the portion of errors when it remained the same. Analyses of variance (ANOVAs) were performed using Type III sums of squares. Planned two-tailed t -test comparisons were adjusted according to Holm (1979) and for all comparisons between samples we used Welch's t test. We analyzed change sensitivity of patients and controls in joint two-way mixed-design ANOVAs with the within subjects factor cue (invalid, valid) and the between subjects factor experimental group (patient, control).

The distance of gaze to the target object was calculated as follows. We defined a rectangular shape around the borders of the target objects, enlarging it by 0.5° of visual angle at the borders to account for deviations in the accuracy of the measured gaze data. When the gaze fell inside this rectangular region, the distance to the object was set to zero and when it fell outside, the distance was defined as the euclidean distance between the measured gaze point and the border of the rectangle.

3.3.6. Data exclusion and spatial accuracy of measured gaze

For the analysis of change detection sensitivity and gaze parameters, we excluded all trials in which the response time was shorter than 200 ms (one trial in the patient monocular condition). Additionally, we excluded all trials with extreme response times, exceeding the mean plus 2.5 standard deviations for each participant. This led to a removal of 2.51 %, 2.45 %, and 2.94 % of all remaining trials in the patient monocular, binocular, and control group respectively.

For the analysis of the gaze data, we additionally excluded all trials in which too many gaze samples were missing due to signal loss. We defined a trial as invalid when it met one of the following conditions: more than 20 % signal loss during the 20s exploration of the initial scene, onset-cue or the following 200ms presentation of the initial scene or more than 50 % signal loss during the test scene. The latter criterion was chosen to be very liberal because many participants blinked when responding, leading to higher signal loss at the end of the trial. Following this procedure, we excluded participants for whom more than half of the trials in one of the cells of the Cue \times Test factor combinations were missing. This led to the exclusion of four controls (average trials excluded 47.92 %, 54.17 %, 37.50 %, 37.50 %, three patients in the monocular (P05, 58.33 %; P06, 47.92 %; P08, 85.42 %) and three in the binocular (P01, 68.75 %; P08, 47.92 %; P17, 41.67 %) condition.

Measurement of eye movements commonly requires foveation of the calibration targets during the setup of the eye tracker. In AMD patients, this procedure is challenging because patients may not be able to foveate the targets, compromising spatial accuracy of the measured gaze. For the analysis of the eye movements, it was therefore important to assure that the measured locus of fixation was consistent across the experiment. It is important to note that using the standard eye tracking methods, however, we cannot derive whether the measured locus of fixation was the fovea or an adapted eccentric location on the retina of the patients. We measured spatial accuracy by computing the distance of the last fixation of each trial to the post-cued target object, that is, immediately before or during the participant responded. We excluded participants showing an average median distance greater than 1° of visual angle to ensure valid analyses of fixation positions, especially considering target fixations during

exploration. This was the case for P03 (1.85°) in the monocular as well as P05 (1.53°) and P06 (3.11°) in the binocular condition.

Thus, 13 controls, 11 patients in the monocular and 12 in the binocular condition remained in the analyses of the gaze data (please note that all patients remaining in the monocular condition were fixating centrally according to the fundus-controlled micropertometry, also see Table 3.2). The average percentage of trials included was 88.94% for controls, 85.98% for patients monocular and 86.11% for patients binocular. The average median spatial deviation of the measured gaze was 0.00° ($SD = 0.00^\circ$) in controls, 0.05° ($SD = 0.18^\circ$) in patients monocular, and 0.08° ($SD = 0.27^\circ$) in patients binocular.

3.4. Results

The main question of the experiment was to examine whether encoding of objects into VLTm, a process that typically depends on attentive foveation in normal vision, can be carried out by extrafoveal vision. For this purpose, we measured change detection performance in a sample of AMD patients suffering from foveal vision loss. Patients performed the change detection task with their more severely affected eye in the monocular condition in which possible effects of diminished foveal vision on VLTm should be most prominent. Please note that two patients could only perform the task with their better eye (P09 and P16, see section 3.3.1 Participants, Tables 3.1 and 3.2) and were excluded from all analyses as they may have profited from masking their worse eye. In the binocular condition, the question was whether the better eye could compensate potential deficits. Concomitantly, binocular viewing has a higher ecological validity and may reflect patients' visual behavior in everyday life more accurately. Anticipating the main results, VLTm was comparable between patients and controls and not related to visual acuity. Patients with greater visual impairment, however, showed fewer and longer fixations during exploration. The spatial onset-cue captured attention for patients and controls alike, however it improved change detection performance only for controls and patients performing the task binocularly.

3.4.1. Change detection sensitivity

A' analysis

Averaged A' are shown in Figure 3.2. We first compared patients' monocular performance with controls. Patients were overall less sensitive for target changes (.70) than controls (.83), as indicated by the significant main effect of experimental group, $F(1, 28) = 10.17$, $p < .01$, $\eta_G^2 = .21$. The main effect of onset cue was also significant, $F(1, 28) = 12.67$, $p < .01$, $\eta_G^2 = .11$, with higher sensitivity in the valid (.82) than invalid (.72) condition. Additionally, the interaction was significant, $F(1, 28) = 7.58$, $p < .05$, $\eta_G^2 = .07$, with an average improvement of sensitivity under valid onset cues by .15 in controls compared to only .02 in patients. Post-hoc t test on the levels of both factors confirmed that controls benefited significantly from the onset cue, $t(16) = 4.70$, $p < .01$, whereas this was not the case for patients, $t(12) = 0.55$, $p = .92$, and performance in controls was significantly better than in patients for valid onset cues, $t(15.49) = 4.07$, $p < .01$. Critically, patients' performance (.69) was comparable to controls (.75), $t(26.05) = 1.23$, $p = .69$, when the onset cue was invalid. This result is important because it indicates normal performance in patients when attention was withdrawn from the target object before the test scene appeared, thus requiring retrieval from VLTm.

When patients explored the scenes binocularly, performance was comparably accurate as in controls. In contrast to the monocular analysis, only the main effect of onset cue was significant, $F(1, 32) = 32.46$, $p < .001$, $\eta_G^2 = .25$, with higher sensitivity in the valid (.87) than invalid (.74) condition. Neither the main effect of experimental group nor the interaction were significant, all F s < 1.60 , all p s $> .21$, all η_G^2 s $< .04$, indicating that patients were overall equally sensitive for target changes and could profit from valid onset cues to a similar amount as controls when vision was not restricted to the worse

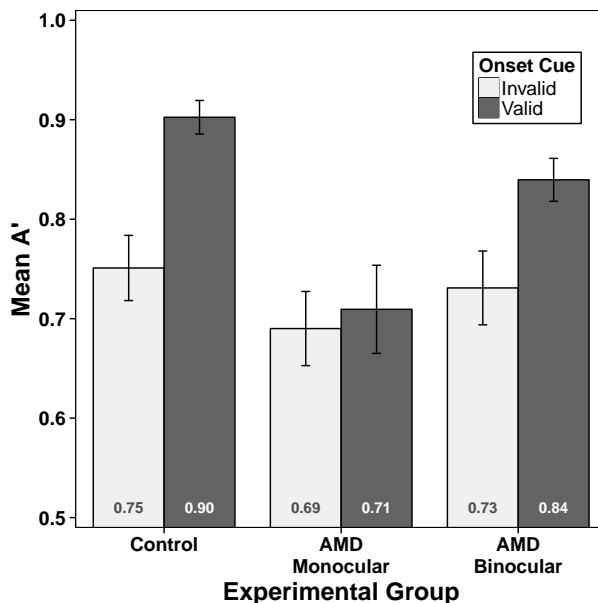


Figure 3.2.: Averaged A' as a function of onset cue validity and experimental group. Error bars depict the standard error of the mean.

eye. Importantly, patients again performed as accurate (.73) as controls (.75) under invalid onset cues probing VLTM.

Individual performance

The A' analysis revealed that VLTM performance, measured with the invalid onset cue condition, remained overall intact in AMD patients who were forced to encode the scene objects with their remaining peripheral vision. Change detection sensitivity might nevertheless be reduced in patients with more severe foveal dysfunction. To test this prediction, we correlated logMAR visual acuity with A' using Kendall's τ nonparametric rank order correlation (see Figure 3.3, Table 3.2 for individual A'). Sensitivity under invalid cues numerically decreased somewhat with greater visual impairment, however, this effect was not significant, $\tau = -.24$, $p = .27$. For valid cues, LogMAR visual acuity correlated negatively with sensitivity, $\tau = -.51$, $p < .05$, showing that patients with more severe foveal impairment profited less from the cue.

The relationship between logMAR visual acuity of the better or worse eye with A' under binocular viewing are depicted in Figure 3.4 and detailed in Table 3.2. For invalid cues, similar to monocular search, sensitivity numerically decreased with greater visual impairment of the better eye, but this relationship was not significant, $\tau = -.26$, $p = .17$, and neither was the correlation with acuity of the worse eye, $\tau = -.05$, $p = .80$. For valid cues, visual acuity of the better eye was significantly correlated with sensitivity, $\tau = -.40$, $p < .05$, whereas this was not the case regarding the visual acuity of the worse eye, $\tau = -.09$, $p = .62$. These results indicate that patients relied more on their better eye to perform the task and that, as long as residual vision of the better eye was sufficient, patients could use the valid onset cue to improve change detection performance.

3. Experiment 1: Visual memory for objects following foveal vision loss

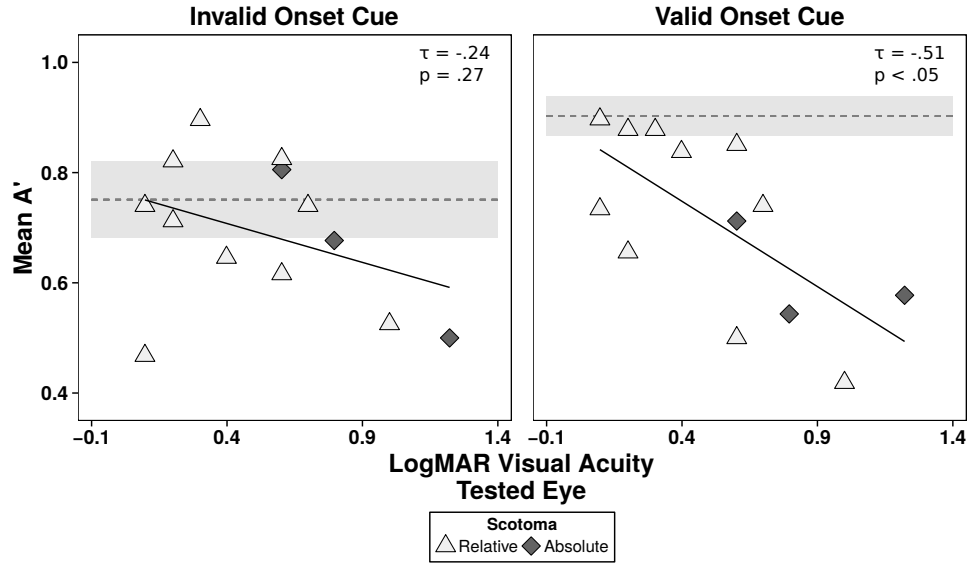


Figure 3.3.: Relationship between the degree of foveal impairment in AMD (logMAR visual acuity) and change detection sensitivity (A') for invalid (left panel) and valid (right panel) onset cues in monocular vision. Rank correlations were quantified using Kendall's τ . The solid line depicts the linear regression for the purpose of visualization. The dashed line represents the averaged mean sensitivity of controls and the shaded area the corresponding 95 % confidence intervals.

Table 3.2.: Individual change detection performance

Patient	Right eye			Left eye			Sensitivity (A')				Availability of valid gaze data	
	Scotoma	Fixation	VA (logMAR)	Scotoma	Fixation	VA (logMAR)	Worse eye		Binocular		Worse Eye	Binocular
							IC	VC	IC	VC		
P10	Absolute^c	Central	1.2	Relative	Central	0.2	0.50	0.58	0.88	0.82	x	x
P05	Absolute	Eccentric	0.8	Absolute^d	Central	0.2	0.68	0.54	0.47	0.70	—	—
P06	Absolute	Eccentric	0.6	Absolute	Eccentric	0.6	0.81	0.71	0.69	0.65	—	—
P14	—	Central	0.0	Relative	Central	1.0	0.53	0.42	0.95	0.95	x	x
P11	Relative	Central	0.1	Relative	Central	0.7	0.74	0.74	0.74	0.71	x	x
P03	Relative	Eccentric	0.6	—	Central	0.0	0.62	0.50	0.54	0.90	—	x
P15	Relative	Central	0.6	Relative	Central	0.0	0.83	0.85	0.74	0.88	x	x
P08	—	Central	-0.1	Relative	Central	0.4	0.65	0.84	0.92	0.90	—	—
P01	Relative	Central	0.2	Relative	Central	0.3	0.90	0.88	0.73	0.93	x	—
P02	Relative	Central	0.2	Relative	Central	0.1	0.71	0.66	0.50	0.75	x	x
P07	Relative	Central	0.2	Relative	Central	0.2	0.82	0.88	0.84	0.90	x	x
P04	Relative	Central	0.1	Relative	Central	0.0	0.74	0.90	0.92	0.87	x	x
P12	Relative	Central	0.1	Relative	Central	-0.1	0.47	0.73	0.68	0.89	x	x
P13 ^b	Absolute	Eccentric	1.0	Relative	Central	0.3	—	—	0.66	0.86	—	x
P09 ^b	Relative	Central	0.0	Absolute	Eccentric	1.3	—	—	0.90	0.90	—	x
P16 ^a	Absolute	Eccentric	1.3	Relative	Central	0.0	—	—	0.66	0.88	—	x
P17 ^b	—	Central	0.2	Absolute	Central	1.3	—	—	0.61	0.78	—	—

Note: VA = visual acuity; LogMAR = logarithmic "Minimum Angle of Resolution"; IC = invalid cues; VC = valid cues. Characteristics of the eye used for monocular testing are shown in boldface.

^a Two patients could not complete the experiment with their more severely affected eye in the monocular condition and were therefore tested with the better eye.

^b Two patients did not perform the experiment monocularly.

^c Fovea spared.

^d Peripheral scotoma.

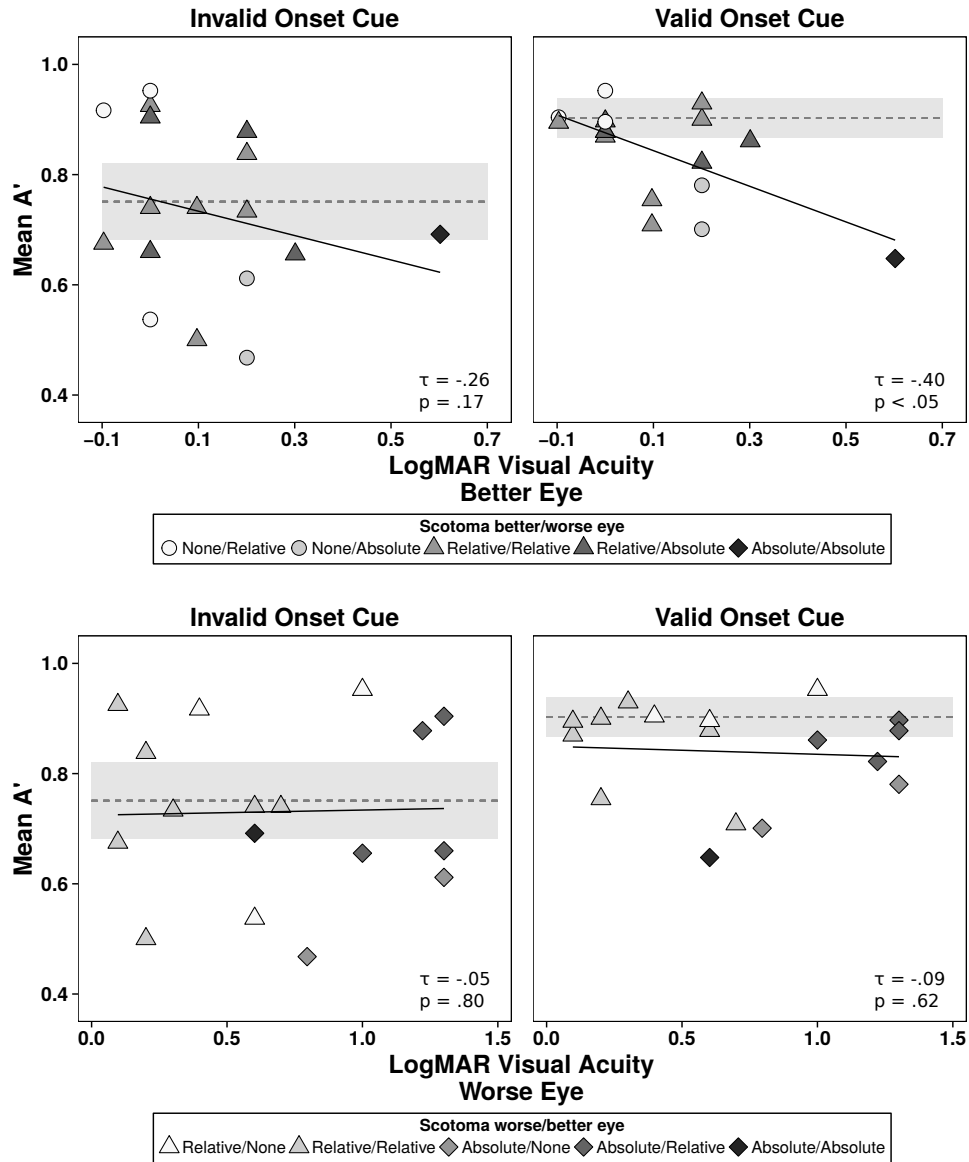


Figure 3.4.: Relationship between the degree of foveal impairment in AMD (logMAR visual acuity) and change detection sensitivity (A') for invalid (left column) and valid (right column) onset cues of the better (top row) and worse eye (bottom row) in binocular vision. Rank correlations were quantified using Kendall's τ . The solid line depicts the linear regression for the purpose of visualization. The dashed line represents the averaged mean sensitivity of controls and the shaded area the corresponding 95% confidence intervals.

3.4.2. Gaze data analysis

Scene exploration

Loss of foveal vision may lead to altered exploration behavior in that the guidance of eye movements becomes more top-down controlled (for example, in order to place a peripheral target not into the malfunctioning fovea but into an intact part of the eccentric retina). We investigated eye movements during the free exploration period to search for such differences. Overall, we did not find any impairment in VLTM for objects in AMD patients and no significant relation of VLTM performance with the degree of visual impairment. Likewise, fixation characteristics of patients and control participants did not differ significantly during the free exploration of the initial scene².

For the analysis of visual exploration, we first compared the overall number and duration of fixations between patients and controls using two-sided Welch t tests. During exploration, controls fixated on average 58.91 times. Patients' number of fixation did neither differ significantly from controls' under monocular (57.08 fixations) nor binocular viewing (61.78 fixations, all t s < 1.08 , all corrected p s $> .59$). The average duration of fixations was 273 ms for controls and comparable to patients under monocular (280 ms) and binocular viewing (251 ms, all t s < 1.43 , all corrected p s $> .33$).

Analogous to the analysis of sensitivity measures, we also correlated number and duration of fixations with visual acuity using Kendall's τ . Interestingly, under monocular viewing, the more severe the visual impairment in patients, the fewer fixations were executed, $\tau = -.80$, $p < .01$ and the longer the eye remained on average at one fixated location, $\tau = .63$, $p < .05$. Thus, the normal VLTM performance may be due to a gradual change of exploration strategy with increasing loss of acuity. Under binocular vision, visual exploration was not clearly related to acuity of the better or worse eye. There was a non-significant trend towards longer fixation durations with increasing impairment of the better eye, $\tau = .40$, $p = .09$, but none of the other correlations approached significance, all absolute τ s $< .30$, all p s $> .20$.

Target encoding

An important precondition for the later retrieval of an object is its previous fixation in normal vision (Hollingworth, 2006). Although patients overall made as many fixations as controls this does not ensure that patients had the chance to encode the target object. A large amount of fixations may have been refixations similar to regression observed during reading (Bullimore & Bailey, 1995; McMahan et al., 1991), leaving not enough time to encode the target at comparable levels as controls. Therefore, we calculated the individual proportion of trials in which the target was fixated at least once and compared the results by means of a two-way mixed-design ANOVA with the between-subjects factor experimental group (patient, control) and the within-subjects factor cue (invalid, valid). Under monocular viewing, patients fixated the target in a slightly lower amount of trials 93.79% than controls 97.01%, however this was not significant, main effect experimental group, $F(1, 20) = 2.24$, $p = .15$, $\eta_G^2 = .08$. Neither the non-significant main effect of cue nor the interaction indicated any difference depending on the cue validity, all F s < 1.30 , all p s $> .26$, all η_G^2 s $< .02$. Similarly, none of the effects was significant under

² Due to the data exclusion procedure, only patients who fixated centrally according to the fundus-controlled microperimetry were included in the gaze data analysis. We reanalyzed change detection sensitivity including only those patients and trials used for the eye movement analysis to ensure that the pattern of results remained comparable. Overall, patients were less sensitive for target changes than controls, $F(1, 20) = 9.92$, $p < .01$, $\eta_G^2 = .24$; .71 for patients and .84 for controls, and change detection was improved for valid onset cues $F(1, 20) = 9.34$, $p < .01$, $\eta_G^2 = .14$; .84 for valid and .74 for invalid cues. The interaction failed to reach significance, $F(1, 20) = 1.54$, $p = .23$, $\eta_G^2 = .03$, but the numerical pattern of results was similar (sensitivity increase of .14 for valid onset cues in controls versus .06 in patients). Performance was numerically elevated in controls for valid (.91 versus .73 in patients), $t(10.26) = 2.88$, $p = .06$, and did not approach significance for invalid onset cues (.78 in controls versus .68 in patients), $t(12.42) = 1.66$, $p = .36$. Furthermore, change detection sensitivity was negatively correlated with visual impairment in patients for valid, $\tau = -.57$, $p < .05$, but not invalid onset cues, $\tau = 0$, $p = 1$.

binocular viewing, all F s < 1.55, all p s > .22, all η_G^2 s < .04; 95.65 % of trials with target fixation in patients. Given the overall low amount of trials in which the target was not fixated, exploration time was thus sufficient to encode the target object for controls as well as patients.

Because the overall number of trials in which the target was fixated at least once was very high, we reexamined exploration of the target region using more sensitive measures. We compared the average absolute amount of fixations and the total amount of time spent on the target as well as the relative fixation amount and time (the number of fixations and fixation time on the target divided by all fixations and total fixation time) per trial by means of two-way mixed-design ANOVAs with the between-subjects factor experimental group (patient, control) and the within-subjects factor cue (invalid, valid). None of the effects comparing patients' monocular exploration with controls' was significant: absolute fixations on target, all F s < 1, all p s > .82, all η_G^2 s < .01; relative fixations on target, all F s < 1, all p s > .70, all η_G^2 s < .01; total fixation time of target, all F s < 1, all p s > .55, all η_G^2 s < .02; relative fixation time of target, all F s < 1, all p s > .53, all η_G^2 s < .02, indicating that controls (4.66 fixations / 7.92 % and 1270 ms / 8.14 %) and patients (4.59 fixations / 8.06 % and 1318 ms / 8.43 %) visited the target region on average equally often and equally long during exploration. The results of patients' binocular exploration were similar. We observed no significant differences comparing the fixation numbers or time on the target, all F s < 2.2, all p s > .16, all η_G^2 s < .04; 4.85 fixations / 7.86 % and 1259 ms / 8.25 % for patients binocular.

Effectiveness of the onset cue

The behavioral results show that, whereas VLTMs for objects remains largely intact, patients failed to profit from valid onset cues under monocular viewing. This may have been simply due to the fact that patients did not perceive the cue, for example, because it was covered by their scotoma. If the onset cue failed to capture patients' attention, invalid onset cues might have been less efficient, potentially leading to artificially inflated detection scores because patients might still be fixating at or close to the target. If, however, the cue effectively captured attention, we expected an overt shift of attention towards the cue location, that is, we expected the locus of the first fixation after the cue presentation to be significantly closer to the target position when it was validly indicating the target position than when it was presented somewhere else in the scene.

Figure 3.5 depicts the average median distance of fixations to the target location during different phases of the trial. We statistically compared the distance of the last fixation to the target object during the initial scene, immediately before the cue presentation, and the first fixation during the second presentation of the initial scene, immediately after the cue presentation. Before the cue is presented, the distance to the target should be independent of the cue validity. If the cue leads to an overt shift of attention, the distance to the target should decrease selectively for valid onset cues, that is, when the cue and the target occur at the same location. We performed a three-way mixed-design ANOVA on the median distance of the fixation to the target with the within-subjects factors cue (invalid, valid) and trial phase (initial scene before cue, initial scene after cue) and the between-subjects factor experimental group (patient, control).

Comparing patients' monocular data with controls, there was no significant main effect of experimental group, $F(1, 20) = 2.92$, $p = .10$, $\eta_G^2 = .04$. The main effect of cue was significant, $F(1, 20) = 137.53$, $p < .001$, $\eta_G^2 = .68$, indicating closer fixations to the target following valid (3.13°) than invalid (6.85°) cues. The main effect of trial phase was also significant, $F(1, 20) = 69.33$, $p < .001$, $\eta_G^2 = .32$, showing overall closer fixations to the target after cue presentation (4.15°) than before (5.83°). Critically, the interaction between cue and trial phase was significant, $F(1, 20) = 135.83$, $p < .001$, $\eta_G^2 = .64$. While the distance to the target was virtually identical for cue identity before the cue was presented (5.99° for invalid and 5.67° for valid onset cues), gaze was shifted towards the target after valid cues (0.59°) and further away after invalid cues (7.71°). None of the other two-way interactions was significant all F s < 2.82, all p s > .10, all η_G^2 s < .02. Importantly, the three-way interaction was also not significant,

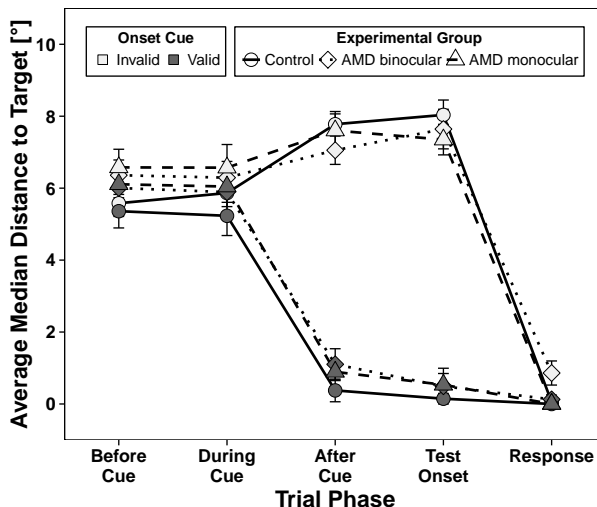


Figure 3.5.: Averaged median distance of the fixation to the target location as a function of trial phase, separated for invalid (light gray) and valid (dark gray) cues and controls (circles) and AMD patients performing the task monocularly (triangles) and binocularly (diamonds). Error bars depict the standard error of the mean.

$F(1, 20) = 0.67$, $p = .42$, $\eta_G^2 = .01$, indicating that the cue lead to an overt shift of attention for controls and patients alike³.

Under binocular viewing, patients' significantly better change detection performance under valid onset cues indicated that the onset cue efficiently captured attention and allowed patients to make use of the target information available during the 200 ms following the cue. The expected overt shift of attention following the cue was confirmed by the analysis of the median distance to the target. As in the monocular analysis, the main effects of cue and trial phase and their interaction were the only significant effects, all F s > 68.93, all p s < .001, all η_G^2 s > .30; all other effects, all F s < 2.86, all p s > .10, all η_G^2 s < .03, emerging from overt shifts of gaze towards the target selectively in cue valid trials in controls and patients alike (from 5.96° and 5.67° for invalid and valid onset cues before to 7.43° and 0.73° after cue presentation).

Contribution of visual long-term memory

A central goal of this study was to investigate the integrity of VLTm after foveal vision loss. Hollingworth (2004) found a contribution of visual short-term memory (VSTM), represented as a recency advantage for the two most recently fixated objects, and a VLTm contribution for objects that had been encoded longer back in a change detection task comparable to the one we used. It is thus possible that the good change detection performance we observed in our patients was partly inflated by VSTM. Previous work suggests that VSTM only holds a limited amount of approximately four simple (Luck & Vogel, 1997) and two to three complex objects at a time (Alvarez & Cavanagh, 2004; Hollingworth, 2004). We therefore

³ The amount of trials in which at least one saccade was made during cue presentation did not differ between patients and controls or cue identity (mixed-design ANOVA with the within-subjects factor cue (invalid, valid) and the between-subjects factor experimental group (patient, control); all F s < 1, all p s > .80, all η_G^2 s < .01; saccade in 77.9 and 76.4% of trials with invalid and 78.5 and 76.4% with valid onset cues for controls and patients respectively). Similarly, the amount of trials including a valid fixation during the 200 ms presentation of the initial scene after the cue was comparable between experimental groups and cue identity, all F s < 1, all p s > .66, all η_G^2 s < .01; fixation in 79.6 and 76.6% of trials with invalid and 79.8 and 78.8% with valid onset cues for controls and patients respectively).

excluded all trials in which less than four intervening fixations on non-target objects were made between the last fixation of the target and the offset of the initial scene during encoding, ensuring that the target was no longer held in VSTM, and reanalyzed A' for invalid trials. If VLTM suffers from loss of foveal vision, patients were expected to perform no different from chance and less accurate than controls. A two-sided paired t test showed that patients' monocular performance was significantly different from chance, $t(8) = 3.71$, $p < .01$, with an average A' of .70. Furthermore, change detection sensitivity was not significantly different from controls ($A' = .79$), Welch two-sided t test, $t(13.69) = 1.29$, $p = .22$, confirming intact VLTM after foveal vision loss. The same was true for patients' binocular performance. Patients performed significantly different from chance (two-sided paired t test, $t(11) = 4.24$, $p < .01$, with an average A' of .74. Change detection sensitivity was not significantly different from controls, Welch two-sided t test, $t(18.16) = 0.80$, $p = .43$.

3.5. Discussion

We investigated whether VLTM for objects suffers in the presence of foveal vision loss. Studies with normal-sighted observers have repeatedly shown that VLTM for objects depends strongly on previous fixation of the remembered objects. This is due to the tight coupling of saccade-target location and selective spatial attention that brings the saccade target into the focus of selective attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). When foveal vision is lost, it may take years to overcome this oculomotor mechanism and develop an extrafoveal PRL as a saccadic reference point (von Noorden & Mackensensen, 1962; White & Bedell, 1990; Whittaker et al., 1991). Until this saccadic rereferencing has been achieved, saccading towards a peripheral object will bring this object into foveal vision. Object perception then depends on corrective saccades that bring the target to a location outside of the area of vision loss, along with covert shifts of attention from the fovea to this new extrafoveal retinal location. We reasoned that this top-down controlled attentional processing may lead to deficits in attentive object processing and in turn to deficient object encoding into VLTM. To investigate VLTM for objects, we tested a sample of AMD patients with foveal vision loss with a token-change detection task after free exploration of everyday indoor scenes (Hollingworth, 2003). The main finding was that VLTM for objects was overall preserved after foveal vision loss, demonstrated by sensitivity to object changes in AMD patients comparable to closely matched controls. Intact VLTM for objects was observed both under binocular and, importantly, monocular vision with the worse eye. Patients' change detection accuracy was not significantly different from that of the controls even when four or more fixations intervened between target encoding and memory test. Given the limited capacity of visual working memory (Luck & Vogel, 2013) this is a clear indication that the original object must have been retrieved from VLTM (Hollingworth, 2004; Hollingworth & Henderson, 2002).

Previous studies with normal-sighted observers (Hollingworth & Henderson, 2002; Pertzov et al., 2009; Tatler et al., 2005) reported a close relationship between the number and duration of fixations and later VLTM performance. Our data agree with these findings in that the patients' normal VLTM performance in the change detection task (with invalid cues) went along with a normal number and duration of fixations on the target objects in free exploration. This was a surprising result. Based on the literature, we had expected that patients may frequently make saccades that bring the target object into foveal vision, requiring corrective saccades to view the object at an extrafoveal location with still intact vision. This was quite obviously not the case, as both the number and duration of fixations did not differ from the control group. We also looked more specifically at the fixations on the target. Again, no differences between patients and control group were observed. There are two possible explanations for this normal fixation pattern. Some of the patients, in which the disease was in an early stage, may still have been able to encode the objects sufficiently with foveal vision to successfully detect object changes. However, patients with an absolute scotoma were not more impaired at change detection than patients with a relative scotoma who still perceived some degraded visual input with their fovea (Figure 3.3,

Table 3.2). Particularly the intact monocular performance of two out of three patients with an absolute central scotoma demonstrates clearly that efficient object encoding can proceed in extrafoveal vision.

It appears that the patients who had to rely on parafoveal vision were able to use an extrafoveal PRL as a reference point for their saccades, so that a saccade to a peripheral target brought the target directly into the PRL region instead of the fovea. Such a saccadic rereferencing would allow much more efficient scene exploration and may contribute to their normal VLTm encoding. For the theoretical question of this paper, this means that object encoding was possible with an extrafoveal part of the retina. More specifically, it shows that when foveal vision is compromised, an extrafoveal region can take over to subserve attentive encoding of visual objects into VLTm. As a caveat, it should be mentioned that saccadic rereferencing to an extrafoveal PRL is not without difficulties. Even if stable saccadic rereferencing to a PRL has been achieved, saccades often show higher latencies and less accurate landing points compared to foveating saccades (White & Bedell, 1990; Whittaker et al., 1991). These effects scale with the eccentricity of the PRL and go hand in hand with a steady decrease of visual resolution, making scene exploration more and more difficult with increasing (and more extensive) vision loss. In our more severely affected patients, this increased difficulty was likely expressed by longer fixation durations.

The interpretation of the fixation pattern as evidence for extrafoveal saccade rereferencing may seem to be at odds with the foveal fixation seen in the diagnostic fundus-controlled microperimetry in most of the patients. However, it should be kept in mind that patients were confronted with a simple fixation task on a non-structured background in the microperimetry, while they were actively exploring a natural scene in the change-detection task. Differences in PRL-use depending on task and stimulation have been observed previously (Crossland, Crabb, & Rubin, 2011; Déruaz et al., 2002; Duret et al., 1999).

In this context, it may be noted that saccadic rereferencing has recently been obtained after a few hours of visual search training in normal-sighted observers with simulated gaze-contingent central scotomata (Kwon, Nandy, & Tjan, 2013; Walsh & Liu, 2014). In contrast, many reports of long-lasting difficulties of saccadic rereferencing in patients with foveal vision loss have relied on simple fixation tasks (Bellmann et al., 2004; Bethlehem et al., 2014; Crossland et al., 2004; Schuchard, 2005; Sunness & Applegate, 2005; Tarita-Nistor, González, Markowitz, & Steinbach, 2008; White & Bedell, 1990; Whittaker et al., 1988; Whittaker et al., 1991). Taken together with the current data, the evidence may point to better saccadic rereferencing to a PRL in a structured search environment.

Comparison of Figures 3.3 and 3.4 shows that binocular vision was dominated by the better eye. The correlation of the worse eye's acuity with detection performance under monocular viewing was lost under binocular viewing. This is an example that binocular performance cannot easily be predicted from monocular performance. In this case, the acuity loss in the worse eye does not seem to have inhibited binocular performance, in contradistinction to mixed patterns of performance de- or increases within AMD samples in other functions, such as contrast sensitivity (Faubert & Overbury, 2000; Valberg & Fosse, 2002) or visual acuity and reading speed (Tarita-Nistor, Brent, Markowitz, Steinbach, & González, 2013).

3.5.1. Caveats

One caveat concerns potential order effects because patients were first tested binocularly, then monocularly using the same scenes. Although patients verbally reported not remembering the scenes or target objects within the scenes, we cannot be sure that patients' VLTm performance in the monocular condition was not inflated because they were already familiar with the stimulus material. We tried to counteract this confound by assigning different cue conditions as well as identities of the test scene to individual scene images. Furthermore, because patients had to identify token changes of largely similar scene objects, even if patients had known about the location of the target object, they would still have had to encode the objects in detail to perform the task. If patients had profited from remembering potential targets, we should have expected more or longer fixations on target locations. This, however,

was not the case. The number of fixations as well as the overall inspection time of the target object during exploration were comparable to controls who were inspecting the scenes for the first time. In the present study, it was difficult to randomize task order as the sample was too small to assess possible interactions between patient factors such as severity of visual impairment and task order. If larger sample sizes become available, however, randomizing the order of binocular and monocular testing would clearly be preferable.

Another limitation concerns possible strategies patients may have used to perform the task, unrelated to VLTM for objects. For example, participants may have maintained the objects using verbal encoding. However, none of our participants reported verbalizing the objects. Furthermore, Hollingworth (2003, Experiment 3) showed that an additional verbal working memory load and articulatory suppression did not change detection performance in the present paradigm, speaking against verbal encoding. Moreover, we investigated token changes, so participants would have needed to verbalize objects with great precision in order to distinguish them from a changed object of the same category. Thus, it is unlikely that VLTM in patients was selectively inflated by verbal encoding.

Objects were designed to be big and distinctive enough to be discriminable with peripheral vision. We wanted to minimize potential confounds of spatial resolution with attentional selection and memory encoding of objects in peripheral vision. Nevertheless, we should keep in mind that spatial resolution of course does limit what can be attended and memorized. Another important limiting factor that deserves investigation may be crowding.

One methodological limitation concerns the measurement of eye movements in AMD patients, more precisely the location of fixation. As we have laid out in the Method section, the standard calibration routine we used requires foveating the calibration targets in normal vision. In our patients however, we cannot clearly conclude whether the calibrated locus of fixation was the fovea or an extrafoveal PRL. We could, however, make sure that the calibrated center of gaze remained consistent across the experiment. For the validation of spatial accuracy we decided not to rely on calibration targets, but rather the position of the target object in the respective scenes. In this way we could be certain that the measured locus of fixation was identical with the one used by the patients during visual exploration.

A salient invalid cue was used to capture attention shortly before the target change in order to assure that participants did not foveate the change location, which would allow change detection by comparing the current stimulus with the most recent content of visual working memory, without recourse to VLTM. In turn, this meant that detection was facilitated when the cue validly indicated the location of the target. This effect was clearly observed in the control group, but in the patients, it was only observed with binocular viewing. The absence of a cue validity effect with monocular viewing could potentially have been problematic for the interpretation of the invalid cue data. If the cues were ineffective in the patients (under monocular viewing), not guiding fixation to a location distant from the target location, the patients might have had an advantage in the invalid cue trials, in that they might have been able to assess object change by comparing the actual stimulus with the last fixation retained in working memory. However, we could rule out this interpretation as patients' and controls' fixation distance to the target location was virtually identical following invalid cues. Thus, the lack of a valid cue advantage in the patients did not reflect a deficit in attentional capture – cue-induced gaze shifts were almost identical in controls and patients (Figure 3.5) – but must have been due to an inability to perceive the target in the 200 ms duration left after the cue when forced to view with their worse eye. In some patients, the saccade elicited by the cue may have projected the cued target object onto the damaged foveal region, degrading object encoding in this way. Even if patients had developed eccentric fixation, the landing point of the saccade following the exogenous cue may have been too inaccurate (Crossland et al., 2004; Tarita-Nistor et al., 2008; White & Bedell, 1990; Whittaker et al., 1991) to ensure proper object encoding. Patients may then have required some time for corrective saccades, making object perception impossible within the short time period of 200 ms the initial scene was presented after the onset cue. In any case, the lack of a valid cue benefit indicates that our patients truly suffered from their foveal vision loss. It is the more remarkable that change detection was unimpaired under monocular

viewing, because this demonstrates that VLTM for objects remained intact in the presence of central vision loss.

3.5.2. Conclusion

In summary, we found remarkably preserved visual long-term memory for objects in the presence of foveal vision loss. Thus, whereas attentive processing and foveal vision are tightly coupled in normal vision, our results show that attentive object encoding can be served by extrafoveal vision if foveal vision is lost. On the one hand, this is an important theoretical finding showing the flexibility of the attentional allocation in the presence of visual pathology. On the other hand, it shows that patients with foveal vision loss may not necessarily suffer from inferior visual object encoding into visual long-term memory.

4 Experiment 2: Impairment of visual memory for objects in natural scenes by simulated central scotomata

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4.1. Abstract

Due to the close link between foveal vision and the spatial deployment of attention, typically only objects that have been foveated during scene exploration may form detailed and persistent memory representations. In a recent study on patients suffering from age-related macular degeneration, however, we found surprisingly accurate visual long-term memory for objects in scenes. Normal exploration patterns suggested that the patients had learned to rereference saccade targets to an extrafoveal retinal location. This rereferencing may allow to use an extrafoveal location as focus of attention for efficient object encoding into visual long-term memory. Here, we tested this hypothesis in normal-sighted observers with gaze-contingent central scotoma simulations. As these observers were inexperienced in scene exploration with central vision loss and had not developed saccadic rereferencing, we expected deficits in visual long-term memory for objects. We used the same change detection task as in our patient study, probing sensitivity to object changes after a period of free scene exploration. Change detection performance was significantly reduced for two types of scotoma simulation diminishing foveal and parafoveal vision – a visible gray disc and a more subtle image warping – compared with unimpaired controls, confirming our hypothesis. The impact of a smaller scotoma covering specifically foveal vision was less distinct, leading to a marginally significant decrease of visual long-term memory performance compared to controls. We conclude that attentive encoding of objects is deficient when central vision is lost as long as successful saccadic rereferencing has not yet developed.

4.2. Introduction

When we explore a complex visual scene, usually only those objects that have been selectively attended are remembered explicitly. Unattended objects, for example, the appearance of an unexpected object in simple visual displays (Mack & Rock, 1998), often go unnoticed. But even when observers are instructed to look for a change in a scene, changes introduced during eye movements are often missed (Bridgeman, Hendry, & Stark, 1975; Grimes, 1996) or take surprisingly long to be detected when an original and

a modified scene are presented in alternation, separated by a brief blank (flicker paradigm; Rensink et al., 1997; Simons & Rensink, 2005). When the changed object becomes fixated, however, detection performance improves significantly (Henderson & Hollingworth, 1999; Hollingworth et al., 2001), an effect that has been attributed to selective attentive processing that is required to encode objects into immediate visual memory (Rensink et al., 1997). Notably, the benefit of attentive object processing is not restricted to immediate memory. Even after attention has been withdrawn, object changes within the same semantic category (token changes) or subtle viewpoint changes are remembered in rich detail (Hollingworth, 2006). Robust visual long-term memory (VLTm) for objects has, for example, been shown across multiple intervening attended objects within the same scene or many different intervening scenes (Brady et al., 2008; Hollingworth, 2004; Hollingworth & Henderson, 2002; Standing, 1973) and even after retention periods of at least one day (Hollingworth, 2005; Vogt & Magnussen, 2007).

One important precondition for successful object encoding into VLTm is, as mentioned above, previous attentive selection that goes along with foveation in normal vision (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). Objects that have never been fixated, and therefore not attended, lead to chance performance in change detection (Hollingworth & Henderson, 2002; Hollingworth et al., 2001; Simons & Rensink, 2005). The close relation between foveation and memory performance is further reflected by an increased later memory success if target objects are fixated more often or for a longer duration during exploration (Hollingworth & Henderson, 2002; Pertzov et al., 2009; Tatler et al., 2005). Moreover, successful change detection critically depends on the distance between the locus of fixation and the changed object (Hollingworth et al., 2001; O'Regan, Deubel, Clark, & Rensink, 2000) and encoding of objects into VLTm may only be successful within a small radius around the current fixation (Nelson & Loftus, 1980).

Here, we ask whether an impairment of central vision interferes with attentive object processing, entailing deficient VLTm for objects. When central vision is lost, all attentive processing that is typically carried out with the fovea needs to be relocated to the remaining peripheral vision. This may not be without problems. When observers are forced to detect changes by covertly shifting attention in peripheral vision, detection becomes significantly delayed and less reliable than when objects can be foveated (Hollingworth et al., 2001; Experiment 2). In a similar fashion, attentive encoding into VLTm may be impaired when attention needs to be decoupled from the fovea during scene exploration. We recently investigated this question in a sample of patients with age-related macular degeneration (AMD), in whom central vision was degraded (Geringswald et al., 2015). Patients were asked to freely explore and memorize every-day objects in natural, computer-generated real-world scenes and were then probed for one specific target object that could either remain the same or be replaced by an object from the same semantic category (token change) in an otherwise identical test scene. A salient onset cue was used to guide attention away from the locus of a potential change to ensure that performance had to rely on memory (Hollingworth, 2003). Surprisingly, we found that VLTm for objects was as good as in normal-sighted, age-matched controls. Taken together with the normal fixation parameters in the patient group, we hypothesized that the patients must have had developed rereferencing of their eye movements to a more eccentric, still functioning, part of the retina (preferred retinal locus [PRL]; von Noorden & Mackensensen, 1962; White & Bedell, 1990; Whittaker et al., 1991) that could then be used as a "pseudofovea" for attentive encoding of objects into VLTm.

Alternatively, it may simply be the case that encoding of objects into VLTm does not depend on attentive foveation at all, as long as observers are given sufficient time to relocate attention to the periphery. To investigate whether VLTm for objects requires attentive foveation in normal vision, we replicated the change detection experiment used in our previous study simulating a gaze-contingent central scotoma in normal-sighted observers who had no previous experience with central vision loss. In the full scotoma condition, we used a scotoma with a radius of 4° of visual angle, roughly encompassing the scotoma sizes of three patients in our previous study that had already developed absolute scotomata and were able to perform the experiment with their worse eye (horizontal scotoma radii of 3.5°, 9°, and 2.5° of visual angle). VLTm performance in two out of these three patients was of similar quality as in

healthy controls. The full scotoma condition in the current study was thus designed as clearly visible gray patch superimposed on the natural scene, extending across foveal and parafoveal vision to simulate an absolute scotoma as in these patients. If object encoding is independent of object foveation (in the fovea or, after foveal vision loss, a pseudofovea), untrained observers should be able to perform as well as unimpaired controls at change detection. If, on the other hand, attentive foveation is a prerequisite to object encoding into VLTM in normal vision, untrained observers, who do not have developed saccadic rereferencing to an extrafoveal PRL, were expected to show reduced VLTM performance. As long as saccadic rereferencing has not been developed, search with a central scotoma affords a high degree of top-down control to avoid objects of interest to become fixated and thereby fall into the scotoma. This top-down controlled exploration was expected to be reflected in the gaze parameters.

The majority of our patients, however, were at earlier stages of the disease and had developed relative scotomata, that is visual depression without a complete loss of light perception. To increase the generality of our findings, we therefore utilized a novel, more subtle image warping implementation that vanished foveal and parafoveal vision in an additional warp scotoma simulation, hypothesized to simulate earlier stages of naturally occurring central vision loss. Due to the degraded visibility of the borders compared to the full scotoma, the warp scotoma simulation additionally enabled us to test whether participants might have learned to rereference saccades to a PRL during the experiment. Recent training studies in normal-sighted observers have indicated that saccadic rereferencing can develop after only a few hours of training (Kwon et al., 2013; Walsh & Liu, 2014). One important precondition, however, was the clear visibility of the scotoma and its borders. If any saccadic rereferencing might develop in our experiment, this was expected to be more difficult in the more subtle warp scotoma condition lacking clear borders. Exploration should then be more cumbersome in comparison with the full scotoma condition where the scotoma and its borders were clearly visible. If no saccadic rereferencing developed, gaze patterns were expected to be highly similar in both simulations.

Recent data on object search in natural scenes suggest that attentive foveation may not be necessary for efficient object encoding as long as parafoveal vision remains available (Nuthmann, 2014). In a third experimental group, we therefore tested more selectively the contribution of foveal vision to attentive object encoding into VLTM by using a small gray-patch scotoma with a radius of 1.5° of visual angle. If parafoveal encoding is sufficient for object encoding into visual memory, change detection performance was expected to be comparable to controls. If foveal vision is a prerequisite to object encoding into VLTM, however, change detection performance was expected to remain inferior.

4.3. Materials and Methods

4.3.1. Participants

Overall, we tested 84 participants. During the initial period of data collection, 20 participants were randomly assigned each to the control (11 females, 3 left handed, 24 years of average age), full (16 females, 1 left handed, 24 years of average age), and warp scotoma (12 females, 2 left handed, 24 years of average age) conditions. The foveal scotoma condition was added post-hoc and included 20 new participants initially, but was increased by four additional participants due to poor data quality compared to the other experimental conditions (see section 4.3.6 Data Exclusion; 11 females, 3 left handed, 22 years of average age).

4.3.2. Apparatus

Stimulus presentation and response collection were carried out with the same equipment as for the patient experiment (see section 3.3.2 Apparatus). Participants viewed the stimuli binocularly and the eye position of the left eye was recorded with a temporal resolution of 1000 Hz. The gaze data retrieved

4. Experiment 2: Impairment of visual memory for objects in natural scenes by simulated central scotomata

for the gaze-contingent scotoma simulation were filtered by the heuristic 1 sample filter (Cornelissen et al., 2002; Stampe, 1993).

4.3.3. Stimuli

Details about the stimuli used in the experiment can be found in Section 2.3.1 Change detection paradigm and examples are depicted in Figure 4.1.

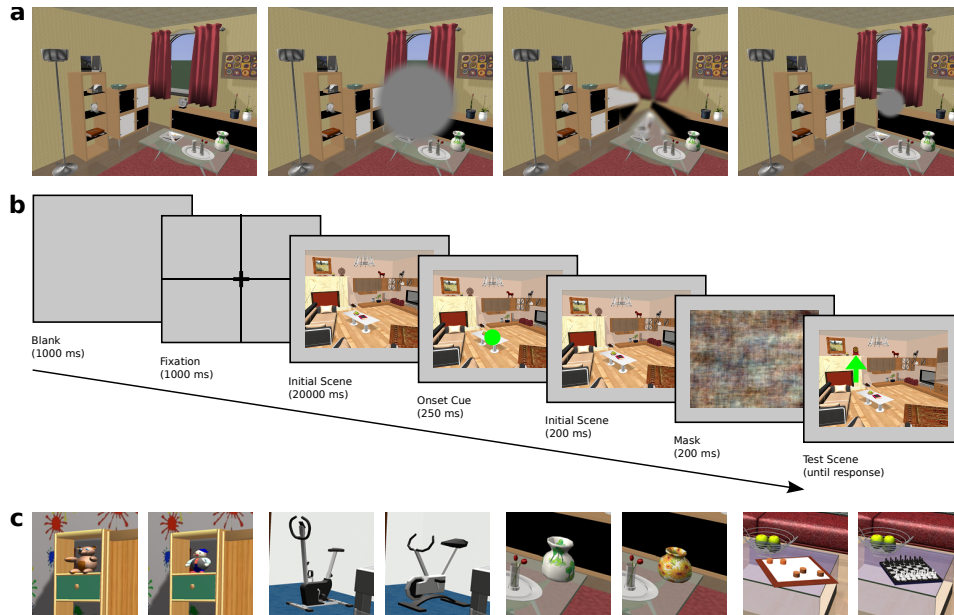


Figure 4.1.: Visualization of the simulated scotomata, schematic diagram of an experimental trial and exemplary target objects. (a) Controls explored scenes with unrestricted vision (first column). The full scotoma was a gray patch superimposed on the visual scene (second column). In the warp scotoma simulation (third column), foveated parts of the scene were logarithmically shifted to the center, making them to disappear. The full and warp scotoma extended across foveal and parafoveal vision with a radius of 4° of visual angle, smoothly fading out across 1° of visual angle at the borders. The foveal scotoma (fourth column) was a gray patch selectively disrupting foveal vision with a radius of 1.5° of visual angle, smoothly fading out across 0.5° of visual angle at the borders. (b) Each trial consisted of a blank screen (1000 ms), followed by the fixation cross (1000 ms), the initial scene (20s), the initial scene and the onset cue (250 ms), the initial scene (200 ms), the mask (200 ms) and the test scene with the post-cue pointing towards the target object (presented until response). In this example, the target object is the clock, the onset cue is invalid and the target object is exchanged with a different type of clock in the test scene. (c) Exemplary pairs of target objects from four different scenes with the object presented during free exploration on the left and its replacement in the change-condition on the right.

The simulated central scotomata (moving mask technique Rayner & Bertera, 1979) extended 4° of visual angle in radius in the full and warp scotoma conditions and 1.5° of visual angle in radius in the foveal scotoma condition. In the full and foveal scotoma conditions, we used a patch colored the same gray as the background. In the warp scotoma condition, we used image warping and Gaussian blurring shaders that efficiently perform all image manipulation directly on the graphics hardware as

implemented in the Psychtoolbox. The pixels within the scotoma were logarithmically shifted towards its center, making the currently fixated stimulus to disappear (see Figure 4.1 for a visualization). For the image warping, we logarithmically transformed the normalized radii of all pixels within a circle of 4° of visual angle around the current fixation location using the formula $\log(1 + 100 * r) / \log(100)$. The difference between the original and the shifted Cartesian coordinates was then fed to the shader, performing the coordinate shifts and interpolation on the texture. In addition, the texture was blurred with a Gaussian 2-D filter with a size of 21 and a standard deviation of 20.5. At the border, the scotomata gradually transitioned from fully visible to fully transparent. For the full and warp scotomata, this was done by setting a circular area with a radius of 3.5° of visual angle to fully visible and applying a circular averaging filter with a diameter of 0.5° of visual angle in the alpha channel of the scotoma. Thus, the fully opaque size of the rendered scotomata extended 3° of visual angle in radius, smoothly fading out at the edges. For the foveal scotoma, the radius set to fully visible extended 1.25° and the circular averaging filter had a diameter of 0.25° of visual angle respectively, leading to a fully opaque size of 1° of visual angle in radius, smoothly fading out at the edges.

4.3.4. Procedure

The procedure was the same as in the patient experiment (see section 3.3.4 Procedure) except for the following differences. In place of orally reminding the participants of the button assignment, a visual reminder of the button assignment was presented on the screen before each trial. Furthermore, we used a 13-point gaze-calibration for setting up the eye tracker, in place of the 9-point routines used in patients. Additionally, to ensure accurate positioning of the gaze-contingent scotoma simulations, the spatial accuracy of the eye tracker was validated using 13 points before each trial. If the average deviation exceeded 1° of visual angle, participants were re-calibrated. One session lasted approximately 60 min.

4.3.5. Data analysis

Change detection performance analysis and all statistical tests were carried out using R (version 3.2.3 R Core Team, 2015). Change detection sensitivity was measured as A' (for details, see section 3.3.5 Data Analysis). Analyses of variance (ANOVAs) were performed using type III sums of squares. Post-hoc two-tailed t-test comparisons were adjusted according to Holm (1979) and for planned comparisons between samples we used Welch's t test. We compared change detection sensitivity between the control, full, warp, and foveal scotoma groups with separate two-way mixed-design ANOVAs with the within-subjects factor cue (invalid, valid) and the between-subjects factor experimental group.

4.3.6. Data Exclusion

As the reliable presentation of the gaze-contingent simulated scotomata depended on the availability of the gaze coordinates retrieved from the eye-tracker, we excluded all trials in which too many gaze samples were missing due to signal loss. We defined a trial as invalid when it met one of the following conditions: more than 20% signal loss during the 20 s exploration of the initial scene, onset-cue or the following 200 ms presentation of the initial scene or more than 30% signal loss during the test scene. The latter criterion was more liberal because many participants either blinked or looked at the button box before responding, leading to higher signal loss at the end of the trial. In Addition, we excluded all trials in which an average spatial accuracy of the eye tracker of at least 1° of visual angle could not be achieved after recalibration. This led to the removal of 15% ($SD = 11.04\%$), 12.29% ($SD = 14.84\%$), 12.81% ($SD = 12.25\%$), and 21.27% ($SD = 21.06\%$) of all trials in the control, full, warp, and foveal scotoma groups respectively. We furthermore excluded all trials in which the response time was shorter than 200 ms or exceeded the mean plus 2.5 standard deviations for each participant. This led to a removal

of 2.60 % ($SD = 2.01$ %), 2.08 % ($SD = 2.03$ %), 2.50 % ($SD = 1.60$ %), and 1.65 % ($SD = 1.84$ %) of all remaining trials in the control, full, warp, and foveal scotoma groups respectively.

Following this procedure, we excluded participants for whom more than half of the trials in one of the cells of the Cue \times Test factor combinations were missing. This led to the exclusion of one participant of the full (overall 58.33 % of all data excluded), one in the warp (overall 43.75 % of all data excluded) and four in the foveal (overall 93.75 %, 43.75 %, 37.50 %, and 54.17 % of all data excluded) scotoma condition.

After data exclusion, 82.40 % ($SD = 10.91$ %), 87.94 % ($SD = 10.22$ %), 86.18 % ($SD = 11.44$ %), and 83.96 % ($SD = 9.82$ %) of all trials for the control, full, warp, and foveal scotoma condition respectively remained in the analysis and the amount of trials included was not significantly different between experimental groups (one-way mixed-design ANOVA with the between-subjects factor experimental group, $F(3, 74) = 1.03$, $p = .38$, $\eta_G^2 = .04$).

4.4. Results

We sought to investigate whether encoding of objects VLTm, a process that depends on attentive foveation in normal vision, is impaired when central vision is diminished by a simulated scotoma in healthy observers. For this purpose, we measured change detection performance with three types of scotoma simulations and compared sensitivity for changes to unimpaired controls. In the full scotoma condition, the scotoma was simulated as a clearly visible gray patch, extending across foveal and parafoveal vision, superimposed on natural scene stimuli. In the warp scotoma group, we used a more subtle simulation implemented with image warping techniques. In the foveal scotoma condition, we specifically tested the contribution of foveal vision to attentive object encoding. Anticipating the main results, VLTm was significantly impaired when central vision, entailing the fovea and parafovea, was impaired. Increased exploration demands due to the loss of central vision were reflected in a reduced number of fixations and larger saccadic amplitudes. Results were highly similar for the full and warp scotoma simulations. Deficits in overall change detection performance were also apparent when foveal vision was disrupted selectively by the smaller foveal scotoma. A decrease in VLTm performance was marginally significant.

4.4.1. Change detection sensitivity

Averaged A' for all experimental groups are shown in Figure 4.2. An overall one-way mixed-design ANOVA on A' with the between-subjects factor experimental group, including controls and all three types of scotoma simulation was significant, $F(3, 74) = 9.06$, $p < .001$, $\eta_G^2 = .27$. To follow up differences in change detection performance between groups, we first compared controls and the full scotoma group in which potential deficits of object encoding should be most prominent.

Full scotoma

A two-way mixed-design ANOVA on A' with the within-subjects factor cue (invalid, valid) and the between-subjects factor experimental group (control, full scotoma) revealed a significant main effect of experimental group, $F(1, 37) = 20.41$, $p < .001$, $\eta_G^2 = .23$, that was due to an overall decline in change detection performance when vision was impaired by the scotoma ($A' = .82$) compared to unimpaired controls ($A' = .92$). The main effect of onset cue validity was also significant, $F(1, 37) = 17.29$, $p < .001$, $\eta_G^2 = .17$, with higher sensitivity in the valid ($A' = .91$) than invalid ($A' = .83$) condition. The interaction between experimental group and cue validity did not approach significance, $F(1, 37) = 0.64$, $p = .43$, $\eta_G^2 = .01$. This result is important because it indicates that the onset cues efficiently guided attention in the scotoma group, which is a prerequisite for the assumption that performance in invalid trials is

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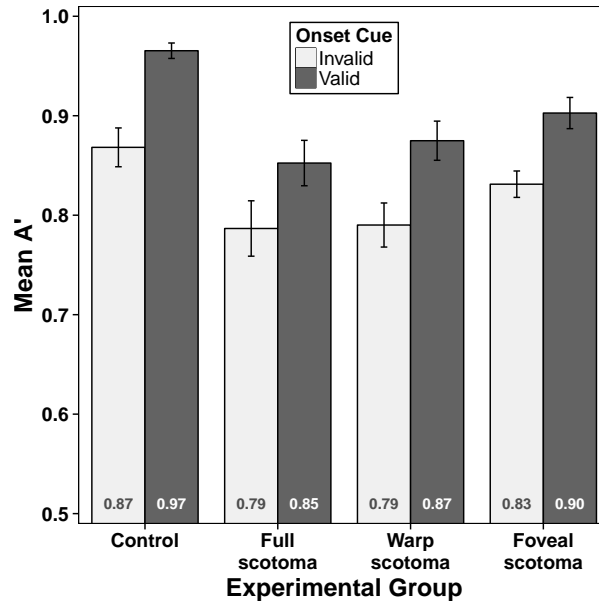


Figure 4.2.: Averaged A' as a function of onset cue validity and experimental group, ranging from .5 (chance) to 1 (perfect sensitivity). Error bars depict the standard error of the mean.

based on object memory. The ANOVA indicated that a simulated scotoma leads to a general drop in performance both for the valid and invalid onset cue condition. To ensure that specifically visual memory suffers in the presence of simulated central vision loss, we reanalyzed sensitivity using only data from the invalid onset cue condition that afforded the use of object memory. A Welch two-sample one-tailed t test confirmed that memory performance was significantly impaired in the full scotoma condition ($A' = .79$) compared to controls ($A' = .87$), $t(32.58) = 2.40$, $p < .05$. Figure 4.2 suggests that, although significantly reduced, memory performance was better than chance in the full scotoma group. This assumption was confirmed by a t test of sensitivity in the invalid onset cue condition against chance, $t(18) = 10.30$, $p < .001$.

Invalid onset cues were used to attract attention away from the target position to ensure that change detection had to rely on visual memory. Hollingworth (2004) reported a recency advantage for the two most recently fixated objects, suggesting that these could be held in working memory. Estimates of visual working memory capacity differ across individuals and test paradigms, but rarely exceed four items (for a recent review, see Luck & Vogel, 2013). To assess the role of visual working memory to change detection performance in our experiments, we calculated the average median number of intervening fixations on non-target objects between the last fixation of the target and the offset of the initial scene for all invalid cue trials. The average amount of intervening fixations was significantly above 3 fixations for controls (14.63 fixations), $t(19) = 11.47$, $p < .001$ and the full scotoma group (13.71 fixations), $t(18) = 8.84$, $p < .001$. More specifically, up to 3 intervening fixations were observed in 19.40% and 20.80% of invalid cue trials in the control and full scotoma group respectively. Given this relatively high amount of trials it is possible that VLTM performance, measured with the invalid cue condition, was inflated by visual short-term memory (VSTM). We therefore recalculated A' after excluding all trials in which less than four intervening fixations were made to ensure that the target was no longer held in VSTM, and all trials in which the target was never fixated (3.53 and 8.52% in the control and full scotoma group respectively). Change detection sensitivity slightly dropped to .86 in controls and did not change numerically in the full scotoma group ($A' = .79$). A Welch two-sample

one-tailed t test confirmed significantly reduced long-term memory performance in the full scotoma condition, $t(35.39) = 1.82$, $p < .05$.

Warp scotoma

The warp scotoma was constructed to simulate earlier stages of central vision loss, before the onset of an absolute scotoma. Results of the two-way mixed-design ANOVA on A' closely mirrored those of the full scotoma condition. A significant main effect of experimental group, $F(1, 37) = 19.14$, $p < .001$, $\eta_G^2 = .23$, revealed significantly impaired change detection performance in the warp scotoma group ($A' = .83$) compared to controls ($A' = .92$). Valid onset cues improved performance ($A' = .92$) compared with invalid onset cues ($A' = .83$), main effect cue validity, $F(1, 37) = 29.75$, $p < .001$, $\eta_G^2 = .26$, to a similar extent for controls and the warp scotoma group, non-significant interaction, $F(1, 37) = 0.14$, $p = .71$, $\eta_G^2 = .01$. While memory performance in the invalid cue condition was clearly above chance, $t(18) = 13.10$, $p < .001$, in the warp scotoma group, it was significantly reduced compared to unrestricted viewing (warp scotoma, $A' = .79$; control, $A' = .87$), Welch two-sample one-tailed t test, $t(36.15) = 2.65$, $p < .01$. A comparison of the full and the warp scotoma group with a two-way mixed-design ANOVA on A' further illustrated the highly similar change detection performance under both simulation types. Overall performance was not significantly different between both scotoma types, main effect experimental group, $F(1, 36) = 0.27$, $p = .61$, $\eta_G^2 = .004$, and the significant main effect of onset cue, $F(1, 36) = 12.39$, $p < .01$, $\eta_G^2 = .13$, confirmed that valid onset cues successfully captured attention to the cued location, leading to improved change detection sensitivity to a comparable extent, non-significant interaction, $F(1, 36) = 0.20$, $p = .66$, $\eta_G^2 = .002$.

Similar to the full scotoma condition, the average amount of intervening fixations in the invalid cue condition was significantly above 3 fixations (18.84 fixations), $t(18) = 8.81$, $p < .001$. The recalculated A' after excluding 19.79% of trials of the invalid cue condition in which less than 4 intervening fixations were made, and 15.42% of trials in which the target was never fixated slightly dropped to .77 and was significantly reduced compared to controls, Welch two-sample one-tailed t test, $t(28.82) = 1.91$, $p < .05$, confirming VLTm impairment.

Foveal scotoma

The foveal scotoma simulation aimed at testing specifically the contribution of attentive foveating while leaving parafoveal vision intact. Overall change detection sensitivity was significantly impaired even when the scotoma simulation spared parafoveal vision, as indicated by the significant main effect of experimental group $F(1, 38) = 10.92$, $p < .01$, $\eta_G^2 = .13$; foveal scotoma, $A' = .87$; control, $A' = .92$. Similar to the full and warp scotoma analyses, performance was significantly improved under valid onset cues ($A' = .93$) compared to invalid onset cues ($A' = .85$), main effect cue validity, $F(1, 38) = 34.82$, $p < .001$, $\eta_G^2 = .30$ and this improvement was comparable between the foveal scotoma group and controls, non-significant interaction, $F(1, 38) = 0.80$, $p = .38$, $\eta_G^2 = .0099$. Visual memory measured with the invalid cue condition was well above chance, $t(19) = 24.94$, $p < .001$, in the foveal scotoma group. A Welch two-sample one-tailed t test comparing the foveal scotoma group to controls on invalid cue trials indicated a trend towards decreased memory performance with the foveal scotoma that was marginally significant (foveal scotoma, $A' = .83$; control, $A' = .87$), $t(33.49) = 1.57$, $p = .06$.

The average amount of intervening fixations in the invalid cue condition was significantly above 3 fixations (11.73 fixations), $t(19) = 9.63$, $p < .001$. To test specifically the contribution of long-term visual memory, we excluded 24.43% of trials from the cue invalid condition in which less than 4 intervening fixations were made, and 1.76% of trials in which the target was never fixated. The recalculated A' slightly dropped to .82. The Welch two-sample one-tailed t test comparing VLTm performance to controls again indicated a non-significant trend towards decreased VLTm performance with the foveal scotoma, $t(34.74) = 1.34$, $p = .09$. To test whether VLTm performance was better with the foveal than

with the full scotoma, we ran an additional Welch two-sample one-tailed t test, yielding no significant differences ($A' = .79$), $t(29.77) = 0.85$, $p = .20$.

4.4.2. Scene exploration

For the analysis of scene exploration, we aggregated the gaze parameters measured during the presentation of the initial scene, where objects had to be memorized by the participants, over onset cue validity and performed one-way ANOVAs with the between-subjects factor experimental group on the number of fixation, fixation duration and saccade amplitude. The impact of the scotoma simulations on the number of fixation, fixation duration and saccade amplitude can be seen in Figure 4.3.

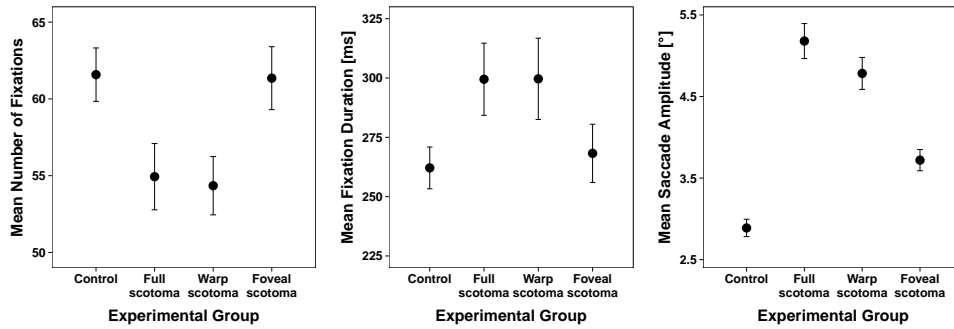


Figure 4.3.: Averaged number of fixations (left), fixation duration (middle), and saccade amplitude (right) during initial scene exploration as a function of experimental group. Error bars depict the standard error of the mean.

The main effect of experimental group was significant for fixation number, $F(3, 74) = 4.04$, $p < .05$, $\eta_G^2 = .14$. The warp scotoma led to significantly reduced fixations (54.35 fixations) compared to controls (61.58 fixations), $t(36.52) = 2.81$, $p < .05$. Although the number of fixations was similarly increased for the full scotoma (54.93 fixations), the comparison to controls failed to reach significance, $t(35.00) = 2.40$, $p = .09$, most likely due to slightly greater variability between participants. Participants of the foveal scotoma group made a comparable amount of fixations as controls (61.35 fixations), $t(37.02) = 0.08$, $p = 1$. Differences in fixation numbers did not reach significance comparing scotoma groups with each other, all $ts < 2.51$, all corrected $ps > .08$. Fixation durations were numerically slightly increased in the full (300 ms), warp (300 ms), and, to a lesser degree, foveal (268 ms) scotoma simulations compared to controls (262 ms), however none of these differences was statistically reliable, $F(3, 74) = 2.17$, $p = .10$, $\eta_G^2 = .08$. The impact of the scotoma simulations on eye movements were most evident in the saccade amplitudes, $F(3, 74) = 39.44$, $p < .001$, $\eta_G^2 = .62$. Saccade amplitudes were significantly greater during exploration with the full scotoma (5.18° of visual angle), $t(26.43) = 9.58$, $p < .001$, warp scotoma (4.78° of visual angle), $t(27.88) = 8.50$, $p < .001$, and foveal scotoma (3.72° of visual angle), $t(36.53) = 4.94$, $p < .001$, compared to controls (2.89° of visual angle). Saccade amplitudes were comparable between the full and warp scotoma, $t(35.71) = 1.37$, $p = .18$ and were significantly greater in both simulations compared to the foveal scotoma, all $ts > 4.52$, all corrected $ps < .001$.

4.5. Discussion

We investigated whether a simulated central scotoma that forces observers to carry out all visual processing with peripheral vision impairs VLTm for every-day objects in natural scenes. This research question was inspired by previous studies demonstrating that VLTm for an object depends on previous

fixation (Hollingworth, 2006) – and concurrent attending (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995) – of the object. Therefore it was surprising that in a recent study on patients suffering from natural central vision loss, their explicit VLTm was as accurate as for healthy, age-matched controls (Geringswald & Pollmann, 2015). We had reasoned that intact attentive object encoding was due to the successful development of saccadic rereferencing to an extrafoveal retinal location (von Noorden & Mackensensen, 1962; White & Bedell, 1990; Whittaker et al., 1991). Under optimal conditions, the development of saccadic rereferencing in observers confronted with central scotoma simulation takes several hours (Kwon et al., 2013; Walsh & Liu, 2014). To investigate the contribution of saccadic rereferencing to successful extrafoveal object encoding into VLTm, we thus examined change detection performance using the same paradigm as in our patient study, this time in normal-sighted observers who were for the first time confronted with a gaze-contingent scotoma simulation.

The main finding was that VLTm for objects was significantly impaired under simulated central vision loss. Change detection sensitivity in the invalid onset cue condition was used to measure memory performance. Cues that validly indicated the target location before a potential change increased change detection performance to a similar extent as in controls, showing that observers oriented their attention to the cued locations. This was a prerequisite to interpret change detection in the invalid cue trials as based on memory, because attention was successfully captured by a non-target region within the scene. In order to ascribe change detection performance to VLTm, we further needed to rule out a contribution of visual working memory. Across all experimental groups, 12 or more fixations were made on average between the last fixation of the target and the offset of the initial scene in invalid cue trials and in approximately 70% of all trials, four or more intervening fixations on non-target objects were made before the memory test. Since this clearly exceeds the capacity of VSTM (Luck & Vogel, 2013), change detection must have relied on VLTm in these trials. To completely rule out a working memory contribution to change detection performance, we ran an additional analysis excluding trials with less than four intervening fixations. The results of these analyses yielded a clear pattern. The full and warp scotoma simulations led to reduced change detection compared to controls. The smaller foveal scotoma also led to numerically reduced change detection but this difference was less reliable, expressed as a marginally significant trend. The smaller scotoma interfered much less with scene exploration than the larger scotomata. This is shown by the gaze parameters, which are more comparable between the foveal scotoma and controls than both other scotoma groups. The effect of the foveal scotoma on VLTm, however, remained somewhat inconclusive. A potential decrease of VLTm compared to controls was not statistically reliable when foveal vision was knocked out selectively, suggesting that the allocation of attentive object encoding to parafoveal vision was more efficient than when objects had to be encoded in peripheral vision with the larger scotomata. This pattern is in agreement with a recent study in which foveal vision was not necessary to efficiently locate and verify a verbally cued target object in natural scenes and costs on target verification only emerged when parafoveal vision was degraded in addition (Nuthmann, 2014). On the other hand, VLTm performance was not significantly better with the foveal compared to the full scotoma, knocking out foveal and parafoveal vision. The loss of foveal vision alone might therefore not be without problems in untrained observers, going along with increased demands on attentive object encoding. VLTm performance with the foveal scotoma might thus take an intermediate position between unimpaired viewing and impairment of foveal and parafoveal vision by the larger scotomata. Further studies incorporating more sensitive within-subject designs and a larger range of scotoma sizes, testing attentive object encoding at different eccentricities, would be desirable to investigate whether a specific minimum scotoma size can be identified that leads to clear VLTm deficits or whether the relationship between scotoma size and quality of VLTm follows a more gradual pattern.

The simulation of small scotomata is not without problems. To ensure that the scotoma covered foveal vision, we included only trials in which the average spatial accuracy of the measured gaze did not exceed 1° of visual angle. In the larger scotomata, deviations in this range are less problematic because the scotoma would still cover foveal vision entirely. In the foveal scotoma group, on the other hand,

partial foveal processing of the objects may occur as soon as the local spatial deviation exceeds 0.5° of visual angle, potentially inflating VLTm performance. The increased saccade amplitude compared to controls, however, indicated that observers targeted saccade locations outside the scotoma in agreement with previous reports (Nuthmann, 2014; for a review), suggesting that the scotoma reliably covered foveal vision.

Compared to controls, the large simulated scotomata led to a reduced average number of fixations during exploration and an absolute increase of fixation duration. This finding contrasts with the normal fixation patterns that we observed in patients suffering from natural central vision loss (Geringswald & Pollmann, 2015) and supports the hypothesis that intact VLTm in AMD patients was mediated by a successful adaptation of saccadic rereferencing to an extrafoveal PRL. Although recent research has demonstrated that such a PRL can similarly be developed by healthy observers after a few hours of visual search training (Kwon et al., 2013; Walsh & Liu, 2014), it is highly unlikely that this was the case in our current study. Training of saccadic rereferencing requires that the scotoma and its borders are clearly visible to the observer. If saccadic rereferencing had taken place in our study, gaze control and, potentially, memory performance should have been better in the clearly visible full scotoma condition compared to the more subtle warp scotoma simulation. This was, however, not the case. Memory performance as well as gaze parameters were virtually identical for both large scotoma simulations. In fact, the reduced number of fixations rather suggests that saccades were inhibited in a top-down controlled fashion. As long as saccadic rereferencing has not yet developed, the automatic process of foveating an attended stimulus (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Theeuwes et al., 1998) quickly becomes a disadvantage during scene exploration with an artificial scotoma because the attended stimulus will be covered by the scotoma after each eye movement. The measured impairment of attentive object encoding may therefore be a result of active saccade inhibition during object exploration. This reasoning is in line with the finding that active saccade inhibition to a target location impairs attentive stimulus processing (Dhawan et al., 2013) as well as change detection sensitivity in the flicker paradigm (Hollingworth et al., 2001).

In contrast to the gray-patch scotoma simulations, the real-time logarithmic shift of visual information in the warp scotoma simulation may have produced motion artifacts during fixation, for example, due to spatial jitter in eye movement measurement. We tried to counteract such effects by blurring visual information within the scotoma with a Gaussian kernel to reduce sharp motion transients. Potential motion artifacts may have interfered with object encoding outside the scotoma due to an increased foveal information load compared to the full scotoma condition. However neither the virtually identical memory performance under both simulation types nor the saccade amplitudes targeting, on average, locations well outside the scotoma indicate that the warping procedure influenced exploration or encoding in a different manner than the full scotoma.

Finally, although VLTm performance was significantly impaired by the large central scotoma simulations extending across foveal and parafoveal vision, participants were nevertheless able to detect object changes well above chance. This shows that foveation is not a necessity for attentive object encoding. However, the quality of VLTm suffers when central vision becomes unavailable.

Conclusion

Can attentive encoding of objects into VLTm be successful if central vision becomes unavailable? Intact explicit VLTm in patients suffering from long-standing central vision loss suggests a flexible deployment of attentive object encoding to peripheral vision. When central vision is diminished in unexperienced observers, however, attentive object encoding with peripheral vision remains limited. These results demonstrate the importance of central vision for attentive object encoding on the one hand. On the other hand they suggest that the successful development of saccadic rereferencing to an extrafoveal location may be indispensable for normal visual memory function in the presence of central vision loss.

5 Experiment 3: Simulated loss of foveal vision eliminates visual search advantage in repeated displays

The content of this chapter has been published in: Geringswald, F., Baumgartner, F., & Pollmann, S. (2012). Simulated loss of foveal vision eliminates visual search advantage in repeated displays. *Frontiers in Human Neuroscience*, 6, 134

5.1. Abstract

In the contextual cueing paradigm, incidental visual learning of repeated distractor configurations leads to faster search times in repeated compared to new displays. This contextual cueing is closely linked to the visual exploration of the search arrays as indicated by fewer fixations and more efficient scan paths in repeated search arrays. Here, we examined contextual cueing under impaired visual exploration induced by a simulated central scotoma that causes the participant to rely on extrafoveal vision. We let normal-sighted participants search for the target either under unimpaired viewing conditions or with a gaze-contingent central scotoma masking the currently fixated area. Under unimpaired viewing conditions, participants revealed shorter search times and more efficient exploration of the display for repeated compared to novel search arrays and thus exhibited contextual cueing. When visual search was impaired by the central scotoma, search facilitation for repeated displays was eliminated. These results indicate that a loss of foveal sight, as it is commonly observed in maculopathies, for example, may lead to deficits in high-level visual functions well beyond the immediate consequences of a scotoma.

5.2. Introduction

Attending to a particular part of the environment can be guided by regularities in the environment, which are often not consciously perceived. To exploit such regularities is clearly adaptive, because it enables us to find stimuli more efficiently than by a random spatial search (for a recent review, see Kristjánsson & Campana, 2010). Repetition of the spatial layout of a scene can facilitate finding the target location. This has consistently been reported in investigations of the contextual cueing effect (first reported by Chun & Jiang, 1998). The core finding is that target detection is facilitated if the spatial arrangement of distractor stimuli is repeated across experimental blocks compared to search for the same target in a new distractor arrangement. This effect may occur although participants are unable to recognize the distractor repetition. Thus, memory for spatial locations, gained by incidental learning, increases the speed of target detection in visual search, an effect that has been observed as long as one week after training (Chun & Jiang, 2003). Facilitation in target detection in repeated distractor

5. Experiment 3: Simulated loss of foveal vision eliminates visual search advantage in repeated displays

layouts has been argued to operate through improvement of attentional guidance to the target location using reaction time measures in inefficient serial search (Kunar et al., 2008) as well as accuracy measures in efficient popout search (Geyer, Zehetleitner, & Müller, 2010), provided that enough time is given to encode the search arrays and develop guidance. Additionally, post-selective processes of response selection at a later stage of processing might be enhanced by contextual cueing (Kunar et al., 2007).

Here, we investigated whether contextual cueing will be affected by the presence of a central scotoma. This research question was inspired by the characteristic retinal pathology of patients with age-related macular degeneration (AMD), in which the macula, the region with the highest density of photoreceptors, degenerates and causes a severe loss of central vision at advanced states of the disease (Lindblad et al., 2009). Thus, the patients are forced to rely on extrafoveal vision for all processes typically carried out in foveal vision. This extrafoveal vision has lower spatial resolution compared to foveal vision. Many studies on low-level visual processing have illustrated the immediate consequences of the loss of foveal vision, for example, reduced visual acuity and contrast sensitivity (Qiu & Leat, 2009) and deficits in orientation discrimination (Bedell, Tong, Woo, House, & Nguyen, 2009) and shape discrimination (Wang, Wilson, Locke, & Edwards, 2002). For a review on psychophysical function in AMD, see Neelam et al. (2009).

Loss of foveal vision may also make the visual exploration of the environment with eye movements more difficult. While some studies found no influence of a central scotoma on eye movement parameters during visual search (Murphy & Foley-Fisher, 1988; Shen, Reingold, Pomplun, & Williams, 2003), other studies found that visual search for high acuity targets could not be compensated efficiently by, for example, longer fixation durations, leading to increased search times (Bertera, 1988; Cornelissen et al., 2005).

However, the loss of acuity is not the only potential problem affecting visual search with a central scotoma. Eye movements are intimately linked to attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). During visual search, attention is often attracted by extrafoveal input (either salient stimuli or features matching the target template), leading to a subsequent fixation of this location. The tendency to fixate a target in order to process it attentively is so dominant, that it has been observed even in the presence of a simulated foveal scotoma, where it is clearly counterproductive (Miellet et al., 2010). This tendency is so stable that it took patients with central scotoma 20 months or more to overcome it (Timberlake et al., 1986) leading to the question whether attentional processing of the target (and its surrounding) becomes compromised in the presence of a central scotoma. This, in turn, may lead to deficient visual memory, because fixating an object is closely tied to its later recall (Hollingworth, 2006). It may also interfere with the use of implicitly learned context cues for efficient visual search that has been shown to depend on selective spatial attention and visuospatial working memory (Jiang & Leung, 2005; Manginelli et al., 2012). Furthermore, search with a simulated central scotoma will very likely lead to an increase of top-down controlled search strategies, until the participants get accustomed to the presence of the scotoma. This may also interfere with search facilitation in repeated displays, as has been shown previously in a comparison of search under stimulus-driven versus top-down controlled search instructions (Lleras & Von Mühlenen, 2004). Additionally, controlling eye-movements with an artificial scotoma might be so demanding in terms of cognitive load that only insufficient capacity might be available for peripheral processing of the spatial arrangement of the search items. High cognitive load in dual tasks has been shown to increase distractor interference (Lavie, Hirst, de Fockert, & Viding, 2004) and thus more top-down controlled search strategies with an artificial scotoma might interfere with the deployment of selective attention to the target in repeated search arrays.

Thus, there are a number of reasons why a central scotoma may lead to reduced search efficiency in familiar environments, an effect that transcends the immediate consequences of the scotoma and may be of importance for patients suffering from a central scotoma. As a first step, we investigated whether the search facilitation in repeated search displays, which is reliably obtained in normal participants, is reduced in the presence of a central scotoma. It is beyond the scope of this paper to discriminate between the possible causes of reduced search efficiency but we will discuss potential future studies

towards this end.

We simulated a central scotoma with gaze-contingent displays in normal-sighted participants (moving mask paradigm, Rayner & Bertera, 1979). This enabled us to investigate the effect of a well-defined scotoma in isolation that is problematic in typical AMD patients as their visual deficits are often highly variable or interact with additional visual or cognitive impairments due to their age. It should be noted that the current study, while it may lead to hypotheses concerning contextual cueing in AMD, does not eliminate the need to carry out AMD-patient studies to investigate this issue.

Contextual cueing leads not only to reduced search times, but also to a reduced number of fixations (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004) and more efficient scan paths (Brockmole & Henderson, 2006; Manginelli & Pollmann, 2009; Tseng & Li, 2004). Because of the interference of the central scotoma with display exploration, we expected selectively reduced search facilitation in repeated displays after sufficient learning, in comparison with search in novel displays. In contrast, the search facilitation with increasing practice that is typically observed for repeated and novel displays alike, due to automatization of search routines, should be unaffected by a central scotoma.

5.3. Method

5.3.1. Participants

30 healthy participants (3 males, 27 females, 25 years average age) participated in the experiment.

5.3.2. Apparatus

We used a 22-inch Iiyama Vision Master Pro 511 CRT monitor that was 400 mm (1280 pixels) wide and 300 mm (960 pixels) high and the vertical refresh rate was 100 Hz. Participants viewed the stimuli binocularly from a distance of 60 cm leading to a pixel size of 0.03° or 1.79 arcmin of visual angle. Eye position was recorded using an iViewX Hi-Speed eye tracking system (SensoMotoric Instruments GmbH, Teltow, Germany), with a temporal resolution of 240 Hz. The gaze data were filtered by the heuristic (stage 1) and the bilateral filters implemented in the iView X software.

5.3.3. Stimuli

For details about the stimuli used in the experiment see Section 2.3.2 Contextual cueing paradigm. Each search item subtended $1.04^\circ \times 1.04^\circ$ of visual angle (Figure 5.1). The offset at the junction of the two segments of the L-shapes was 0.12° of visual angle. The imaginary concentric circles used for creating the stimulus positions had radii of 2.03° , 4.74° , 7.43° and 10.15° of visual angle. The overall size of the search display on the screen extended a circular area with a diameter of 21.34° of visual angle.

The simulated central scotoma was created as a circular area with a diameter of 7° of visual angle which completely covered the visual stimulus. At the border of the scotoma the transparency gradient followed the increasing slope of a Gaussian distribution with a deviation of 1° of visual angle. After rendering the patch with the Gaussian filter, a concentric disk with a diameter of 7° within the alpha channel was set to 100%. Thus, the fully opaque size of the scotoma extended 7° smoothly fading out at the edges. The scotoma was superimposed on the search display and colored the same gray as the background. Therefore the scotoma could only be perceived by the participant when it covered a stimulus patch of a distinct color as the masked part of the display became invisible to the participant, thus simulating the negative effect of a central scotoma.

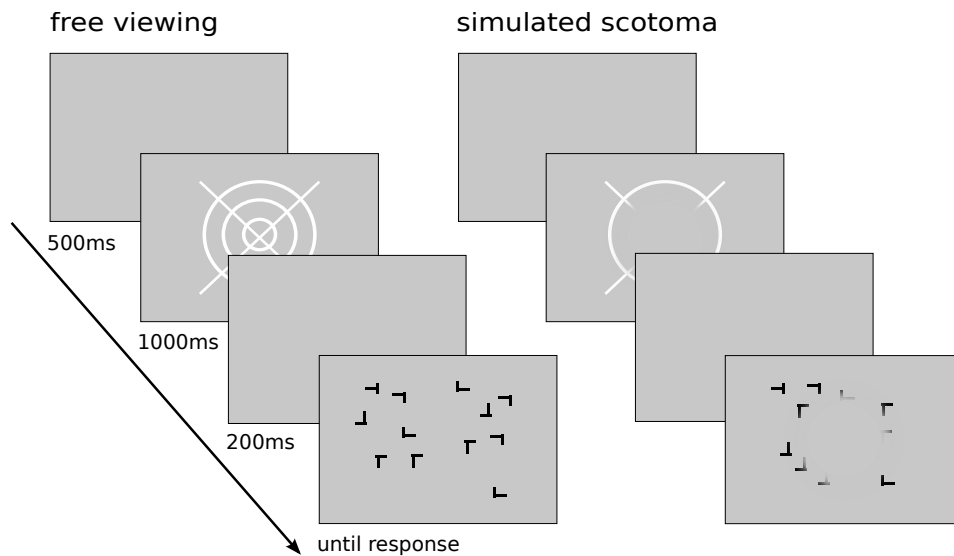


Figure 5.1.: Schematic diagram of an experimental trial. A trial consisted of the presentation of a blank screen (500 ms), a fixation target (1000 ms), another blank screen (200 ms) and the search display (presented until response). Left: A trial in the unimpaired control condition. Right: Visualization of the display layout with the simulated central scotoma covering parts of the screen. The scotoma had a diameter of 9° smoothly fading out at the edges. The fully opaque area of the scotoma measured 7° in diameter which appeared invisible to the participant while the visibility of the stimulus display gradually increased at the edge of the opaque area.

5.3.4. Procedure

Participants searched for a left- or right tilted T among L-shaped distractors and indicated its orientation with left and right mouse button presses with the right hand. Each participant completed one experimental session with and one without the gaze-contingent central scotoma within a period of approximately one week. The order of the sessions was randomized across participants and a set of distinct old displays was generated for each session. Each session started with a 13-point gaze calibration, followed by a short training period to familiarize participants with the task, the actual search experiment and a recognition test. In the scotoma session, the simulated central scotoma was present throughout all tasks except when instructions were presented on the screen.

The training was composed of 24 trials with randomly generated displays containing target positions that were not used in the experimental configurations. The search experiment consisted of 20 blocks of 24 trials each. Every trial started with the presentation of a blank for 500 ms followed by the fixation stimulus for 1000 ms. Another blank was shown for 200 ms before the search display was presented. The search display remained on the screen until the participant responded (Figure 5.1). Auditory feedback was provided for correct (a 2000 Hz high-pitch tone) and wrong answers (a 500 Hz low-pitch tone). Participants were instructed to search for the target T as fast and accurately as possible. They were further asked to follow their intuition and search for the target T passively as suggested by Lleras and Von Mühlelen (2004). In the session with the simulated central scotoma, participants were asked to try to place the gray patch at the center of the fixation target in order to equalize starting positions in the search task.

The recognition test included the original 12 repeated and another 12 new randomly generated con-

figurations presented in randomized order. Participants were asked to indicate whether they had seen the displays during the course of the experiment or not by mouse button presses. No feedback about the correctness of the answer was given. Participants started each block by pressing a key, allowing for self-terminated breaks between the blocks. One session lasted approximately one hour.

5.3.5. Gaze Data analysis

Two dependent measures were calculated from the fixation events. First, we measured the number of fixations required to find the target stimulus from the onset of the search display until the mouse button was pressed. The second measure of interest was the efficiency of the scan path toward the target which was calculated as the ratio between the total distance covered by the eye during the search for the target, that is, the sum of distances between each consecutive fixation, and the shortest path possible, that is, the distance between the first fixation and the target location (Brockmole & Henderson, 2006). Thus, more direct scan paths toward the target position are characterized by lower scan pattern ratios.

5.3.6. Data exclusion

We applied three data exclusion criteria for the analysis of search times and gaze parameters. First, we removed all erroneous responses from the data set. Participants whose average performance in the discrimination task was below the average minus two times the standard deviation of all participants' performance in at least one viewing condition were excluded. This criterion led to the exclusion of two participants. The first participant exhibited a mean performance of 90.21 % in the unimpaired control and 82.29 % in the scotoma condition and the second participant a mean performance of 93.96 % in the control and 81.04 % in the scotoma condition. As the reliable presentation of the scotoma during search depended on the availability of the gaze coordinates retrieved from the eye-tracker, we furthermore decided to remove search trials in which more than 20 % of the gaze samples were missing due to signal losses. Third, we excluded trials in which the search time was shorter than 200 ms or longer than two standard deviations than the participant's average search time in the remaining trials.

After removing all invalid data we calculated the overall percentage of data excluded for each participant and each experimental session and identified data sets in which more than 20 % of all trials were classified as invalid. This method led to the exclusion of three further participants: the first participant's data in the unimpaired control condition contained 28.33 % of invalid data, the second participant's data 23.96 % in the scotoma condition and the third participant's data 32.08 % in the scotoma condition. The two latter steps of preprocessing were also applied before accuracy analysis. Thus, 25 participants were included in all further analyses. The average percentage of invalid noise trials was 3.84 % ($SD = 4.59\%$) in the unimpaired control condition and 2.98 % ($SD = 3.26\%$) in the scotoma condition. Search time outliers amounted to 1.73 % ($SD = 0.61\%$) of the data in the unimpaired control condition and 1.73 % ($SD = 0.45\%$) in the scotoma condition.

In summary, all three steps of the exclusion procedure led to the rejection of 6.04 % ($SD = 4.75\%$) of invalid data in the unimpaired control condition and 7.25 % ($SD = 3.73\%$) in the scotoma condition. There was no difference in the amount of data excluded for the control versus the scotoma condition, $t(24) = 1.32, p = .20$.

5.4. Results

5.4.1. Accuracy

The accuracies ranged from 93.96 % to 100 % (average 98.29 %) in the unimpaired control condition and from 90.21 % to 99.58 % (average 96.86 %) in the scotoma condition. In order to test for differences in

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accuracies concerning the viewing conditions an ANOVA on errors with the factors viewing condition (control vs. central scotoma) and configuration (repeated vs. novel) was carried out. It revealed a significant main effect of viewing condition, $F(1, 24) = 11.07$, $p < .01$, $\eta_P^2 = .32$, $\eta_G^2 = .093$, reflecting less accurate performance when vision was impaired by the artificial scotoma. Neither the main effect of configuration, $F(1, 24) = 2.18$, $p = 0.15$, $\eta_P^2 = .08$, $\eta_G^2 = .006$, nor the interaction, $F(1, 24) = 0.12$, $p = .73$, $\eta_P^2 = .01$, $\eta_G^2 < .001$, were significant.

5.4.2. Search times

Experimental blocks were aggregated to four epochs, each containing five blocks, in order to increase power. Averaged search times for the four epochs for repeated and novel displays separated by viewing condition can be seen in Figure 5.2. In a first step, two separate two-way, repeated measures analyses of variance (ANOVAs) for the two experimental conditions with the factors configuration (repeated, novel) and epoch (1,4) were performed on search times. We decided to compare only the first and the last epoch of the search experiment to increase the power in order to detect differences at the beginning of the session, when learning effects should be small, and at the end of the session, when contextual cueing should be most prominent. The mean differences between repeated and novel displays for all epochs are reported in Table 5.1. In the unimpaired control condition, the main effects of epoch, $F(1, 24) = 36.70$, $p < .001$, $\eta_P^2 = .60$, $\eta_G^2 = .156$, and configuration, $F(1, 24) = 19.19$, $p < .001$, $\eta_P^2 = .44$, $\eta_G^2 = .012$, were significant. The interaction of configuration and epoch was also significant, $F(1, 24) = 8.58$, $p < .01$, $\eta_P^2 = .26$, $\eta_G^2 = .005$. Thus, in addition to a general improvement of search speed over time, a robust advantage for repeated displays (that is, a contextual cueing effect) developed over the course of the experiment.

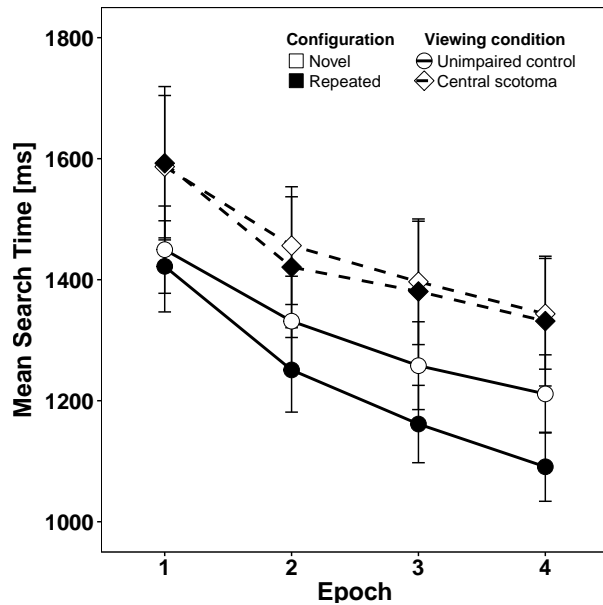


Figure 5.2.: Averaged search times in the visual search task for the control (circles) and central scotoma (triangles) viewing conditions for repeated (filled symbols) and novel (open symbols) displays as a function of epoch. Error bars represent the standard error of the mean.

In the central scotoma condition, there was also a general improvement in search times over time as revealed by a significant main effect of epoch, $F(1, 24) = 18.86$, $p < .001$, $\eta_P^2 = .44$, $\eta_G^2 = .050$.

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Table 5.1.: Mean difference between novel and repeated configurations

Condition	Epoch 1		Epoch 2		Epoch 3		Epoch 4	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Search time (ms)								
Control	28	120	81	150	96	138	120	112
Central scotoma	-6	160	36	193	16	193	12	175
Number of fixations (counts)								
Control	0.16	0.44	0.26	0.62	0.35	0.57	0.44	0.41
Central scotoma	0.05	0.53	0.12	0.62	0.10	0.64	0.15	0.58
Scan pattern ratio (quotient)								
Control	0.18	0.59	0.29	0.82	0.33	0.48	0.55	0.53
Central scotoma	-0.24	0.75	0.21	1.01	-0.12	1.62	0.05	1.07

However, neither the main effect of configuration, $F(1, 24) = 0.02$, $p = .90$, $\eta_P^2 < .01$, $\eta_G^2 < .001$. nor the interaction, $F(1, 24) = 0.17$, $p = .69$, $\eta_P^2 < .01$, $\eta_G^2 < .001$, reached significance indicating that the simulated scotoma interfered with contextual cueing.

Next, we were specifically interested in search performance in the last epoch of the session. We compared participants' search times by means of a two-way, repeated measures ANOVA with the factors viewing condition (control, central scotoma) and display type (repeated, novel). The main effect of viewing condition was significant, $F(1, 24) = 5.75$, $p < .05$, $\eta_P^2 = .19$, $\eta_G^2 = .050$, with higher search times in the scotoma (1338 ms) than in the control condition (1151 ms). The main effect of display type did also reach significance, $F(1, 24) = 12.64$, $p < .01$, $\eta_P^2 = .34$, $\eta_G^2 = .007$, with an average advantage of 66 ms in repeated displays. Additionally, the interaction between viewing condition and display type was significant, $F(1, 24) = 5.71$, $p < .05$, $\eta_P^2 = .19$, $\eta_G^2 = .004$, indicating that the search facilitation for repeated displays was reduced when search was impaired by the scotoma. While search times for repeated and novel displays were similar in the scotoma condition (1332 ms versus 1344 ms respectively), repeated displays speeded up search in the control condition by 120 ms. This indicates that at the end of the sessions, after participants had been able to get used to the search with the scotoma, the visual impairment was still affecting search efficiency. In addition, search facilitation for repeated displays was reduced in search with the scotoma compared to the control condition.

5.4.3. Gaze

Number of fixations

Figure 5.3 depicts the mean number of fixations for repeated and novel displays in the unimpaired control and the central scotoma condition. Analogous to search times, participants needed less fixations in order to find the target over the course of the experiment in the control condition as revealed by a significant main effect of the factor epoch, $F(1, 24) = 38.41$, $p < .001$, $\eta_P^2 = .62$, $\eta_G^2 = .128$. Furthermore, a significant main effect of display type, $F(1, 24) = 21.10$, $p < .001$, $\eta_P^2 = .47$, $\eta_G^2 = .011$, was observed with less fixations in the repeated displays. The interaction between epoch and display type was also significant, $F(1, 24) = 6.48$, $p < .05$, $\eta_P^2 = .21$, $\eta_G^2 = .002$, indicating that contextual learning lead to more efficient search strategies requiring less fixations for repeated displays.

In the central scotoma condition, we could only observe a significant main effect of epoch, $F(1, 24) = 17.58$, $p < .001$, $\eta_P^2 = .42$, $\eta_G^2 = .043$, which indicates that participants were able to find more efficient search strategies after repeatedly searching through the stimulus arrays with the scotoma. However, neither the main effect of display type, $F(1, 24) = 1.36$, $p = .26$, $\eta_P^2 = .05$, $\eta_G^2 < .001$,

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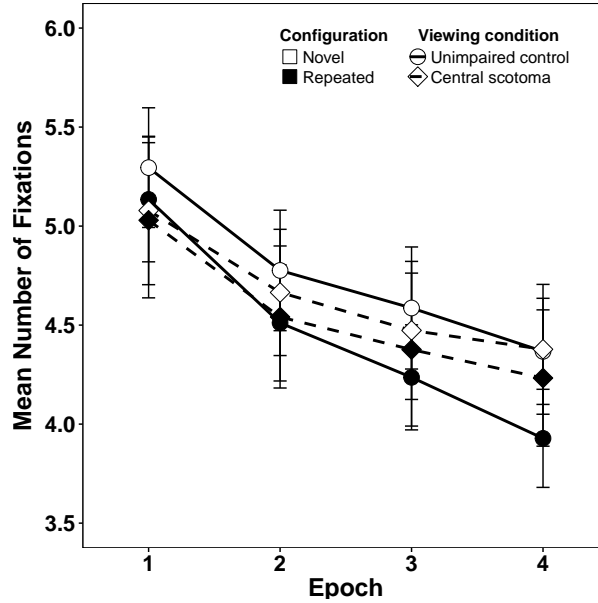


Figure 5.3.: Averaged number of fixations for the control (circles) and central scotoma (triangles) viewing conditions for repeated (filled symbols) and novel (open symbols) displays as a function of epoch. Error bars represent the standard error of the mean.

nor the interaction, $F(1, 24) = 0.42$, $p = .52$, $\eta_P^2 = .02$, $\eta_G^2 < .001$, were significant, thus the amount of fixations necessary to find the target in random and repeated search arrays did not differ.

Additionally, we examined the number of fixations of the last epoch under impaired and unimpaired search with a two-way, repeated measures ANOVA with the factors viewing condition (control, central scotoma) and display type (repeated, novel). The main effect of viewing condition was not significant, $F(1, 24) = 0.39$, $p = .54$, $\eta_P^2 = .02$, $\eta_G^2 = .003$, revealing that the average number of fixations required to find the target was equal for the control (4.15 fixations) and the scotoma condition (4.31 fixations). The main effect of display type reached significance, $F(1, 24) = 21.19$, $p < .001$, $\eta_P^2 = .47$, $\eta_G^2 = .010$. In repeated displays the target was detected after an average of 4.08 fixations whereas 4.37 fixations were necessary in random displays. The interaction between viewing condition and display type did not reach significance, $F(1, 24) = 3.53$, $p = .07$, $\eta_P^2 = .13$, $\eta_G^2 = .003$. When searching with the scotoma, observers needed 4.38 fixations on average for novel and 4.23 fixations for repeated displays. Without the scotoma, the average number of fixations was 4.37 in novel displays and 3.93 in repeated displays.

Scan pattern ratio

The development of average scan pattern ratios for repeated and novel displays in the two viewing conditions can be seen in Figure 5.4. A repeated measures ANOVA on the factors display type and epoch revealed a significant main effect of the factor epoch, $F(1, 24) = 30.16$, $p < .001$, $\eta_P^2 = .56$, $\eta_G^2 = .124$, a significant main factor of display type, $F(1, 24) = 17.48$, $p < .001$, $\eta_P^2 = .42$, $\eta_G^2 = .022$, and a significant interaction, $F(1, 24) = 7.20$, $p < .05$, $\eta_P^2 = .23$, $\eta_G^2 = .006$, in the unimpaired viewing condition. Thus, scan paths became not only more efficient with repeated search for the target, but repeated displays additionally revealed more direct scan paths than random search arrays.

In the central scotoma condition, scan paths shortened over time as shown by a significant main effect of epoch, $F(1, 24) = 11.52$, $p < .01$, $\eta_P^2 = .32$, $\eta_G^2 = .024$, but repeated displays did not show an additional advantage as neither the main effect of display type, $F(1, 24) = 0.61$, $p = .44$, $\eta_P^2 = .02$,

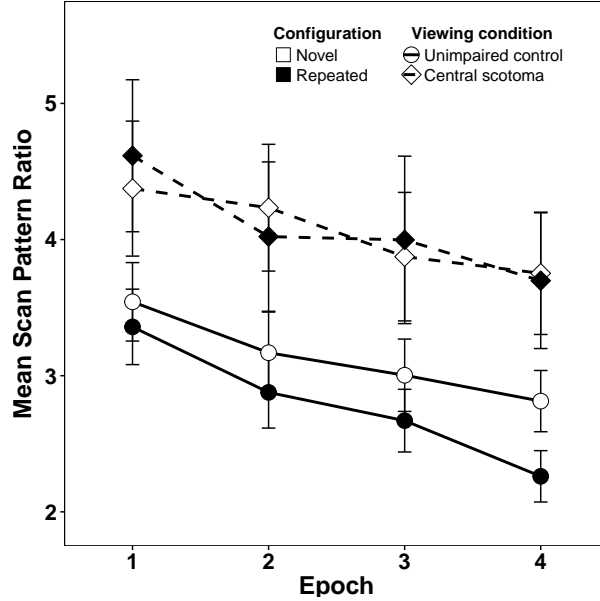


Figure 5.4.: Averaged scan pattern ratios for the control (circles) and central scotoma (triangles) viewing conditions for repeated (filled symbols) and novel (open symbols) displays as a function of epoch. Error bars represent the standard error of the mean.

$\eta_G^2 < .001$, nor the interaction, $F(1, 24) = 1.10$, $p = .30$, $\eta_P^2 = .04$, $\eta_G^2 < .001$, reached significance.

Analogous to the analyses above, we carried out a two-way, repeated measures ANOVA with the factors viewing condition (control, central scotoma) and display type (repeated, novel) on scan pattern ratios of the last epoch of the experiment. The main effect of viewing condition was significant, $F(1, 24) = 9.67$, $p < .01$, $\eta_P^2 = .29$, $\eta_G^2 = .099$, showing that the average scan paths were less efficient when search was impaired by the scotoma. The scan paths were 3.72 times the direct distance from the first fixation to the target in the scotoma condition and 2.54 times the direct distance in the control condition. The main effect of display type did also reach significance, $F(1, 24) = 6.41$, $p < .05$, $\eta_P^2 = .21$, $\eta_G^2 = .007$, with an average scan pattern ratio of 2.98 in repeated displays and 3.28 in novel displays. Additionally, the interaction between viewing condition and display type was significant, $F(1, 24) = 4.39$, $p < .05$, $\eta_P^2 = .15$, $\eta_G^2 = .005$. When search was impaired by the scotoma, the scan pattern ratios for repeated and novel displays were nearly identical. In repeated displays, the eye of the participants moved on average 3.75 times the most direct line compared to 3.70 times in repeated displays. In the control condition, the scan pattern ratio improved from 2.81 in novel displays to 2.26 in repeated search arrays.

5.4.4. Recognition test

Mean recognition accuracy in the control condition was 57.17% ($SD = 10.10\%$). Participants correctly classified repeated displays as old (the hit rate) on 57.33% ($SD = 21.29\%$) of trials and falsely reported 43.00% ($SD = 15.33\%$) of novel displays as old (the false alarm rate). A paired t test on the hit and false alarm rates reached significance, $t(24) = 3.55$, $p < .01$. In order to test for a correlation between the size of the contextual cueing effect and recognition accuracy we calculated the individual amount of search facilitation for repeated displays for each subject in the last epoch. This was done by calculating the difference in mean reaction times between the novel and the repeated displays. We then divided

these absolute differences by the mean reaction times of novel displays in order to standardize the contextual cueing effects. The normalized magnitude of contextual cueing did not correlate with the recognition accuracy, $r = -.20$, $p = .33$.

Mean recognition accuracy in the central scotoma condition was 55.33% ($SD = 11.10\%$) with a mean hit rate of 49.00% ($SD = 19.88\%$) and a mean false alarm rate of 42.33% ($SD = 16.30\%$). A paired t test on hit and false alarm rates did not reach significance, $t(24) = 1.50$, $p = .15$. The normalized magnitude of contextual cueing correlated positively with the recognition accuracy, $r = .41$, $p < .05$.

5.5. Discussion

Does the loss of foveal vision affect efficient search in repeated environments? To answer this question, we investigated the impact of a simulated central scotoma on contextual cueing effects in visual search. The central finding was that visual search with a central scotoma eliminated the search facilitation in repeated displays that was observed, in agreement with many previous studies, in search without a scotoma. This elimination of search facilitation in search with a scotoma was observed in search times as well as in eye gaze parameters such as number of fixations and scan pattern ratios. Thus, while in non-scotomatous search, the repeated displays could be used to speed up overall search time by more efficient scanning of the display, this was not the case with a simulated scotoma.

Visual search was generally slower with the simulated scotoma than without, reflecting the unusual need to use exclusively peripheral vision to explore the search display. We observed comparable improvements of search times and gaze parameters over the course of the experiment with and without scotoma. Thus, search with a scotoma benefitted from training, but was still less efficient than unimpaired search at the end of the experiment. Nevertheless, participants performed reasonably well at the search task as indicated by accuracy rates well above 95% and search times below 1.5 s in the scotoma condition. Thus, the search displays were well designed in order to investigate peripheral search behavior.

Noteworthy, search with a scotoma did not require more fixations in order to find the target. We did not expect this, but, in hindsight, it is perhaps not surprising that search with a simulated scotoma did not lead to an increase of fixations compared with unimpaired search. This may reflect the need to control the exploration of the search displays in a more top-down controlled manner when a scotoma is simulated than in its absence, making each fixation more "costly" in terms of programming.

This top-down controlled search, however, was not as efficient as the search without scotoma. Other than for number of fixations, there was not only a clear advantage for repeated, but also for novel displays searched without scotoma. The scan paths for random displays were about 3.8 times longer than the most direct path to the target from the first fixation in the presence of a scotoma whereas they were only 2.8 times longer in its absence. For repeated displays, the efficiency of the scan paths additionally increased to a score of 2.3 times the most direct distance (due to contextual cueing) whereas the scan pattern ratio for novel and repeated displays was virtually identical for search with a scotoma. Together, these data indicate that the need to adapt exploration to maximize visual sampling in the periphery led to less efficient search with the scotoma. This less efficient search is characterized by an equal number of fixations that were placed less efficiently than in unimpaired search.

The inefficient top-down controlled search mode may be one possible reason why we did not observe search facilitation for repeated displays in search with a scotoma. A reduction of search facilitation for top-down controlled search strategies in comparison with more stimulus-guided search has been described previously (Lleras & Von Mühlenen, 2004). Future experiments with longer training, leading to more automatic search with simulated scotomata, may address this question. The same issue is of course highly relevant for the question whether patients with AMD in whom the foveal vision impairment develops gradually, thereby leaving time to adapt visual search behavior, will also lack a search facilitation in repeated displays.

It has been shown that search facilitation in repeated displays depends on attending to the repeated

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display items (Jiang & Chun, 2001). Similarly, filling visuospatial working memory capacity by a concurrent task eliminated the search advantage in repeated displays (Manginelli et al., 2012). These demands on attentional and working memory capacity were primarily observed when previously learned templates needed to be retrieved in order to speed up search in repeated displays, while learning of repeated displays itself was still observed when attention or visual working memory was reduced by secondary demands (Jiang & Leung, 2005; Vickery et al., 2010). Thus it is likely that the presence of a scotoma, by impairing the free exploration of a search display (or other environment) may make the match between search templates from long-term memory and the current search display more difficult, thereby reducing or eliminating the search advantage for repeated displays observed in non-scotomatous participants. Similarly, Fiske and Sanocki (2011) presented evidence for a reduction of the efficiency of attentional guidance in repeated displays by crowding. Whereas Fiske and Sanocki (2011) increased crowding by reducing the spacing between search items, using peripheral vision for search also increases crowding, because the minimum distance for uncrowded viewing increases towards the periphery of the visual field (Pelli & Tillman, 2008). Future research may address the question whether the interference observed for contextual cueing in the present experiment may also be observed for other kinds of cueing, such as probability cueing of the target location (Geng & Behrmann, 2002) or distinct priming of target or distractors in visual search (Kristjánsson & Driver, 2008).

Brady and Chun (2007) proposed a model of contextual cueing assuming that mostly the local context information close to the target location is learned in repeated displays, suggesting that a “snapshot” of the target and its surrounding distractors is made when the target is detected by the observer. Nevertheless, they also observed a contribution of global regularities to contextual cueing. van Asselen and Castelo-Branco (2009) examined the contribution of peripheral vision to contextual cueing. In their study, participants were instructed to fixate centrally throughout display presentation. Fixation was monitored by gaze tracking. The search items in their study were presented at eccentricities between 2.4° and 4.1° of visual angle. They observed a robust contextual cueing effect which was maintained during a period of ten days after the initial learning experiment. The authors concluded that contextual learning can take place in peripheral vision and is thus not dependent on high-acuity foveal resolution. In contrast, we did not observe facilitation for repeated displays in the scotoma condition in which observers were forced to use peripheral vision for target detection.

Two important differences between the study of van Asselen and Castelo-Branco (2009) and our data have to be considered. First, the stimulus positions used by van Asselen and Castelo-Branco (2009) fell approximately into the area covered by the scotoma in our study, that covered an area of 3.5° of visual angle (4.5° including the Gaussian fading at the border which additionally degraded the visual input to some extent). Thus it may be argued, that the presently used scotoma size impaired the parafoveal region which might be crucial for the learning of the statistical associations between target and surrounding distractor stimuli in repeated displays. This, however, appears unlikely, because previous data have shown that contextual cueing can occur across much larger distances as long as there is no interference of non-repeated distractors placed between predictive distractors and the target (Olson & Chun, 2002). A second important difference to the study by van Asselen and Castelo-Branco (2009) concerns the use of eye-movements. Their observers were forced to inhibit eye-movements and perceived the complete search display peripherally “at a glance”. Thus, the perceived spatial relations between items remained static throughout the search trial, which could potentially contribute to learning of the context information. In contrast, eye-movements were necessary in our study due to the increased search difficulty introduced by making the distractors look more similar to the target. The observed number of fixations clearly shows, that our observers did indeed move their eyes in order to find the target. As a consequence of those eye-movements, the scotoma dynamically changed the appearance of the search displays by rendering parts of the stimulus arrays invisible to the observer. Thus, the memory templates for the repeated search displays may have been more patchy in the scotoma condition as the observers were never able to perceive the complete stimulus arrays at one glance which, in turn, might lead to the observed lack of contextual cueing. It would be interesting to see if contextual cueing was

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intact using smaller scotoma sizes which may still impair the planned execution of eye-movements and lead to inefficient scan paths compared to unimpaired search but allow for a more holistic peripheral processing of the search displays. Taken together the results of van Asselen and Castelo-Branco (2009) and our results might suggest that an optimal search strategy with a scotoma leading to the development of contextual cueing might be to reduce eye-movements and covertly shift attention across the stimuli perceived in the periphery. This issue might be addressed comparing the relation between the magnitude of contextual learning and eye-movement patterns in trained and untrained search with the scotoma.

Interestingly, we found a positive correlation between the awareness of context repetition and the magnitude of contextual cueing in the scotoma condition. Whereas many studies pointed out the implicit nature of contextual cueing (Chun & Jiang, 1998; Chun & Phelps, 1999; Howard et al., 2004; Manginelli & Pollmann, 2009), Smyth and Shanks (2008) and Geyer, Shi, and Müller (2010) provided evidence that explicit memory of context repetition may at least be present for a subset of repeated displays, a fact that may have been overlooked in previous studies because explicit recognition tests had less statistical power than the implicit memory measure. In the current experiments, the explicit recognition test carried out immediately after the search task yielded evidence for at least partly explicit learning in unimpaired search, whereas no such evidence was obtained in the scotoma experiment. As in previous studies (Geyer, Shi, & Müller, 2010; Smyth & Shanks, 2008), individual explicit memory scores were not correlated with the size of search facilitation in unimpaired search. In contrast, there was a significant correlation in the scotoma experiment. Taken together, these results may indicate that in our experiment, observers in both viewing conditions became aware of repeated search arrays which facilitated target detection. If repeated displays gain access to conscious perception, this might be a sign that the (implicit) memory traces of the repeated layouts gain so much strength that observers eventually become aware of the repetition as more cognitive resources might be available to encode the exact positions of the stimuli during "automatic" search. In the scotoma condition, aware observers might thus have improved their search strategies so efficiently that they were able to build up robust memory representations of the repeated search arrays whereas in the control condition visual search was much less demanding such that strong associations between target and distractor positions may have evolved in all observers, leading to significant awareness on a group level. Until today, there is no evidence that explicitly recognized search layouts improve contextual cueing effects. Future studies might address this issue with more elaborated recognition tests, for example, one could ask the subjects to submit confidence ratings on whether they have seen the display before and analyze the results in terms of more sophisticated measures of signal detection theory. The aim of the present study was primarily to investigate whether incidental (that is, non-instructed) learning of spatial configurations could be used for more efficient visual search in repeated search environments. Whether this incidental learning occurs in a truly implicit way (that is, without awareness) is not easy to assess (Merikle & Reingold, 1992; Wiens, 2007). Although interesting in itself it was not our prime concern to investigate this issue because we wanted to know whether patients with a central scotoma, for example, due to AMD, might be impaired in visual search in repeated environments at all.

Another important aspect that needs to be addressed in future studies is whether the learning of spatial configurations itself is impaired in search with a central scotoma or if the use of learned configurations is impaired, for example, due to the need for top-down controlled search suggested by our data. On the one hand, the importance of fixating (and thereby attending) an object for later explicit recall has been clearly demonstrated (Hollingworth, 2006). On the other hand, it has been shown that incidental context learning in visual search may proceed in the absence of focused attention on the repeated search items (Jiang & Leung, 2005). Thus it remains an open question whether the presence of a central scotoma interferes with learning of context cues. Future studies may address this question by removing the scotoma after a learning phase with scotoma, something that obviously cannot be done with natural scotomata.

The investigation of scotoma effects on contextual cueing was inspired by the presence of foveal viewing deficits in patients with AMD. The present results show that AMD patients may suffer from

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deficits in contextual cueing that may complicate their exploration of the environment in addition to their low-level visual impairments. There are, however, several caveats before the present results can be taken to reflect contextual cueing in AMD. On the one hand, our data present a purer view on the effect of a scotoma on contextual cueing than the performance of AMD patients, which may present with additional visual or cognitive impairments. On the other hand, patients may develop adaptive strategies over time that may help them to regain contextual cueing to some degree.

5.5.1. Conclusion

To our knowledge, this is the first demonstration that the presence of a central scotoma impairs contextual cueing in visual search. The gaze-contingent scotoma simulation prevented participants to use learned spatial configurations to improve the efficiency of visual search. The effect of the simulated scotoma was specific for visual learning of repeated displays. In contrast, unspecific procedural learning over the experimental session led to an equal acceleration of search with and without scotoma, independent of repetition or novelty of the displays. This specific lack of a search facilitation in repeated displays was not due to an increased number of fixations but rather due to a less efficient scanpath used to search the display. Future studies are needed to investigate the causes of this deficit, which may be interference with contextual learning itself or interference with the later use of previously learned contexts, and finally how training can improve visual learning and its use for efficient visual search with a central scotoma.

6 Experiment 4: Contextual Cueing Impairment in Patients with Age-Related Macular Degeneration

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6.1. Abstract

Visual attention can be guided by past experience of regularities in our visual environment. In the contextual cueing paradigm, incidental learning of repeated distractor configurations speeds up search times compared to random search arrays. Concomitantly, fewer fixations and more direct scan paths indicate more efficient visual exploration in repeated search arrays. In previous work, we found that simulating a central scotoma in healthy observers eliminated this search facilitation. Here, we investigated contextual cueing in patients with age-related macular degeneration (AMD) who suffer from impaired foveal vision. AMD patients performed visual search using only their more severely impaired eye ($n = 13$) as well as under binocular viewing ($n = 16$). Normal-sighted controls developed a significant contextual cueing effect. In comparison, patients showed only a small non-significant advantage for repeated displays when searching with their worse eye. When searching binocularly, they profited from contextual cues, but still less than controls. Number of fixations and scan pattern ratios showed a comparable pattern as search times. Moreover, contextual cueing was significantly correlated with acuity in monocular search. Thus, foveal vision loss may lead to impaired guidance of attention by contextual memory cues.

6.2. Introduction

Visual attention can be guided by past experience of regularities in the environment. One incidental form of visual context learning has been termed contextual cueing (Chun & Jiang, 1998). In contextual cueing, visual search is faster in repeated compared to random distractor arrangements. In this way, incidental learning of invariant spatial locations facilitates attentional guidance to the target position, as is evident in faster search times (for example, Chun & Jiang, 1998), fewer fixations and more direct scanpaths (Brockmole & Henderson, 2006; Geringswald et al., 2012; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004).

What happens to contextual cueing, if foveation is compromised? During the exploration of a scene, visual attention is closely linked to the fovea (Deubel & Schneider, 1996; Hoffman & Subramaniam,

1995) and, in turn, foveating a stimulus increases its chance to be remembered explicitly (Hollingworth, 2006). If contextual cueing is a form of implicit learning (Chun & Jiang, 1998), it may not be affected at all by degraded foveal vision. Moreover, repeated distractor configurations can be learned even if they are ignored (that is, not attentively processed; Jiang & Leung, 2005). The story may not be that simple, however. Learning in contextual cueing appears to be highly local (Brady & Chun, 2007; Olson & Chun, 2002) such that repetition of the distractors close to the target yields the highest search benefit. This may indicate that, during foveation of the target, a mental "snapshot" of the target and its surroundings is learned and used to guide search in invariant contexts. This process may well depend to some degree on foveal processing, like the advantage observed in explicit learning (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995), so it may be predicted that contextual cueing suffers in the presence of foveal vision impairment.

In normal-sighted observers, learning of contextual cues was diminished when only three out of twelve stimulus locations were repeated during learning, even when the whole display was repeated in a later test phase. Conversely, when the whole display was repeated during learning, repetition of only 3 or 4 items in a later test phase was sufficient to guide search efficiently in previously learned contexts (Song & Jiang, 2005). In visual search of patients with macular scotomata, parts of the search displays may not be perceived - or not perceived as well as in normal vision - even after eye movements. In analogy to the findings of Song and Jiang (2005), because patients with central vision loss may not perceive the whole context, learning of contextual cues and the establishment of robust visual memory traces for repeated displays may thus be impaired, in return reducing efficient guidance to target positions in previously encountered search arrays.

In line with this reasoning, no contextual cueing was observed in a group of normal-sighted young adults who searched in the presence of a gaze-contingent simulated central scotoma (Geringswald et al., 2012). However, visual search with a simulated central scotoma is a highly artificial situation and we cannot rule out that contextual cueing was absent because the observers needed to control the exploration of the search display voluntarily in order to compensate for the scotoma. Behavioral tasks in normal observers have shown that contextual cueing, particularly the use of learned memory traces, depends on attentional and working memory capacity (Jiang & Leung, 2005; Manginelli et al., 2012; Manginelli, Langer, et al., 2013; Travis, Mattingley, & Dux, 2013; Vickery et al., 2010). A cumbersome top-down controlled exploration of search displays forced by a simulated scotoma may leave not enough capacity to use contextual cues for attentional guidance in repeated displays.

This may be different in patients who suffer from progressive degeneration of the macula – age-related macular degeneration (AMD) – leading to diminished foveal vision (Arroyo, 2006; Nazemi et al., 2005), and, possibly, a central scotoma (Lindblad et al., 2009). On the one hand, one may expect AMD patients to show at least as severe deficits in contextual cueing as young, normal sighted observers searching with an artificial central scotoma. On the other hand, patients with macular degeneration may use their remaining peripheral vision more efficiently because they have adapted their exploration behavior to eccentric viewing. This may lead to a more automatic search leaving more attentional and working memory capacity available for guiding search by contextual memory cues. One complicating aspect is the progressive deterioration of foveal vision in AMD. Therefore we would expect a beneficial effect of practice with impaired foveal vision to occur rather in mild stages of AMD, when patients already had months or even years to become accustomed to explore their environment in the presence of impaired foveal vision, but before the development of a central scotoma leads to severe vision loss. The central aim of the present study was to investigate whether patients with AMD suffer from impaired contextual cueing. To our knowledge, this question has not been investigated previously. It is of practical importance, because impaired contextual cueing in AMD would be an additional burden for these patients beyond their basic visual deficits (for a review on psychophysical function in AMD, see Neelam et al., 2009). It is also of theoretical interest, because impaired contextual cueing following degraded foveal vision would indicate that contextual cueing does not occur automatically in the absence of attentional and working memory resources (Manginelli, Langer, et al., 2013).

We examined search behavior and eye movements in AMD patients and closely matched healthy, normal-sighted controls. In the control group, we expected search time reduction in repeated displays, as it has been observed in healthy elderly observers (Howard et al., 2004). Furthermore, we expected this search facilitation in repeated displays to go along with a reduced number of fixations and more efficient scan paths in familiar search contexts, a pattern that has repeatedly been reported in younger observers (Brockmole & Henderson, 2006; Geringswald et al., 2012; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004), but would be first demonstrated in elderly observers here. Because the severity of visual impairment in AMD often differs between both eyes, patients were tested with monocular and binocular vision. In the monocular condition, patients viewed the search displays with their more severely impaired eye. If contextual cueing depends on foveal vision, we expected selectively reduced search facilitation for repeated displays in search times and gaze parameters. Additionally, we expected the individual amount of search facilitation to correlate negatively with the magnitude of visual impairment of the eye tested. In binocular vision, the central question was to what degree the better eye could compensate deficits in contextual cueing. One extreme might be that contextual cueing depends only on vision of the better eye. On the other hand, vision loss in the worse eye might interfere with contextual cueing even in binocular vision.

6.3. Methods

6.3.1. Participants

Patients

16 patients (all except P17) described in section 2.1.2 Patient experiments, took part in the binocular and monocular session of the experiment (for details, see Table 2.1). The average age of the patient group was 71 years, ranging from 67 to 76 years. The mean educational level of the patient group was 13 years of education, ranging from 8 to 19 years.

For monocular testing, we measured the more severely affected eye, in which possible effects of foveal dysfunction should be most prominent, in all but three patients who were not able to perform the task with their worse eye (P09, P14, and P16).

Across all patients, the average logarithmic “Minimum Angle of Resolution” (LogMAR) was 0.11 (decimal visual acuity 0.78) in the better eye and 0.65 (decimal visual acuity 0.22) in the worse eye. For the eye used for monocular testing, average LogMAR was 0.42 (decimal visual acuity 0.38).

Controls

16 controls (7 females, 9 males; 1 left-handed) participated in the study. Their mean age was 68 years ranging from 60 to 73 years. The mean educational level of the control group was 14 years years of education ranging from 10 to 18 years. Controls were matched to patients individually considering sex, age and years of education (for details see Table 6.1). In ten controls, normal visual acuity was confirmed in an ophthalmological examination prior to testing (best corrected decimal near visual acuity ≥ 0.8). The other six controls performed the Freiburg Vision Test (Bach, 1996, 2007) to ensure normal vision (decimal visual acuity ≥ 0.8 ; for more details, see section 2.1.2 Patient experiments).

6.3.2. Apparatus

We used a 22-inch Samsung SyncMaster 2233RZ LCD monitor that was 474 mm (1680 pixels) wide and 296 mm (1050 pixels) high and the vertical refresh rate was 120 Hz. Responses were recorded with a ResponsePixx Handheld five button response box (VVPixx Technologies Inc.; <http://www.vpixx.com>). The distance to the screen was kept constant at 85 cm leading to a pixel size of 0.019° of visual angle.

Table 6.1.: Sample characteristics

Patients				Matched controls		
Patient	Sex	Age (years)	Education (years)	Sex	Age (years)	Education (years)
P01	M	75	19	M	72	17
P02	M	76	18	M	73	18
P03	M	73	18	M	71	18
P04	F	68	16	F	66	10
P05	M	70	8	M	69	12
P06	M	68	11	M	63	10
P07	F	69	8	F	66	10
P08	M	70	18	M	70	17
P09 ^a	F	76	8	F	70	10
P10	M	68	12	M	63	15
P11	F	75	8	F	70	10
P12	F	70	8	F	70	15
P13	M	67	10	M	60	18
P14 ^a	M	75	17	M	72	12
P15	F	74	13	F	70	18
P16 ^a	F	67	10	F	62	13

Note: M = male; F = female.

^a Three patients could not complete the experiment with their more severely affected eye in the monocular condition and were therefore tested with the better eye.

The eye position was recorded using an Eyelink 1000 Desktop Mount (SR Research Ltd., Mississauga, Ontario, Canada) using corneal reflection and pupil tracking. The temporal resolution of the eye tracker was 1000 Hz.¹

6.3.3. Stimuli

For details about the stimuli used in the experiment see Section 2.3.2 Contextual cueing paradigm. Each search item subtended $1.23^\circ \times 1.23^\circ$ of visual angle (Figure 6.1). The offset at the junction of the two segments of the L-shapes was 0.12° of visual angle for controls. There was no offset for patients. The imaginary concentric circles used for creating the stimulus positions had radii of 2° , 4° , 6° and 8° of visual angle. The overall size of the search display on the screen extended a circular area with a diameter of 17.23° of visual angle.

6.3.4. Procedure

Participants searched for a left- or right-tilted T among L-shaped distractors and indicated its orientation with button presses of the left and right index finger. For the experimental sessions, patients' visual acuity was corrected individually. Patients wore custom-made trial-frames and we adjusted trial lenses, based on results of the optical refraction, until patients reported optimal visibility of stimuli on the computer screen. When necessary, for example, because of wearing progressive lenses, we applied the same procedure to controls referring to their eyeglass prescription.

¹ One patient (P08) was tested in the lab of Gisela Müller-Plath in Halle (Saale), Germany, in the monocular condition. In this setup, we used a 20-inch CRT monitor which was 400 mm (1600 pixels) wide and 300 mm (1200 pixels) high running at a vertical refresh rate of 85 Hz. The viewing distance was 55.1 cm leading to a pixel size of 0.026° of visual angle. We adapted all visual stimuli to match in size and eccentricity in degrees of visual angle as we had implemented in our lab. Eye position was recorded with an Eyelink II head-mounted gaze-tracking system (SR Research Ltd., Mississauga, Ontario, Canada) with a temporal resolution of 500 Hz.

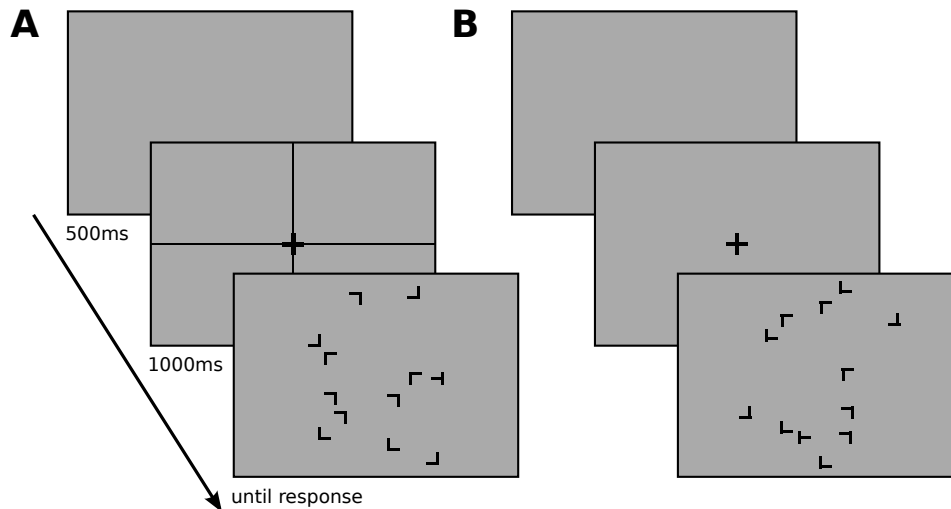


Figure 6.1.: Schematic diagram of an experimental trial for patients (A) and controls (B). Each trial consisted of the presentation of a blank screen (500 ms) followed by a fixation cross (1000 ms) and the search display (presented until response). Displays used in the experiment in the patient monocular and binocular condition each contained one tilted target T and eleven randomly rotated distractor Ls (A). In the control condition, search difficulty was increased by shifting the line segments of the distractors to make them perceptually more similar to the target T (B)

Patients performed visual search binocularly in their first session and were tested again approximately within two weeks using only their more severely affected eye using a new set of search displays. Each session started with a nine-point gaze-calibration, followed by a short training to familiarize participants with the task, the actual search experiment and a recognition test at the end of the session. One session lasted approximately 60 min for controls and between 60 to 120 min for patients depending on the severity of the visual defect.

The other procedures were the same as in the scotoma simulation experiment (see section 5.3.4 Procedure) except for the following differences. There was no blank between the presentation of the fixation cross and the search display (Figure 6.1) and we used a 9-point gaze-calibration for setting up the eye tracker, in place of the 13-point routines used in the scotoma simulation experiment.

6.3.5. Data Analysis

Response accuracy as well as search time analysis and all statistical test were carried out using R (version 2.15.2 R Core Team, 2012). For the analyses of the contextual cueing effects, response times and gaze parameters were aggregated to four epochs, each containing five blocks, in order to increase statistical power. Analyses of variance (ANOVAs) were performed using type III sums of squares. We analyzed the data of patients and controls in joint three-way mixed-design ANOVA with the within subjects factors epoch (1-4) and configuration (novel, repeated) and the between-subjects factor experimental group. If the experimental group factor or interactions involving the experimental group factor became significant, we ran additional two-way within-subjects ANOVAs for each group, followed by planned comparisons between novel and repeated configurations for each epoch to detect significant contextual cueing if the factor configuration or the interaction became significant. These planned, two-tailed *t* test comparisons were adjusted according to Holm (1979). For all statistical test, the alpha level was set at

.05.

The number of fixations and scan path efficiency were calculated as dependent measures from the fixation events (for details, see Section 5.3.5 Gaze Data analysis).

6.3.6. Data Exclusion and Spatial Accuracy of Gaze Data

Data Exclusion

For the analysis of the reaction times and the gaze parameters, we excluded all erroneous responses from the data set. In a next step, we removed all trials in which the search time was shorter than 200 ms (two trials in the control condition). To detect and remove reaction time outliers, we applied the recursive procedure proposed by Van Selst and Jolicoeur (1994) for each participant and experimental session individually leading to the exclusion of 3.52 % in the patient monocular, 2.01 % in the patient binocular, and 2.59 % in the control condition respectively.

For the analysis of the gaze data we additionally excluded all trials in which more than 20 % of the gaze samples were missing due to signal losses. Following this procedure we decided to exclude subjects from the gaze data analysis who had more than 20 % of their gaze data identified as invalid. This led to the exclusion of two patients from the monocular (P06, 43.82 %, and P08, 74.51 % of invalid gaze data) and two patients from the binocular condition (P07, 35.82 %, and P08, 27.60 % of invalid gaze data).

Thus, 16 controls, 11 patients in the monocular and 14 in the binocular condition remained in the analyses of the gaze data. The average percentage of excluded invalid trials of the remaining participants was 4.48 % ($SD = 6.13\%$) in the patient monocular, 4.56 % ($SD = 5.86\%$) in the patient binocular, and 1.59 % ($SD = 2.64\%$) in the control condition.

Spatial accuracy of Gaze Data

Measurement of eye movements required foveation of the calibration targets during the set-up of the eye-tracker. In AMD patients, this procedure is challenging because patients may not be able to foveate the targets, compromising spatial accuracy of the measured gaze. In order to test spatial accuracy, we computed the median distance of the last fixation to the center of the target stimulus, averaged for each participant across the experiment, between patients and controls. The average median distance of the last fixation was 0.60° ($SD = 0.20^\circ$) for the control condition. As expected, for the patients the distance of the last fixation was slightly larger. The average median distance was 1.30° ($SD = 1.07^\circ$) in the patient monocular and 1.44° ($SD = 1.75^\circ$) in the patient binocular condition. 99.04 % of all last fixations in the control condition lay within an area surrounding the center of the target by 3.0° of visual angle. This was the case for 87.57 % of fixations in the patient monocular and 86.96 % in the binocular conditions. Thus, as expected, eye-tracking accuracies for patients were inferior to those of controls. However, the average deviations measured for the patients, that is, the spatial accuracy of the measured gaze data, fell well within 1.5° of visual angle which can be considered as reasonable regarding the further analysis of the eye-movement data.

6.4. Results

6.4.1. Patients monocular

In the monocular condition, patients searched with their more severely affected eye and thus possible effects of foveal defects on contextual cueing should be most prominent under monocular search.

Response Accuracy

Search accuracy was high, ranging from 87.29 to 100% (average 98.15%) in the patient, and from 97.08 to 99.79% (average 99.09%) in the control condition. We compared response accuracies between patients and controls using a mixed-design ANOVA with the within-subjects factor configuration (novel, repeated) and the between-subjects factor experimental group (patient, control). We did not observe any significant differences in accuracies between patients and controls, experimental group, $F(1, 30) = 1.29$, $p = .26$, $\eta_P^2 = .04$, $\eta_G^2 = .040$; configuration, $F(1, 30) = 0.47$, $p = .50$, $\eta_P^2 = .02$, $\eta_G^2 < .001$; experimental group \times configuration, $F(1, 30) = 0.12$, $p = .73$, $\eta_P^2 < .01$, $\eta_G^2 < .001$, indicating that response accuracies were comparable between experimental groups and display configurations.

Search Times

Averaged search times are shown in Figure 6.2, top row, and standardized search facilitation scores in Figure 6.3, green bars.

The three patients who performed search with their better eye (P09, P14, and P16, see 6.3.1 Patients) were excluded from this analysis as they may have profited from masking their worse eye. Results of the three-way mixed-design ANOVA are summarized in Table 6.2. Overall search times were comparable between patients and controls, experimental group, $F(1, 27) = 0.05$, $p = .82$, $\eta_P^2 < .01$, $\eta_G^2 = .002$. A significant main effect of epoch, $F(3, 81) = 10.02$, $p < .001$, $\eta_P^2 = .27$, $\eta_G^2 = .010$, indicated general improvement over time. The significant main effect of configuration, $F(1, 27) = 7.55$, $p < .01$, $\eta_P^2 = .22$, $\eta_G^2 = .003$, and significant epoch \times configuration interaction, $F(3, 81) = 2.81$, $p < .05$, $\eta_P^2 = .09$, $\eta_G^2 < .001$, revealed significant contextual cueing. A significant three-way interaction between experimental group, epoch and configuration, $F(3, 81) = 2.82$, $p < .05$, $\eta_P^2 = .09$, $\eta_G^2 < .001$, suggested that contextual cueing differed between patients and controls. To further investigate the nature of this interaction, we ran separate repeated-measures ANOVAs with the factors epoch (1-4) and configuration (novel, repeated) for patients and controls respectively. Results of these ANOVAs are summarized in Table 6.3. In patients, we observed a marginally significant effect of skill learning, epoch, $F(3, 36) = 2.67$, $p = .06$, $\eta_P^2 = .18$, $\eta_G^2 = .004$, with decreasing response times from 2241 ms in the first to 2042 ms in the last epoch. However, patients did not additionally profit from repeated contexts as indicated by a non-significant main effect of configuration, $F(1, 12) = 1.64$, $p = .22$, $\eta_P^2 = .12$, $\eta_G^2 = .0007$, and a non-significant epoch \times configuration interaction, $F(3, 36) = 0.43$, $p = .73$, $\eta_P^2 = .03$, $\eta_G^2 = .0001$. Controls showed a pronounced effect of general skill learning reflected by a highly significant main effect of epoch, $F(3, 45) = 9.79$, $p < .001$, $\eta_P^2 = .40$, $\eta_G^2 = .052$. Search times decreased from 2195 ms in the first epoch to 1955 ms in the last epoch. Additionally, responses to repeated displays were significantly faster than to novel search arrays as confirmed by a significant main effect of configuration, $F(1, 45) = 7.22$, $p < .05$, $\eta_P^2 = .33$, $\eta_G^2 = .021$. The significant interaction, $F(3, 45) = 6.07$, $p < .01$, $\eta_P^2 = .29$, $\eta_G^2 = .010$, furthermore indicated that this contextual cueing built up over the course of the experiment. Whereas response times were not significantly faster for repeated displays throughout epochs 1 to 3, all $t_s < 2.08$, all corrected $p_s > .16$, responses were significantly speeded in the last epoch, $t(15) = 4.11$, $p < .01$. Thus, in contrast to patients, we obtained robust contextual cueing in controls searching in displays that were matched for difficulty².

² In an additional experiment, controls performed visual search in displays identical to those of patients. This was done in order to exclude the possibility that contextual cueing observed in controls was specific to the perceptually more demanding displays. We expected controls to show general skill learning as well as contextual cueing over the course of the session. A highly significant main effect of epoch confirmed general learning in the easy condition, $F(3, 45) = 23.20$, $p < .001$, $\eta_P^2 = .61$, $\eta_G^2 = .070$. Performance improved from 1194 to 1071 ms in the first and last epoch. The main effect of configuration was not significant, $F(1, 15) = 0.80$, $p = .39$, $\eta_P^2 = .05$, $\eta_G^2 < .001$. However, the significant interaction, $F(3, 45) = 4.47$, $p < .01$, $\eta_P^2 = .23$, $\eta_G^2 = .006$, confirmed that contextual cueing in controls was not specific to the more difficult search displays. Similarly to the difficulty-matched condition, responses to repeated displays were significantly faster in the last epoch, $t(15) = 4.02$, $p < .01$; all $t_s < 1.70$, all corrected $p_s > .33$.

6. Experiment 4: Contextual Cueing Impairment in Patients with Age-Related Macular Degeneration

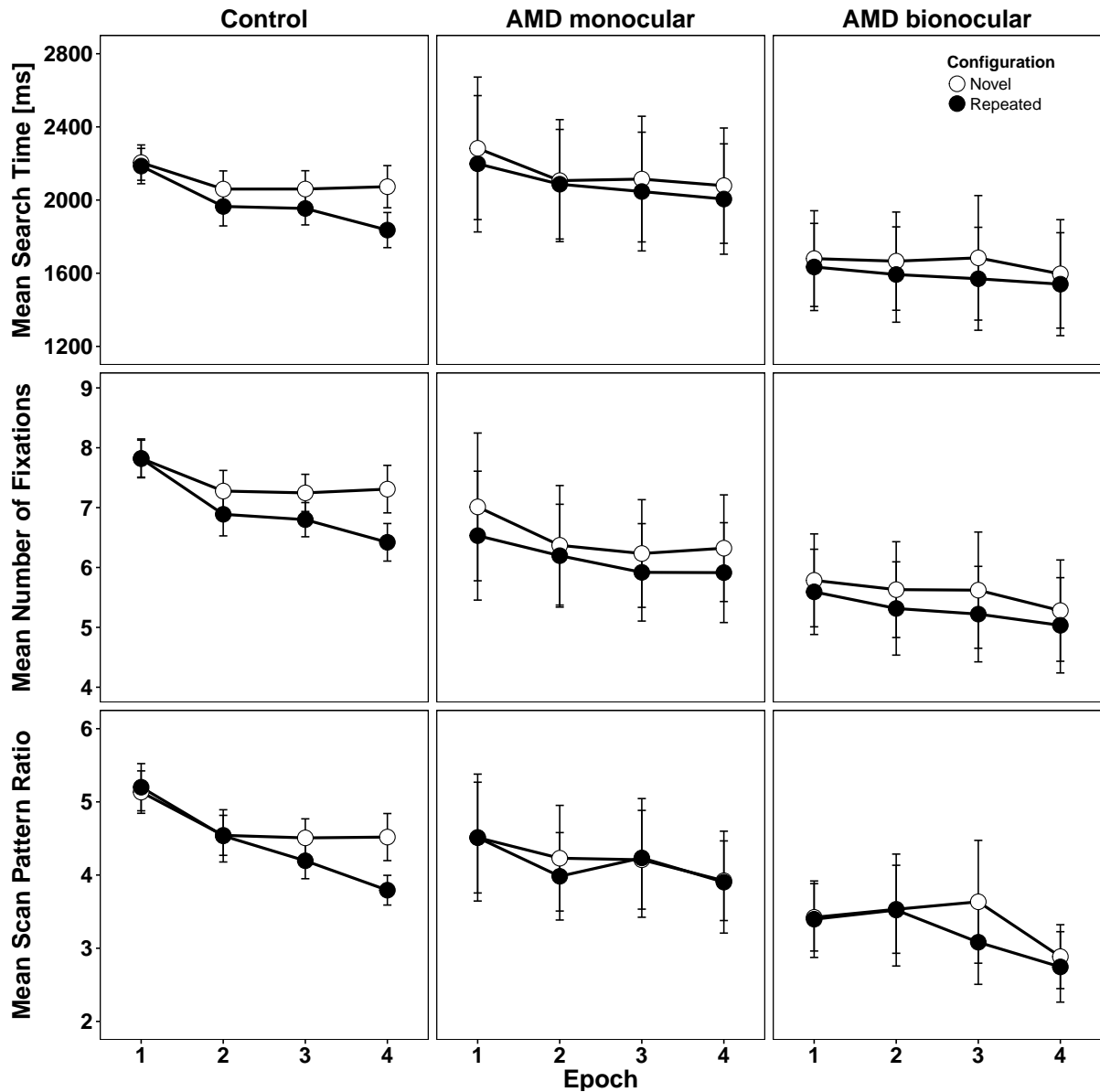


Figure 6.2.: Averaged search times, numbers of fixations and scan pattern ratios for controls and AMD patients. Search times (top row), number of fixations (middle row) and scan pattern ratios (bottom row) were aggregated to epochs (each epoch containing 5 blocks) and are plotted for controls (left column), patients searching with their worse eye (middle column) and binocularly (right column). The three measures of visual search are plotted separately for repeated (filled symbols) and novel displays (open symbols). Error bars depict the standard error of the mean.

If the successful use of contextual cues is related to foveal vision, contextual cueing should be more impaired in patients with greater foveal dysfunction. To test this prediction, we correlated the general visual performance, as indicated by logMAR visual acuity, and the normalized gain in repeated displays

6. Experiment 4: Contextual Cueing Impairment in Patients with Age-Related Macular Degeneration

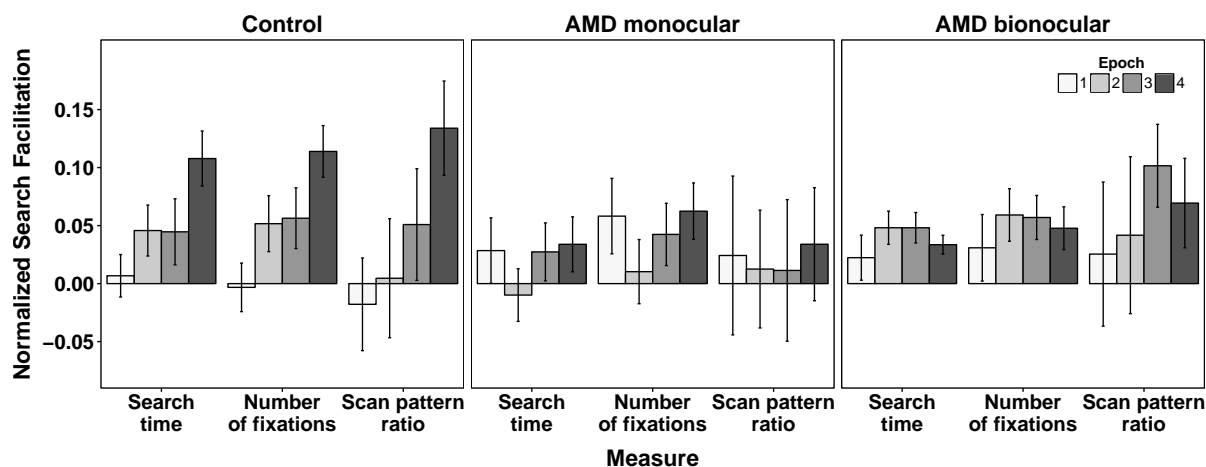


Figure 6.3.: Averaged normalized search facilitation for controls and AMD patients as a function of epoch and measure. Normalized search facilitation was obtained by individually calculating the difference between novel and repeated displays and standardizing this difference by the mean of novel displays and are plotted for controls (left panel), patients searching with their worse eye (middle panel) and binocularly (right panel). Positive values indicate a benefit for repeated configurations. Error bars depict the standard error of the mean.

Table 6.2.: Statistical results of the group comparison for search time, number of fixations and scan pattern ratio.

Effect	Measure											
	Search time				Number of fixations				Scan pattern ratio			
	F	p	η_p^2	η_G^2	F	p	η_p^2	η_G^2	F	p	η_p^2	η_G^2
Patient monocular versus control												
Group	0.05	.82	<.01	.002	1.08	.31	.04	.038	0.34	.57	.01	.011
Epoch	10.02	<.001	.27	.010	10.90	<.001	.30	.020	7.95	<.001	.24	.028
Configuration	7.55	<.05	.22	.003	11.11	<.01	.31	.008	1.69	.21	.06	.002
Group \times Epoch	0.10	.96	<.01	<.001	0.38	.77	.01	<.001	0.92	.44	.04	.003
Group \times Configuration	0.69	.41	.02	<.001	0.14	.71	<.01	<.001	0.62	.44	.02	<.001
Epoch \times Configuration	2.81	<.05	.09	<.001	3.31	<.05	.12	.001	1.18	.32	.05	.002
Group \times Epoch \times Configuration	2.82	<.05	.09	<.001	4.03	<.05	.14	.002	1.91	.14	.07	.003
Patient binocular versus control												
Group	2.08	.16	.06	.063	4.66	<.05	.14	.14	4.81	<.05	.15	.124
Epoch	8.15	<.001	.21	.005	15.36	<.001	.35	.01	8.28	<.001	.23	.029
Configuration	11.97	<.01	.28	.003	14.60	<.001	.34	.007	4.23	<.05	.13	.004
Group \times Epoch	2.59	.06	.08	.002	2.44	.07	.08	.002	2.34	.08	.08	.008
Group \times Configuration	0.60	.44	.02	<.001	0.58	.45	.02	<.001	0.09	.77	<.01	<.001
Epoch \times Configuration	4.06	<.01	.12	<.001	4.42	<.01	.14	.001	2.53	.06	.08	.004
Group \times Epoch \times Configuration	3.93	<.05	.12	<.001	3.58	<.05	.11	.001	1.29	.28	.04	.002

in the last epoch (Figure 6.4). We used Kendall's τ non-parametric rank order correlation and included all patients of the monocular condition. Normalized contextual cueing was obtained by individually calculating the difference in mean reaction times between novel and repeated displays and standardizing this absolute difference by the mean reaction time of novel displays. LogMAR visual acuity correlated negatively with the size of contextual cueing, $\tau = -.47$, $p < .05$, implying that patients with larger foveal impairments profited less from contextual cues and that, on the other hand, in mild cases contextual

6. Experiment 4: Contextual Cueing Impairment in Patients with Age-Related Macular Degeneration

Table 6.3.: Statistical results of the within-group analyses for search time, number of fixations and scan pattern ratio.

Effect	Measure											
	Search time				Number of fixations				Scan pattern ratio			
	F	p	η_P^2	η_G^2	F	p	η_P^2	η_G^2	F	p	η_P^2	η_G^2
Patient monocular												
Epoch	2.67	.06	.18	.004	2.58	.07	.20	.008	1.21	.32	.11	.009
Configuration	1.64	.22	.12	<.001	3.61	.09	.26	.003	0.15	.70	.02	<.001
Epoch \times Configuration	0.43	.73	.03	<.001	0.74	.54	.07	<.001	0.22	.88	.02	<.001
Patient binocular												
Epoch	1.17	.33	.07	<.001	5.61	<.01	.30	.004	2.33	.09	.15	.016
Configuration	4.72	<.05	.24	.001	6.87	<.05	.35	.002	2.28	.15	.15	.002
Epoch \times Configuration	0.98	.41	.06	<.001	0.45	.72	.03	<.001	0.84	.48	.06	.003
Control												
Epoch	9.79	<.001	.40	.052	11.36	<.001	.43	.076	12.56	<.001	.46	.104
Configuration	7.22	<.05	.33	.021	8.57	<.05	.36	.027	2.26	.15	.13	.012
Epoch \times Configuration	6.07	<.01	.29	.010	7.90	<.001	.35	.015	4.25	<.01	.22	.019

cueing was preserved to some extent.

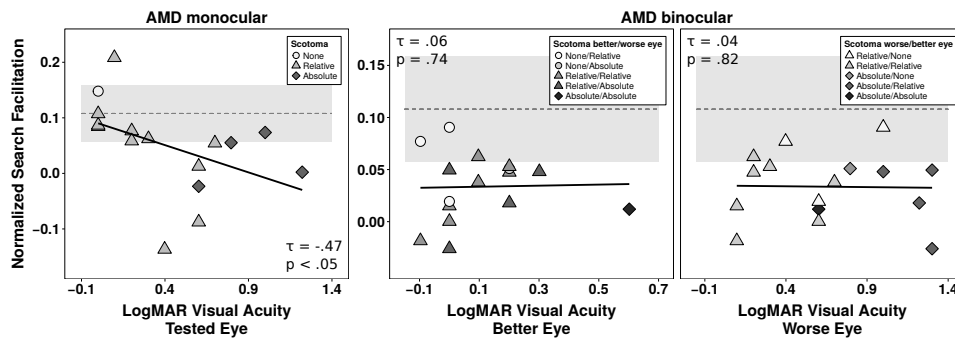


Figure 6.4.: Relationship between the degree of foveal impairment in AMD (logMAR visual acuity) and normalized contextual cueing in search time in the last epoch in monocular (left panel) and binocular search considering the better (middle panel) or worse eye (right panel). Normalized contextual cueing was obtained by individually calculating the difference in mean reaction times between novel and repeated displays and standardizing this absolute difference by the mean reaction time of novel displays. Positive values indicate a benefit for repeated configurations. Rank correlations were quantified using Kendall's τ . The solid line depicts the linear regression for the purpose of visualization. The dashed line represents the averaged mean sensitivity of controls and the shaded area the corresponding 95 % confidence intervals.

To summarize, we did not find evidence for contextual search facilitation in patients searching with their worse eye in the group analysis whereas matched healthy controls showed a significant development of contextual cueing over repeated searches. Additionally, search facilitation co-varied with the magnitude of foveal impairment.

Gaze

Analogous to reaction times, we investigated whether search facilitation for repeated displays was evident in eye-movement patterns³. If contextual search facilitation for repeated displays emerged, this should be reflected in a more efficient sampling of the search arrays, that is, a reduction of number of fixations executed until the target is identified, compared to novel search arrays. In addition, the scan pattern ratio illustrates the efficiency of the placement of fixations on the search array, by standardizing the summed distance the eye traveled across the display on the shortest path possible from the first fixation. Facilitation for repeated displays in contextual cueing is expressed by lower scan pattern ratios in repeated compared to novel search arrays. To our knowledge, search facilitation for repeated displays in eye movements have only been reported for younger observers (Brockmole & Henderson, 2006; Geringswald et al., 2012; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004). We expected similar effects of contextual cueing in our older controls as well. In AMD patients, we expected a reduction of search facilitation in repeated displays.

Number of Fixations. Figure 6.2, middle row, depicts the averaged number of fixations and average standardized search facilitation scores can be seen in Figure 6.3, purple bars. We again excluded the three subjects who performed search with their better eye (see 6.3.1 Patients). In addition, two patients dropped out due to significant amounts of missing gaze data (see 6.3.6 Data Exclusion).

The three-way mixed-design ANOVA yielded similar results as observed in response times (Table 6.2), showing a significant three-way interaction as well, $F(3, 75) = 4.03$, $p < .05$, $\eta_P^2 = .14$, $\eta_G^2 = .002$. The separate two-way repeated-measures ANOVAs did not reveal any statistically significant effects in patients' number of fixations (Table 6.3), indicating that contextual cueing was impaired in this measure as well. In contrast to response times, we observed a non-significant trend towards less fixations in repeated compared to novel displays, configuration, $F(1, 10) = 3.61$, $p = .09$, $\eta_P^2 = .26$, $\eta_G^2 = .003$. We note, however, that we had to exclude two patients from the gaze analysis due to significant amounts of missing gaze data. One of them (P06) had a severe absolute scotoma such that the removal of this subject might have lead to higher general levels of contextual cueing within the patient group as observed in response times, presumably producing the non-significant trend towards general contextual benefits in the patient group. In contrast to patients, controls showed a pronounced effect of general skill learning as well as contextual cueing, building up over the course of the experiment. Whereas a similar amount of fixations was needed in repeated compared to random configurations in epochs 1 to 3, all t s < 2.27 , all corrected p s $> .11$, contextual cueing was significant in the last epoch, $t(15) = 4.44$, $p < .01$.

In more impaired patients, the foveal defect should be accompanied by a generally increased number of fixations to explore parts of the displays which may be covered by a scotoma. To test this relationship, we correlated the individual average number of fixations of all patients with the visual impairment. The correlation with logMAR visual acuity was significant, $r = .59$, $p < .01$, indicating that more severely impaired patients did indeed fixate more often during visual search.

³ Before we carried out the analyses on gaze parameters, we reanalyzed search times including only those subjects and those trials, which were not discarded from eye-movement analyses due to invalid or missing gaze data. This was done to ensure that the pattern of results for search times remained comparable to results of the gaze data. The main pattern of results remained similar. Search times were comparable between patients' monocular search and controls, experimental group, $F(1, 25) = 0.08$, $p = .77$, $\eta_P^2 < .01$, $\eta_G^2 = .002$, and the three-way interaction was significant, $F(3, 75) = 2.97$, $p < .05$, $\eta_P^2 = .11$, $\eta_G^2 < .001$. Patients did neither show significant general learning, epoch, $F(3, 30) = 1.93$, $p = .15$, $\eta_P^2 = .16$, $\eta_G^2 = .005$, nor contextual cueing, configuration, $F(1, 10) = 2.74$, $p = .13$, $\eta_P^2 = .21$, $\eta_G^2 = .002$; interaction, $F(3, 30) = 0.87$, $p = .47$, $\eta_P^2 = .08$, $\eta_G^2 < .001$, whereas this was the case for controls, all F s > 5.97 , all p s $< .01$, all η_P^2 s $> .28$, all η_G^2 s $> .01$. Under binocular viewing, patients' response times did not differ significantly from controls, experimental group, $F(1, 28) = 1.37$, $p = .25$, $\eta_P^2 = .05$, $\eta_G^2 = .045$. The three-way interaction just missed significance, $F(3, 84) = 2.68$, $p = .05$, $\eta_P^2 = .09$, $\eta_G^2 < .001$, most likely due to decreased statistical power. In patients, the main effect of epoch was not significant, $F(3, 39) = 1.27$, $p = .30$, $\eta_P^2 = .09$, $\eta_G^2 = .001$, and the main effect configuration was marginally significant, $F(1, 13) = 3.78$, $p = .07$, $\eta_P^2 = .23$, $\eta_G^2 = .001$.

Scan Pattern Ratio. The development of average scan pattern ratios is plotted in Figure 6.2, bottom row, and the standardized average search facilitation scores can be seen in Figure 6.3, orange bars.

Results of the three-way mixed-design ANOVA are summarized in Table 6.2. Neither the factor configuration nor any interaction involving configuration was significant, suggesting that contextual cueing affected neither patients' nor controls' scan paths, all F s < 1.91 , all p s $> .13$, all η_P^2 s $< .08$, all η_G^2 s $< .003$. Thus, we decided to conduct follow-up repeated-measures ANOVAs for each group (Table 6.3) to investigate whether contextual cueing was completely absent in controls albeit Figures 6.2 and 6.3 suggest that contextual benefits emerged over time. Overall search benefits for repeated search arrays were not significant in controls, however, contextual cueing developed over the course of the experiment, $F(3, 45) = 4.25$, $p < .05$, $\eta_P^2 = .22$, $\eta_G^2 = .019$. Whereas similar scan pattern ratios were observed in repeated compared to random configurations in epochs 1 to 3, all t s < 1.27 , all corrected p s $> .68$, contextual cueing was significant in the last epoch, $t(15) = 3.22$, $p < .05$. In patients, we did not find any evidence for contextual cueing. None of the effects were significant, all F s < 1.22 , all p s $> .32$, all η_P^2 s $< .12$, all η_G^2 s $< .010$.

Thus, facilitation of scan path efficiency in repeated displays was impaired in patients searching with their worse eye. To some extent, contextual cueing also appeared reduced in controls. Possibly, contextual benefits stabilized only late in the experiment and were more variable between participants than search times and number of fixations, thereby leading to non-significant interactions involving the factor configuration in the three-way ANOVA.

6.4.2. Patients binocular

We next examined contextual cueing in binocular viewing in patients. In this condition, patients might partially accommodate visual deficits of their worse eye and might be more amenable to context repetitions. This might result in generally higher amounts of benefits from contextual cues in the group statistics. Concomitantly, binocular viewing has a higher ecological validity and may reflect patients' visual behavior in everyday life to a greater extent.

Response Accuracy

Patients' performance was again very high, ranging from 97.08 to 100% (average 99.02%). It was not significantly different from controls' performance and comparable between display configurations, experimental group, $F(1, 30) = 0.06$, $p = .80$, $\eta_P^2 < .01$, $\eta_G^2 = .001$; $F(1, 30) = 0.72$, $p = .40$, $\eta_P^2 = .02$, $\eta_G^2 = .007$; experimental group \times configuration, $F(1, 30) = 3.12$, $p = .09$, $\eta_P^2 = .09$, $\eta_G^2 = .031$.

Search Times

The three-way mixed-design ANOVA yielded similar results as for the comparison between patients' monocular search and controls (see Table 6.2). Overall search times were comparable between patients and controls and the significant three-way interaction, $F(3, 90) = 3.93$, $p = .01$, $\eta_P^2 = .12$, $\eta_G^2 < .001$, suggested differences in contextual cueing. General skill learning was not significant in patients (Table 6.3), performance improved from 1657 ms in the first to 1568 ms in the last epoch. However, in contrast to monocular search, patients could use repeated configurations to speed up search by 72 ms, $F(1, 15) = 4.72$, $p < .05$, $\eta_P^2 = .24$, $\eta_G^2 = .001$. The non-significant interaction between epoch and configuration, $F(3, 45) = 0.98$, $p = .41$, $\eta_P^2 = .06$, $\eta_G^2 < .001$, suggested that the magnitude of contextual benefits did not differ across experimental epochs. Planned comparisons between novel and repeated configurations for each epoch indicated that patients benefited from repeated search displays early in the experiment. While response times to repeated and novel search displays were comparable in the first epoch, $t(15) = 0.96$, $p = .35$, responses were significantly faster for repeated displays in the second, $t(15) = 3.10$, $p < .05$, as well as in the last epoch, $t(15) = 2.99$, $p < .05$. This difference failed to reach

significance in the third epoch, $t(15) = 1.79$, $p = .19$, indicating that contextual cueing may have an early onset, but also be less stable in patients. In addition, a comparison of the magnitude of contextual cueing effects in the last epoch with controls suggests that search facilitation was significantly reduced in patients searching binocularly, Welch two sample t test, $t(18.13) = 2.98$, $p < .01$. On average, patients' contextual cueing amounted to 56 ms compared to 237 ms in healthy controls. Although average search times between patients and controls did not differ significantly, Figure 6.2 suggests that search might have been slower in controls, inflating contextual cueing. Thus, we carried out an additional Welch two-sample t test comparing normalized contextual cueing effects between patients and controls. This test confirmed decreased search facilitation in patients, $t(18, 49) = 2.96$, $p < .01$. Facilitation accumulated to 3.36% in patients and to 10.78% in controls.

To test whether the individual amount of contextual search facilitation was related to visual impairment, we correlated the visual impairment of the better and worse eye with the normalized magnitude of contextual cueing of the last epoch. We did not find any significant relationships between contextual cueing and logMAR visual acuity (Figure 6.4) of the better, $\tau = .06$, $p = .74$, or worse eye, $\tau = .04$, $p = .82$.

Gaze

Number of Fixations. The three-way mixed-design ANOVA yielded overall similar results as for search times, with a significant three-way interaction indicating differences in contextual cueing between patients and controls (Table 6.2). In contrast to search times, the main effect of experimental group was also significant, with a reduced number of fixations committed by patients (on average 5.44 fixations) compared to controls (on average 7.20 fixations). Different from search times, patients showed significant general skill learning in the number of fixations (Table 6.3). Performance improved from 5.69 in the first to 5.16 fixations in the last epoch. As observed before, patients overall benefited significantly from repeated contexts, making on average 0.29 fixations less in repeated configurations. The magnitude of these contextual benefits did not differ significantly between epochs. Planned comparisons between novel and repeated configurations for each epoch did not reach statistical significance. However, in accordance with search times, we observed a trend for significant contextual cueing in epochs 2, $t(13) = 2.65$, $p = .08$, and 4, $t(13) = 2.62$, $p = .08$, but not for the first, $t(13) = 0.97$, $p = .35$, and third epoch, $t(13) = 1.98$, $p = .14$. The magnitude of contextual cueing effects in the last epoch was significantly smaller compared to controls regarding absolute benefits, Welch two sample t test, $t(21.11) = 2.91$, $p < .01$, as well as normalized contextual cueing, $t(27.64) = 2.29$, $p < .05$.

Scan Pattern Ratio. Results of the three-way mixed-design ANOVA were similar to the number of fixations (Table 6.2). Patients (ratio on average 3.28) searched the displays overall more efficiently than controls. The interaction between experimental group, epoch and configuration failed to reach significance, $F(3, 84) = 1.29$, $p = .28$, $\eta_P^2 = .04$, $\eta_G^2 = .002$. A finer analysis of the patient data, including the factors epoch and configuration, did not reveal any significant effects (Table 6.3).

Fixation Duration. Patients found the target with fewer eye movements than controls. On average, they made 5.44 fixations during search, that is 1.76 fixations less than controls, and this difference was statistically significant in the above analyses. Concomitantly, scan paths were significantly more efficient in the patient group. However, search times did not differ significantly between patients and controls. One possible reason for this inconsistent result may be that patients had an increased fixation duration. Increased fixation durations have been reported, for example, in artificial scotoma simulations, increasing with the size of the scotoma (Cornelissen et al., 2005). To test this possibility, we calculated the median fixation duration for each patient and control across the whole experiment. A Welch two-sample t test on median fixation durations indicated a non-significant trend towards longer fixation durations in patients, $t(22.56) = 1.60$, $p = .12$. Patients fixated on average for 234 ms, controls for

215 ms. The individual median fixation duration was significantly correlated with the logMAR visual acuity of the better eye, $\tau = .47$, $p < .05$, but not with the visual acuity of the worse eye, $\tau = -.01$, $p = .96$. Thus, patients with a greater visual impairment in their better eye fixated longer than less affected patients.

6.4.3. Recognition Test

Mean recognition accuracy in the patient monocular condition was 55.73% ($SD = 10.42\%$). Patients correctly classified repeated displays as old (the hit rate) on 52.60% ($SD = 22.71\%$) of trials and falsely reported 41.15% ($SD = 21.83\%$) of novel displays as old (the false alarm rate). A paired t test on hit and false alarm rates was significant, $t(15) = 2.20$, $t(.04) =$, indicating that patients may have become aware of display repetitions when they searched monocularly. Howard et al. (2004) found that contextual cueing was disrupted in older individuals who became aware of the display repetitions and linked these results to the use of different search strategies in aware compared to unaware participants. In order to test whether such a relationship was also present in our data, we carried out correlation tests between response accuracy as an indicator of awareness and the individual normalized contextual cueing of the last epoch in reaction times, using Kendall's τ non-parametric rank order correlation. The correlation between the normalized magnitude of contextual cueing and awareness did not reach significance, $\tau = -.22$, $p = .25$.

Mean recognition accuracy in the patient binocular condition was 49.48% ($SD = 10.53\%$) with a mean hit rate of 52.08% ($SD = 20.30\%$) and a mean false alarm rate of 53.13% ($SD = 23.35\%$). A paired t test on the hit and false alarm rates was not significant $t(15) = 0.20$, $p = .85$, indicating that the patient group was generally not aware of the display repetitions. Recognition accuracy and normalized contextual cueing in search times did not correlate significantly, $\tau = -.09$, $p = .65$.

In the control condition, mean recognition accuracy accumulated to 56.77% ($SD = 11.17\%$) with a mean hit rate of 61.98% ($SD = 21.72\%$) and a mean false alarm rate of 48.44% ($SD = 21.78\%$). A paired t test on the hit and false alarm rates was significant, $t(15) = 2.43$, $p < .05$, indicating that controls became aware of the display repetitions. The correlation between recognition accuracy and normalized contextual cueing in search times did not reach significance, $\tau = -.24$, $p = .22$.

6.5. Discussion

We investigated whether the loss of foveal vision in AMD affects efficiency of visual search in repeated contexts. To this end, we examined search performance in patients with AMD in the contextual cueing paradigm. The central finding was that search facilitation in repeated displays was reduced in AMD patients, while it was preserved in closely matched healthy controls (Howard et al., 2004). In the patients, reduced or absent contextual cueing was observed in search times as well as in the number of fixations and the efficiency of the scan path.

Overall, the successful use of contextual information was related to the amount of visual impairment in AMD patients. Under monocular viewing, we found a correlation of visual acuity and contextual cueing. Particularly patients with mild acuity deficits profited from contextual cues. Under binocular viewing, we found evidence for contextual cueing in AMD patients, which, however, was reduced in comparison to the control group and did not increase over time, as would be typical for contextual cueing.

Previous studies have shown that contextual cueing increases with search difficulty, by minimizing attentional allocation to irrelevant items (Chun & Jiang, 1998; Jiang & Chun, 2001). In order to match search difficulty between visually impaired patients and controls, we used perceptually more demanding search displays for controls. Response times clearly indicate that this matching was successful, that is, that the difficulty of the task was comparable between patients and controls. The drawback, however,

was that patients and controls searched different items. When controls were given the same search displays as patients, significant contextual cueing developed in controls, however, as expected, the absolute contextual benefits were smaller than in the difficult displays. It is a dilemma often observed in patient studies that on the one hand, presentation of identical tasks requires increased effort from patients and, on the other hand, equalizing effort affords unequal task parameters. We think that equalizing search difficulty was important for a fair comparison between patients and controls. However, we acknowledge that there is a remaining uncertainty in how far the different search displays affected the size of contextual cueing in unknown ways. Future studies might try to minimize this dilemma by using search difficulties that are intermediate between the presently used searches, so that they are not too difficult for patients and not too easy for controls.

Another caveat concerns potential order effects. Patients were first tested binocularly, then monocularly. We hoped that the easier binocular condition would lead to general learning of the experimental setup (unrelated to contextual cueing) that may help the patients to carry out the more difficult monocular task. Likewise, controls were first tested with the easier search task. Both patients and controls showed evidence for explicit recognition in the second testing session, possibly due to greater experience with the task or the explicit recognition test at the end of the first session. However, explicit recognition did not correlate with size of contextual cueing – neither in patients nor controls – so that it is unlikely that task order had a systematic influence on the contextual cueing data. One reason not to randomize task order in the present study was that the sample was too small to assess possible interactions between patient factors such as severity of visual impairment and task order. However, if larger sample sizes become available in future studies, randomizing the order of binocular and monocular search would be clearly preferable.

Notably, the size of the contextual cueing did not correlate with the acuity of the better or worse eye in binocular search, in contrast to the correlation between acuity and contextual cueing in monocular search. This may hint at an interaction of the worse eye's vision on vision with the better eye. For example, it has been shown that unequal damage to the retina in both eyes may lead to binocular inhibition in some AMD patients (Faubert & Overbury, 2000; Quillen, 2001; Valberg & Fosse, 2002). The new finding is that interference between unequal vision in both eyes might also affect high-level visual functions such as visual learning and memory.

Brady and Chun (2007) showed that the local context information close to the target location contributes most to contextual cueing. In AMD patients, this "snapshot" of the target and its surrounding distractors may be compromised either because of acuity loss in mild cases or due to a central scotoma, requiring peripheral "fixation" in more severe cases. Brady and Chun (2007) also observed a contribution of global regularities to contextual cueing. Consistent with this global contextual cueing, van Asselen and Castelo-Branco (2009) found intact contextual cueing in participants who had to keep central fixation and perceived search stimuli only in their visual periphery, and contextual cueing remains intact when search displays are presented only briefly, curtailing eye movements (Chun & Jiang, 1998). These results challenge the idea that central vision is necessary for contextual cueing. We know from the spatial cueing experiments developed by Posner, Snyder, and Davidson (1980) that covert spatial attention can be moved away from central fixation. This may be one mechanism that mediates guidance of attention in contextual cueing when eye movements are restricted. However, the reverse appears to be impossible, that is, making a saccade without a concomitant shift of attention (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). Thus, when eye movements are necessary in visual search, like in our experiment, elimination of foveal sight impairs contextual cueing.

The above suggests that it may be advantageous for AMD patients, to make as few eye movements as possible and to rely more on global regularities, minimizing the demands of exploring the search array. In contrast to the studies by van Asselen and Castelo-Branco (2009) or Chun and Jiang (1998) however, patients with central visual impairment will not perceive the whole stimulus configuration uniformly as the macular scotoma will cover parts of the search array. For example, in van Asselen and Castelo-Branco (2009), attention may be shifted peripherally between search items while the search

array itself remains static, facilitating the learning of spatial relations between search items. If patients with central vision loss do not move their eyes, the strength of memory representations of spatial configurations should be reduced in such displays because less visual information is available to them, compared to unimpaired controls. On the other hand, if patients want to encode information covered by the scotoma, exploration via eye movements is mandatory and may result in reduced contextual cueing as observed in our study. Consequently, for larger central vision loss due to AMD more eye movements should be needed to explore the scotomized area and a larger loss of contextual cueing should be evident.

Previously, we observed reduced contextual cueing with simulated central scotomata in healthy observers (Geringswald et al., 2012). In comparison, our AMD patients benefited more from contextual cues than the students with a simulated central scotoma, who showed virtually no contextual cueing. A likely explanation is that the patients have learned to adapt scene exploration to the presence of their vision loss, requiring less attentional resources for the top-down controlled exploration of the search displays, for instance for inhibiting foveation of the to be inspected parts of the display, as in untrained search with a simulated scotoma. Thus, a more stimulus-driven search in patients may allow for contextual cueing, as observed in the binocular condition (Lleras & Von Mühlenen, 2004). There is a caveat, however, in that the mild cases among the patients had less foveal vision loss than that introduced by the simulated scotoma in our previous study. Further simulation studies with varying degree of foveal vision degradation will be needed to address this question.

Even if patients may search more automatically than students with artificial scotomata, contextual cueing was at least significantly reduced compared to healthy controls. The link between the deployment of attention to and subsequent foveation of a visual target appears to be an automatic process, which is so dominant that it takes AMD patients several months to adapt the oculomotor system to eccentric fixating (Crossland et al., 2005) and may not be complete even years after the onset of the disease (Crossland et al., 2004; Tarita-Nistor et al., 2008; White & Bedell, 1990; Whittaker et al., 1991). The attentional resources needed to suppress foveation and explore search displays with peripheral vision are thus not available for contextual cueing. Search facilitation in repeated displays, especially the retrieval and use of learned contextual cues, depends on attending to the display items (Jiang & Chun, 2001; Jiang & Leung, 2005) and on free visuospatial working memory capacity (Manginelli et al., 2012; Manginelli, Langer, et al., 2013; Travis et al., 2013; Vickery et al., 2010). Converging evidence comes from functional magnetic resonance imaging (fMRI) data showing that parietal and occipital areas that are modulated by visual working memory capacity are also involved in contextual cueing (Manginelli, Baumgartner, & Pollmann, 2013). Due to their foveal vision loss, AMD patients suffer from increased attentional demands on the programming of eye movements during the exploration of search displays. This may lead to impairments in the deployment of selective attention to the environment and thus interfere with attentional guidance in familiar environments. Similarly, the planning and execution of eye movements in AMD patients may require visuospatial working memory capacity which may make the match between search templates from long-term memory and the current search display more difficult, thereby reducing contextual benefits observed in healthy controls. With the patient data, it is difficult to discriminate between potential causes of impaired contextual cueing, that is, (a) direct interference of foveal vision loss with learning contextual cues or (b) competition for working memory resources between top-down controlled display exploration and memory-guided search. If the AMD patients of the present study show impaired contextual cueing, further studies with simulated scotomata could selectively address the influence of scotoma size, duration of practice with a central scotoma or scotoma presence in learning versus test phases in a more controlled setting than is possible with patient data.

Learning of contextual cues can be dissociated from more general skill learning, which occurs over time for repeated and novel displays alike. Patients failed to show general learning in search time data. This lack of general skill learning appeared more pronounced in the binocular than in the monocular condition, although eye movements became more efficient during search. In patients, the eye movements are more costly in terms of programming and execution. A more optimized search strategy would thus be the reduction of eye movements and a more peripheral processing of search items during each fixation.

The trend of longer fixation durations in patients' binocular search supports this idea. Due to reduced peripheral acuity (compared to foveal search), patients may have needed longer to discriminate the target from distractors (that is, longer dwell times) than controls, leading to longer overall search times. Contextual benefits were completely absent in the efficiency of the scan path in patients, although less fixations were placed in repeated displays in binocular search, which further supports the idea that processing of search items was more peripheral compared to controls.

Patients searching monocularly and control participants appeared to be not completely unaware of the display repetitions in our experiments. Initially, it was thought that contextual cueing was a form of implicit learning (Chun & Jiang, 1998; Chun & Phelps, 1999; Manginelli & Pollmann, 2009). More recent studies with more sensitive explicit memory tests, however, provided evidence that explicit memory of context repetition may at least be present for a subset of repeated displays (Geyer et al., 2012; Geyer, Shi, & Müller, 2010; Schlagbauer et al., 2012; Smyth & Shanks, 2008). In these studies, the size of the contextual cueing effect was not related to explicit or implicit learning. We found no significant correlation of contextual cueing and explicit memory, in contrast to Howard et al. (2004) who reported that contextual cueing was reduced in older individuals who became aware of the context repetitions.

It may be surprising, that patients showed reduced or absent contextual cueing in our experiments, given that an efficient utilization of global regularities should be prioritized by the visual system to improve visual exploration of the environment, possibly by reducing costly eye movements to a minimum. However, we demonstrated impaired contextual cueing in AMD using abstract stimuli in a semantically not very meaningful environment. A question that thus remains to be investigated is whether AMD patients show similar deficits in the use of contextual information in more realistic scenes or whether they would be more efficient in using much richer semantic relations between objects in a scene to improve visual search. Patients might additionally profit from more realistic scenes as the transfer of exploration strategies from every-day behavior should be easier than in search for rather non-meaningful objects as in standard contextual cueing tasks.

6.5.1. Conclusion

In summary, our results demonstrate that the loss of foveal vision in AMD impairs contextual cueing in visual search. This deficit was correlated with the degree of visual impairment when patients searched monocularly with their worse eye. In binocular search, patients overall benefited from contextual cues, however this search facilitation was reduced compared to age-matched controls. Thus, loss of foveal vision in AMD severely interferes with search facilitation in familiar environments, an effect that transcends the immediate consequences of foveal vision loss. Future research is needed to investigate whether learning of contextual cues depends on foveal vision or whether the use of previously learned contextual memory cues is impaired following foveal vision loss, possibly due to competition for visuospatial working memory capacity.

7 Experiment 5: Central and peripheral vision loss differentially affects contextual cueing in visual search

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7.1. Abstract

Visual search for targets in repeated displays is more efficient than search for the same targets in random distractor layouts. Previous work has shown that this contextual cueing is severely impaired under central vision loss. Here, we investigated whether central vision loss, simulated with gaze-contingent displays, prevents the incidental learning of contextual cues or the expression of learning, that is, the guidance of search by learned target-distractor configurations. Visual search with a central scotoma reduced contextual cueing both with respect to search times and gaze parameters. However, when the scotoma was subsequently removed, contextual cueing was observed in a comparable magnitude as for controls who had searched without scotoma simulation throughout the experiment. This indicated that search with a central scotoma did not prevent incidental context learning, but interfered with search guidance by learned contexts. We discuss the role of visuospatial working memory load as source of this interference. In contrast to central vision loss, peripheral vision loss was expected to prevent spatial configuration learning itself, because the restricted search window did not allow the integration of invariant local configurations with the global display layout. This expectation was confirmed in that visual search with a simulated peripheral scotoma eliminated contextual cueing not only in the initial learning phase with scotoma, but also in the subsequent test phase without scotoma.

7.2. Introduction

Visual search is faster when spatial distractor configurations are repeated compared to search for the same target in random stimulus layouts. This effect has been termed contextual cueing (Chun & Jiang, 1998), a form of incidental learning of spatial regularities that facilitates attentional guidance to the target position after repeated exposure to invariant contexts. Along with faster search times, visual exploration with eye movements becomes more efficient in repeated search configurations. Typically, contextual cueing leads to target detection with fewer fixations and more direct scan paths as well as an earlier onset of the monotonic gaze path, the final search phase in which the eye approaches the target

monotonically (Brockmole & Henderson, 2006; Geringswald et al., 2012; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004).

Recently, we reported diminished contextual cueing when visual exploration of the search displays was complicated by central vision loss. In one study, contextual cueing was reduced in patients suffering from age-related macular degeneration (AMD; Geringswald, Herbig, Hoffmann, & Pollmann, 2013) in whom the progressive loss of foveal vision impaired visual exploration (Arroyo, 2006; Lindblad et al., 2009; Nazemi et al., 2005). This lack of contextual search facilitation was especially pronounced at later stages of the disease, in patients who were on the verge of developing or already suffering from dense absolute central scotomata. Complementary to the patient data, a loss of contextual cueing was also observed in healthy young observers whose exploration was constrained by a simulated gaze-contingent dense central scotoma (Geringswald et al., 2012). Taken together, these findings show that intact central vision plays a crucial role in contextual cueing.

Data from normal-sighted observers suggest that it is mainly the spatial configuration of distractors in the vicinity of the target that contributes to contextual cueing (Bellaera, von Mühlenen, & Watson, 2014; Brady & Chun, 2007; Olson & Chun, 2002). At the end of a successful search trial, the target is foveated and may be implicitly memorized together with the distractors in its vicinity. Thus, one explanation for the loss of contextual cueing due to foveal vision loss may be that such an automatic, snapshot-like learning of the distractor configuration surrounding the target would no longer be possible. This explanation, however, would not be in line with a model of visual search that proposes encoding of absolute item locations within a display, in contrast to location coding relative to the target location (Brady & Chun, 2007).

However, there may be an alternative explanation why foveal vision loss may disrupt contextual cueing. Foveal vision loss may not interfere with the learning of repeated spatial contexts, but rather with the expression of learning in visual search of repeated displays. The need to use peripheral non-scotomized parts of the retina for exploration of the environment leads to a more top-down controlled mode of exploration. The automatic foveation of possible targets in the periphery needs to be suppressed for efficient exploration. Saccade rereferencing to a perifoveal preferred retinal locus (PRL) often takes very long to develop after foveal vision loss, for example, following macular degeneration (von Noorden & Mackensensen, 1962; White & Bedell, 1990; Whittaker et al., 1991). As long as rereferencing has not developed, each new saccade brings a peripheral saccade target into the fovea, forcing the observer to make corrective saccades or enlarge the attentional focus to get around the foveal vision loss. Even when saccadic rereferencing to a PRL has been established, exploration is still more cumbersome because of the reduced spatial resolution of the peripheral retina. We know from normal-sighted observers that top-down controlled exploration strategies may prevent the contextual cueing effect to occur (Lleras & Von Mühlenen, 2004). Thus, it may be that foveal vision loss does not prevent the incidental learning of repeated spatial configurations, but rather the expression of learning for the benefit of efficient search guidance in repeated displays.

Interference of task demands with the expression of contextual learning is not without precedence. It has been shown that efficient search guidance in learned displays depends on the availability of attentional (Jiang & Leung, 2005) and visuospatial working memory resources (Annac et al., 2013; Manginelli, Langer, et al., 2013). These behavioral findings are complemented by neuroimaging findings that visual working memory and contextual cueing draw on a set of the same brain areas (Manginelli, Baumgartner, & Pollmann, 2013). In the case of foveal vision loss, the above-mentioned visual exploration deficits and the ensuing need for top-down controlled search may deprive observers of the necessary attentional and working memory resources needed for successful search guidance by learned spatial patterns.

In the current experiment, a learning phase, during which observers' vision was impaired by a gaze-contingent scotoma simulation was followed by a test phase, during which the scotoma simulation was removed to allow normal visual search. If vision loss interferes with the expression of spatial contextual learning, but leaves the incidental learning of spatial configurations intact, we expected contextual cueing to be reduced or absent during the learning phase, but to reappear in the test phase. In contrast, if

search with a scotoma prevents the incidental learning of spatial configurations, no contextual cueing should be observed in either the learning phase or the test phase.

As mentioned, there is evidence that the spatial configuration in the vicinity of the target contributes most to the contextual cueing effect (Bellaera et al., 2014; Brady & Chun, 2007; Olson & Chun, 2002). This translates loosely to the area of foveal vision when the observer has foveated the target at the end of a successful search. If the snapshot-like learning hypothesis outlined above is true, loss of foveal vision may be more detrimental to contextual cueing than an otherwise equally severe peripheral scotoma. In contrast, if vision loss interferes with the expression of contextual learning rather than learning per se, increased exploration difficulties with a severe peripheral scotoma may lead to equally severe loss of contextual cueing as with a central scotoma (Zang, Jia, Müller, & Shi, 2014).

Furthermore, Brady and Chun (2007; Experiment 4) observed that contextual cueing by repeated local patterns (in the quadrant of the target location) was abolished when this invariant quadrant was allowed to shift locations from trial to trial. They concluded "not only is the local context important for such contextual cuing but also its place relative to the global context" (p. 814). If search is restricted by a peripheral scotoma, creating tunnel vision, this integration of an invariant local context with the global context of the display may be compromised, potentially creating problems not only for the expression of learning of repeated spatial contexts but for the learning of these contexts itself.

In summary, the available evidence favors diminished expression of learning of repeated spatial contexts in search with a central scotoma, rather than impaired learning of these contexts. Therefore, we expected contextual cueing to be reduced or absent in search with a simulated central scotoma, but to recover when the central scotoma is removed. There is less evidence regarding potential deficits of contextual cueing in search with a peripheral scotoma. Search with tunnel vision should interfere less with learning of local context around the target than central scotoma simulation, but may prevent the integration of local with global context, previously shown to be necessary for contextual cueing (Brady & Chun, 2007). Therefore, search with a peripheral scotoma may lead to reduced learning of spatial contexts that persists when the peripheral scotoma simulation is removed.

7.3. Materials and Methods

7.3.1. Participants

We collected data of overall 75 participants, randomly assigning 25 participants to each the control (13 females, no left handed, 25 years average age), central scotoma (17 females, 5 left handed, 25 years average age) and peripheral scotoma (17 females, 1 left handed, 23 years average age) conditions.

7.3.2. Apparatus

We used a 22-inch Samsung SyncMaster 2233RZ LCD monitor that was 474 mm (1680 pixels) wide and 296 mm (1050 pixels) high and the vertical refresh rate was 120 Hz. Responses were recorded with a ResponsePixx Handheld five button response box (VVPixx Technologies Inc.; <http://www.vpixx.com>). The stimuli were viewed binocularly from a distance of 85 cm leading to a pixel size of 0.019° of visual angle. The eye position was recorded using an Eyelink 1000 Desktop Mount (SR Research Ltd., Mississauga, Ontario, Canada) with a temporal resolution of 1000 Hz, using corneal reflection and pupil tracking. The gaze data retrieved for the gaze-contingent scotoma simulation were filtered by the heuristic 1 sample filter (Cornelissen et al., 2002; Stampe, 1993) implemented in the Eyelink software, removing single-sample noise artifacts.

7.3.3. Stimuli

For details about the stimuli used in the experiment see Section 2.3.2 Contextual cueing paradigm. Each search item subtended $1.05^\circ \times 1.05^\circ$ of visual angle (Figure 7.1). The offset at the junction of the two segments of the L-shapes was 0.13° of visual angle. The imaginary concentric circles used for creating the stimulus positions had radii of 2° , 4° , 6° and 8° of visual angle. The overall size of the search display on the screen extended a circular area with a diameter of 17.05° of visual angle.

The simulated central scotoma (moving mask technique Rayner & Bertera, 1979) was created as a circular patch colored the same gray as the background. The alpha channel of a quadratic gray texture spanning 9° of visual angle followed the slope of a Gaussian distribution with a deviation of 1, leading to a gradual transition from centrally fully visible to fully transparent at the borders. A concentric disk with a diameter of 7° of visual angle within the alpha channel was set to fully visible. Thus, the fully opaque size of the rendered scotoma extended 7° of visual angle, smoothly fading out at the edges. The scotoma was superimposed on the search display, covering approximately 28% of the search display corresponding to roughly 3.36 search items. As it was colored the same as the background, it was only perceptible when it covered a stimulus of a distinct color, making the masked part of the display invisible to the participant similar to the negative effect of a central scotoma.

The simulated peripheral scotoma (moving window paradigm McConkie & Rayner, 1975) was created similar to the central scotoma. We applied the same filtering procedures to the alpha channel of a quadratic subpart of the search display texture extending 9° of visual angle and centered on the current eye position. We then presented this rendered part of the stimulus texture superimposed on the gray background, updating its content based on the current gaze location. The fully visible size of the resulting circular window extended 7° of visual angle and smoothly faded out at the edges. Complementary to the central scotoma, roughly 3.36 search items were visible through the central tunnel. The moving window thus led to the impression of exploring subparts of the search display, centered around fixation, through a tunnel.

7.3.4. Procedure

Participants searched for a left- or right-tilted T among L-shaped distractors and indicated its orientation with button presses of the left and right index finger.

Each session started with a 13-point gaze calibration and validation and consisted of a short training to familiarize participants with the task, the main search experiment subdivided into a learn and test phase, and a subsequent recognition test. In the artificial central and peripheral scotoma conditions, the gaze-contingent scotoma simulations were present throughout training and the learning phase, except when instructions were presented on the screen. One session lasted approximately 60 to 90 min.

The other procedures were the same as in the first scotoma simulation experiment (see section 5.3.4 Procedure) except for the following differences. The main search experiment consisted of 25 blocks of 24 trials each. The first 20 blocks constituted the learning phase immediately followed by 5 test blocks. In the artificial scotoma conditions, search was carried out with the central or peripheral scotoma during the learning phase (Figure 7.1). During the test phase, the scotoma was removed. The control group performed the whole experiment under unimpaired viewing. Participants of the central and peripheral scotoma group were told before the experiment that the visual restriction would be removed at some point. This was done to prevent participants, for example, from interrupting the experiment because they may have assumed an error in the experimental or eye-tracking procedures. No details were given about when the removal of the visual restriction would occur. Before each block, spatial accuracy of the eye tracker was validated using 13 points. If the average deviation exceeded 1° of visual angle, participants were re-calibrated.

The recognition tests included the original 12 repeated and another 12 new randomly generated configurations presented in randomized order. The target T was replaced by a randomly oriented

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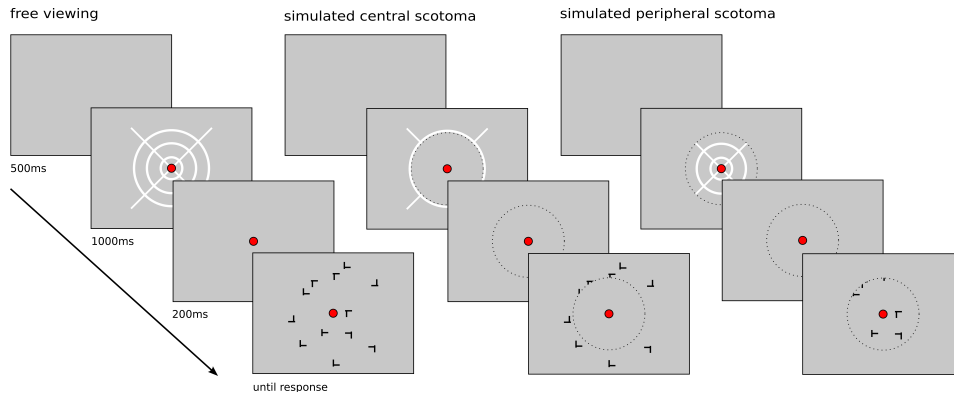


Figure 7.1.: Schematic diagram of an experimental trial for the control (left), central scotoma (middle) and peripheral scotoma (right) condition. Each trial consisted of a blank screen (500 ms), followed by the fixation stimulus (1000 ms) and another blank screen (200 ms) and the search display (presented until response). The red disk represents the hypothetical current location of the fixation and the black dashed circles the extent of the used central and peripheral scotoma. Neither of them were shown during the experiment.

distractor. In each trial, participants were first asked to indicate by button presses whether they had seen the display during the course of the experiment or not. Thereafter, participants were asked to replace one distractor with a randomly oriented, tilted white target T. They were asked to choose a position where they would most likely expect a target T in the given configuration. Only positions overlapping with distractors could be selected. Participants freely moved the target T with the mouse and when the target overlapped with a distractor its color was changed to black. Participants could then accept the chosen position by pressing the left mouse button. No feedback about the correctness of the response was given.

After the experiment was completed, participants were given a questionnaire. We assessed the difficulty, duration, concentration and adherence to start search from the center of the screen with rating scales to identify participants who may have performed the experiment under suboptimal conditions. Furthermore, the use of search strategies, quality of the simulation and general remarks were examined with open questions. If participants reported the use of search strategies, we asked them to specify how they searched the displays and whether they adhered to the strategy throughout the whole experiment.

Each participant of the central and peripheral scotoma group was randomly matched to one control participant prior to the beginning of the experiment. The participant of the central or peripheral scotoma group was given the same repeated and novel displays following the same presentation sequence as the matched control. Thus, each experimental configuration setup was used three times with only the viewing condition differing between unimpaired search, search with a central and a peripheral scotoma.

7.3.5. Data Analysis

Response accuracy as well as search time analysis and all statistical tests were carried out using R (version 3.0.2 R Core Team, 2013). Experimental blocks were aggregated to five epochs, each containing five blocks, in order to increase statistical power. Analyses of variance (ANOVAs) were performed using type III sums of squares. For all statistical tests, the alpha level was set to 0.05. We report partial eta squared (η_p^2) for comparison with studies using a similar design and generalized eta squared (η_G^2) for comparison with studies employing different designs (Bakeman, 2005; Lakens, 2013; Olejnik & Algina, 2003).

To investigate contextual cuing, we performed three-way mixed-design ANOVAs with the between-subjects factor experimental group (control, central scotoma, peripheral scotoma) and the within-subjects factors epoch (1,4) and configuration (repeated, novel) for the learning phase and two-way mixed-design ANOVAs with the between-subjects factor experimental group (control, central scotoma, peripheral scotoma) and configuration (repeated, novel) for the test phase. We included only the first and last epochs in the learning phase analyses to increase statistical power for detecting differences at the beginning, when contextual cueing effects should be small, and at the end, when contextual cueing should be most prominent (see also Geringswald et al., 2012). When the main factor experimental group or interactions including this factor were significant, we ran post-hoc Dunnett’s tests, comparing each scotoma group to controls. In the learning phase, we expected reduced contextual cueing development and increased search times in both scotoma groups and therefore used one-tailed post-hoc tests. All other post-hoc tests were two-tailed.

For the analysis of the recognition task and comparisons between the learning and test phases, we used normalized contextual cueing effects to control for individual differences in search difficulty. Normalized contextual cueing was obtained for each block by subtracting the search time for repeated from novel configurations and dividing this difference by the search time for novel configurations, that is, the individual baseline, and aggregated to five epochs.

The number of fixations and scan path efficiency were calculated as dependent measures from the fixation events (for details, see Section 5.3.5 Gaze Data analysis). In addition, we calculated the onset of the monotonic gaze path, characterizing the onset of a more direct path towards the target location after an initial inefficient search phase. The start of the monotonic search phase was calculated as the first fixation after which all following fixations approached the target monotonically. Each of these measures has previously been shown to carry information about contextual cueing. Typically, observers show less fixations, more efficient scan paths and an earlier onset of the monotonic gaze approach in repeated configurations, accompanying speeded response times (Brockmole & Henderson, 2006; Geringswald et al., 2012; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004).

7.3.6. Data Exclusion

Following the initial period of data collection, two participants of the control and eight participants of the central scotoma condition had to be replaced with new volunteers who performed the exact identical experiment, that is, they were given the same repeated and novel displays following the same presentation sequence. Two participants of the control and one of the central scotoma condition were replaced because they reported consistent systematic search (clockwise or counterclockwise search throughout the experiment) in the post-experimental questionnaire. Four participants of the central scotoma condition were replaced because their error rates exceeded the mean plus two times standard deviation of the central scotoma group (their error rates lay between 11.8 and 19.4%). Three further participants of the central scotoma condition were replaced because of highly variable response times (The standard deviation of their response times exceeded the mean plus two times standard deviation of the averaged central scotoma group).

As the reliable presentation of the gaze-contingent scotoma simulations depended on the availability of the gaze coordinates retrieved from the eye-tracker, we removed all search trials in which the amount of signal loss exceeded an individual threshold (mean percent signal loss plus two standard deviations of all trials performed by the participant) or a maximum threshold of 20%. This affected on average 1.59% ($SD = 1.38\%$), 2.34% ($SD = 1.98\%$), and 2.65% ($SD = 1.86\%$) of trials in the control, central and peripheral scotoma group. We further removed trials with search times shorter than 200 ms or exceeding the individual, recursively determined outlier threshold (Van Selst & Jolicoeur, 1994), affecting 2.19% ($SD = 0.88\%$), 4.67% ($SD = 2.73\%$), and 2.18% ($SD = 0.91\%$) of the remaining trials in the control, central and peripheral scotoma group. Search times and gaze parameters were only analyzed for correct responses.

7.4. Results

7.4.1. Learning phase

During the learning phase, we expected the typical development of contextual cueing, that is, search facilitation in repeated compared to novel displays, in controls. The central and peripheral scotoma simulations were expected to have immediate effects on general performance, making search overall more difficult, and to severely interfere with contextual cueing.

The three-way mixed-design ANOVA on accuracies did not indicate any potential speed-accuracy trade-offs regarding configuration type (none of the effects involving configuration was significant; all F s < 1 , all p s $> .52$, all η_P^2 s $< .02$, all η_G^2 s $< .003$). Accuracy was overall high (98.93, 92.70 and 98.55 % correct for controls, central, and peripheral scotoma respectively), but selectively reduced in the central scotoma group, experimental group, $F(2, 72) = 46.07$, $p < .001$, $\eta_P^2 = .56$, $\eta_G^2 = .400$; control versus central scotoma, $p < .001$; control versus peripheral scotoma, $p = .82$. Accuracy improved over time, epoch, $F(1, 72) = 17.44$, $p < .001$, $\eta_P^2 = .19$, $\eta_G^2 = .046$ and the magnitude of this improvement was significantly greater in the central scotoma group, experimental group \times epoch, $F(2, 72) = 9.20$, $p < .001$, $\eta_P^2 = .20$, $\eta_G^2 = .048$; 0.35, 3.76 and 0.48 % improvement for controls, central and peripheral scotoma respectively; control versus central scotoma, $p < .001$; control versus peripheral scotoma, $p = .98$.

Averaged search times for the five epochs of the learning phase for repeated and novel displays separated by viewing condition can be seen in Figure 7.2 and the mean differences between repeated and novel configurations are reported in Table 7.1. The three-way mixed-design ANOVA on search times yielded a significant main effect of experimental group, $F(2, 72) = 9.71$, $p < .001$, $\eta_P^2 = .21$, $\eta_G^2 = .185$. Responses were significantly faster in controls (1604ms) compared with the peripheral scotoma group (2038 ms), $p < .001$, whereas the difference to the central scotoma group did not reach significance (1790 ms), $p = .06$. The significant main effect of epoch, $F(1, 72) = 203.77$, $p < .001$, $\eta_P^2 = .74$, $\eta_G^2 = .181$ reflected general improvement from the first (1986 ms) to the last epoch (1635 ms). Neither the main effect of configuration, $F(1, 72) = 2.40$, $p = .13$, $\eta_P^2 = .03$, $\eta_G^2 = .002$ nor any of the three simple interactions were significant, all F s < 1.59 , all p s $> .21$, all η_P^2 s $< .05$, all η_G^2 s $< .003$. Importantly, the interaction between experimental group, epoch, and configuration was significant, $F(2, 72) = 3.14$, $p < .05$, $\eta_P^2 = .08$, $\eta_G^2 = .003$, indicating that contextual cueing differed between experimental groups. Post-hoc one-tailed Dunnett's tests showed that the development of contextual cueing from the first to the last epoch was significantly reduced in the central (39 versus 10 ms), $p < .05$, and peripheral (-8 versus -10 ms), $p < .05$, compared with the control group (3 versus 146 ms). Thus, in accordance with our previous study (Geringswald et al., 2012), search with a simulated central scotoma abolished contextual cueing. In agreement with a recent report (Zang et al., 2014), contextual cueing was also eliminated when peripheral vision was not available.

7.4.2. Test phase

In the test phase, the artificial scotoma simulations were removed and all participants could now explore the displays without any visual restriction. As an immediate consequence, performance converged on an equally high level for all experimental groups (non-significant main effect of experimental group, $F(2, 72) = 0.67$, $p = .52$, $\eta_P^2 = .02$, $\eta_G^2 = .009$; 99.10, 99.00 and 98.77 % correct for controls, the central, and peripheral scotoma group, respectively). Neither the main effect of configuration nor the interaction were significant, all F s < 1.64 , all p s $> .20$, all η_P^2 s $< .05$, all η_G^2 s $< .023$. The analysis of the learning phase clearly showed that the central as well as the peripheral scotoma disrupted contextual cueing, compared to unimpaired controls. The crucial question was whether this lack of contextual cueing was due to impaired learning of repeated configurations. If the scotoma interfered with learning, we would not expect any contextual benefits after its removal. If, on the other hand, contextual information

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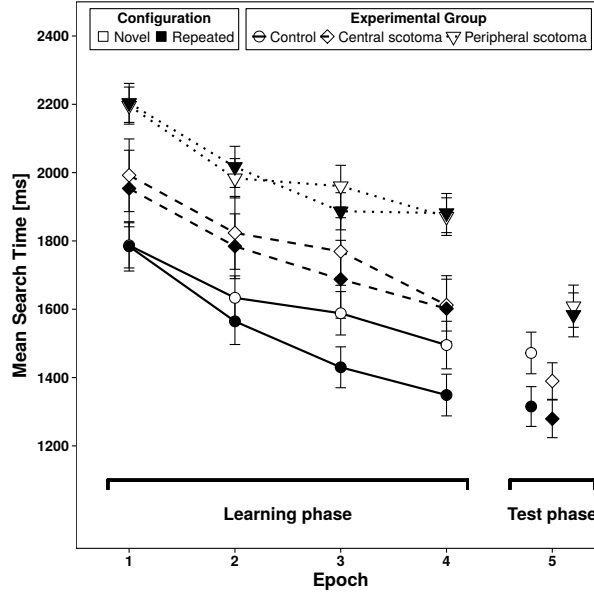


Figure 7.2.: Averaged search times for controls (circles), central scotoma (diamonds) and peripheral scotoma (triangles) separated for repeated (filled symbols) and novel displays (open symbols). During the learning phase, the scotoma groups viewed the displays either with a central or peripheral gaze-contingent scotoma while controls' vision was unimpaired. In the test phase, the artificial scotomata were removed. Error bars depict the standard error of the mean.

Table 7.1.: Mean difference between novel and repeated configurations.

Condition	Learning phase								Test phase	
	Epoch 1		Epoch 2		Epoch 3		Epoch 4		Epoch 5	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Search time (ms)										
Control	3	190	69	161	158	166	146	155	157	135
Central scotoma	39	224	39	215	81	249	10	258	111	136
Peripheral scotoma	-8	167	-33	188	74	241	-10	256	25	187
Number of fixations (counts)										
Control	0	0.75	0.27	0.63	0.61	0.64	0.59	0.64	0.65	0.54
Central scotoma	0.08	0.82	0.14	0.69	0.26	0.76	0.13	0.80	0.42	0.54
Peripheral scotoma	-0.02	0.59	-0.05	0.73	0.33	0.91	-0.04	1.04	0.13	0.81
Scan pattern ratio (quotient)										
Control	-0.01	0.89	0.31	0.66	0.51	0.58	0.50	0.62	0.6	0.52
Central scotoma	0.02	1.71	0.34	1.10	0.47	1.28	0.22	1.22	0.45	0.48
Peripheral scotoma	0.10	0.62	-0.03	0.65	0.22	0.64	-0.05	0.73	0.33	0.68
Onset of the monotonic scan path (counts)										
Control	0.03	0.72	0.29	0.63	0.60	0.65	0.58	0.62	0.69	0.52
Central scotoma	0.06	0.84	0.13	0.66	0.31	0.78	0.18	0.78	0.44	0.53
Peripheral scotoma	0.14	0.52	0.06	0.77	0.30	0.87	0.01	0.99	0.17	0.77

had been successfully learned, contextual cueing should emerge immediately after the removal of the scotoma.

Search times differed significantly between groups, experimental group, $F(2, 72) = 5.79$, $p < .01$, $\eta_P^2 = .14$, $\eta_G^2 = .130$, with overall comparable search times for controls (1394 ms) and the central scotoma group (1334 ms), $p = .68$, but slowed responses in the peripheral scotoma group (1596 ms),

$p < .05$. The main effect of configuration was also significant, $F(2, 72) = 29.84$, $p < .001$, $\eta_P^2 = .29$, $\eta_G^2 = .028$ due to overall faster responses to repeated (1393 ms) than novel configurations (1490 ms). Importantly, the interaction was significant, $F(2, 72) = 4.65$, $p < .05$, $\eta_P^2 = .11$, $\eta_G^2 = .009$, indicating group differences in contextual cueing. Post-hoc two-tailed Dunnett’s tests revealed that search benefits for repeated configurations were comparable between controls (157 ms) and the central (111 ms), $p = .47$, but significantly decreased in the peripheral scotoma group (25 ms), $p < .01$. An additional paired-sample t test comparing contextual cueing in the last epoch of the learning phase and the test phase (using normalized contextual cueing scores to account for the difference in search difficulty in the learning phase) was significant in the central scotoma group (-0.02 to 0.06), $t(24) = 2.48$, $p < .05$, confirming that contextual cueing amplified after the removal of the scotoma, but not for the peripheral scotoma group (-0.03 to -0.004), $t(24) = 0.82$, $p = .42$. These results indicated that while context information could still be learned with the central scotoma, this was not the case with the peripheral scotoma.

However, one potential source of the emergence of contextual cueing in the central scotoma group could have been new learning of repeated displays in the test phase. We therefore compared contextual cueing of the test phase, which should occur instantaneously after the removal of the scotoma, with contextual cueing in controls during the first epoch of the learning phase, where repeated configurations were initially learned. If repeated configurations were not newly learned, we expected significantly greater contextual cueing in the central scotoma group. A Welch t test on normalized contextual cueing scores, accounting for general search time differences, was significant, $t(47.71) = 2.73$, $p < .01$, revealing greater contextual cueing in the central scotoma group in Epoch 5 (normalized score: 0.06) than in controls in Epoch 1 (normalized score: -0.01).

During the learning phase, visual search with the peripheral scotoma was overall more difficult. This could potentially have reduced contextual learning. To investigate whether the absence of contextual learning in the peripheral scotoma condition was due to increased search difficulty, we reexamined the central scotoma group that clearly showed contextual learning. We performed a median split on the individual mean response times of the novel configurations in the last epoch of the learning phase to divide the central scotoma group into fast and slow searchers. A two-sample t test on search times for novel configurations was not significant, $t(33.31) = 0.87$, $p = .39$, between slow searchers with the central scotoma (1934 ms) and all participants of the peripheral scotoma group (1871 ms), indicating comparable search difficulty. We then reanalyzed contextual cueing in the slow central scotoma searchers. In the learning phase, results mirrored the previously reported disruption of contextual cueing. Only the main effect epoch was significant, $F(1, 11) = 19.56$, $p < .01$, $\eta_P^2 = .64$, $\eta_G^2 = .200$, indicating general learning, but neither the main effect of configuration nor the interaction were significant, all F s < 1 , all p s $> .46$, all η_P^2 s $< .06$, all η_G^2 s $< .002$. In the test phase, after the removal of the central scotoma, a paired t test on repeated and novel configurations confirmed contextual cueing, $t(11) = 2.48$, $p < .05$ (average benefit 116 ms). Thus, contextual cues could be learned under central vision loss, even in participants for whom search was equally slow as in the peripheral scotoma condition.

7.4.3. Recognition Test

To analyze explicit awareness of configuration repetition, we analyzed the euclidean distance between target placement and its actual position with a three-way mixed-design ANOVA with the between-subjects factor experimental group (control, central scotoma, peripheral scotoma) and the within-subjects factors configuration (repeated, novel) and the forced-choice response (repeated, novel). If participants became aware of the target-distractor associations, they should place the target closer to its actual position in repeated configurations, and perform most accurately in hit trials (repeated configurations correctly classified in the forced recognition task). Four participants of the peripheral and two of the central scotoma group were excluded because of missing data, for example, because they never responded "repeated" to a "novel" configuration. The only effect reaching significance was the interaction between experimental group and configuration, $F(2, 66) = 4.04$, $p < .05$, $\eta_P^2 = .11$, $\eta_G^2 = .026$, due to

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the peripheral scotoma group placing the target slightly closer to its true location in repeated than novel configurations (6.03 versus 6.94°), $p < .05$, than controls (7.30 versus 7.03°). The central scotoma group was not significantly different from controls (6.95 versus 6.47°), $p = .88$. The interaction between configuration and response failed to reach significance, $F(1, 66) = 3.43$, $p = .07$, $\eta_P^2 = .05$, $\eta_G^2 = .014$. Numerically, targets were placed slightly closer in hit than false alarm trials (6.43 versus 6.90°), however, this was not reliably different from generation accuracy when participants responded "novel" (6.73° in correct rejection and 7.16° in miss trials). None of the other effects were significant, all F s < 2.55 , all p s $> .08$, all η_P^2 s $< .08$, all η_G^2 s $< .024$.

These results hint towards some explicit awareness about the target position in repeated configurations. To investigate whether awareness was related to contextual cueing we correlated the normalized contextual cueing effects and the normalized proximity of target placement (the difference between the euclidean distance in novel and repeated configurations divided by novel configurations as the baseline) using Kendall's τ for each group. None of the correlations between awareness and normalized contextual cueing at the end of the learning phase, all absolute τ s $< .24$, all uncorrected p s $> .10$, nor in the test phase, all absolute τ s $< .08$, all uncorrected p s $> .60$, were significant.

7.4.4. Gaze data

The gaze data overall showed the same pattern as the search times, although in some instances, where significant differences were observed between search times, there were only trends in the gaze data. For better readability, we present the contextual cueing effects on the gaze data in Table 7.1 and the analysis in Table 7.2 and refer only to those findings that yield additional insights into how search with a scotoma affects contextual cueing.

Table 7.2.: Statistical results of the between-group analyses of contextual cueing in the learning and test phase for number of fixations, scan pattern ratio and monotonicity of the scan path.

Effect	Measure											
	Number of fixations				Scan pattern ratio				First fixation of monotonic path			
	F	p	η_P^2	η_G^2	F	p	η_P^2	η_G^2	F	p	η_P^2	η_G^2
Learning phase												
Group	12.11	<.001	.25	.221	8.31	<.001	.19	.158	3.77	<.05	.09	.079
Epoch	212.16	<.001	.75	.190	109.85	<.001	.60	.137	185.16	<.001	.72	.192
Configuration	2.89	.09	.04	.002	1.84	.18	.02	.001	5.97	<.05	.08	.004
Group \times Epoch	3.12	.05	.08	.007	14.02	<.001	.28	.039	3.89	<.05	.10	.010
Group \times Configuration	1.70	.19	.05	.002	0.45	.64	.01	<.001	1.08	.34	.03	.002
Epoch \times Configuration	3.53	.06	.05	.001	1.66	.20	.02	<.001	2.68	.11	.04	.001
Group \times Epoch \times Configuration	3.09	.05	.08	.002	1.73	.18	.05	.002	3.36	<.05	.09	.003
Test phase												
Group	5.93	<.01	.14	.132	5.15	<.01	.13	.114	5.61	<.01	.13	.124
Configuration	29.63	<.001	.29	.029	49.58	<.001	.41	.062	37.21	<.001	.34	.044
Group \times Configuration	4.17	<.05	.10	.008	1.45	.24	.04	.004	4.41	<.05	.11	.011

In the learning phase, we found numerically decreased development of contextual cueing in the central scotoma group (number of fixations: 0.08 to 0.13, scan pattern ratio: 0.02 to 0.22, onset of the monotonic path: 0.06 to 0.18) and the peripheral scotoma group (number of fixations: -0.02 to -0.04, scan pattern ratio: 0.10 to -0.05, onset of the monotonic path: 0.14 to 0.01) compared to controls (number of fixations: 0 to 0.59, scan pattern ratio: -0.01 to 0.50, onset of the monotonic path: 0.03 to 0.58). Compared to the control group, only the lack of contextual cueing improvement in the peripheral scotoma group in the onset of the monotonic path was significant (post-hoc Dunnett's test), $p < .05$.

In the test phase, contextual cueing was not significantly different between controls (number of fixations: 0.65, onset of the monotonic path: 0.69) and the central scotoma group (number of fixations: 0.42, onset of the monotonic path: 0.44; all $ps > .27$ compared to controls), whereas contextual cueing was absent in the peripheral scotoma group (number of fixations: 0.13, onset of the monotonic path: 0.17), all $ps > .008$, compared to controls. Contextual cueing increased significantly from the last epoch of the learning to the test phase in the central scotoma group (number of fixations: -0.04 to 0.06; onset of the monotonic path: -0.04 to 0.09), all $ts > 2.47$, all $ps < .02$, but not in the peripheral scotoma group (number of fixations: -0.04 to 0.002; onset of the monotonic path: -0.06 to 0.006), all $ts < 1.30$, all $ps > .20$. Scan pattern ratios showed a similar trend, were, however, not statistically reliable (controls, 0.60; central scotoma, 0.45; peripheral scotoma, 0.33).

The significant main effects of experimental group in the gaze measures indicated that search with the scotoma overall led to altered exploration patterns. To investigate these effects more closely, we performed one-way ANOVAs with the between-subjects factor experimental group on the number of fixation, fixation duration and saccade amplitude. We included only novel configurations of the last epoch of the learning phase, when observers had become accustomed to the scotoma (Figure 7.3). All effects were significant, all $F_s < 10.37$, all $p_s > .0001$ all $\eta_p^2_s > .22$, all $\eta_G^2_s > .223$. Search with the central scotoma led to a comparable amount of fixations (5.13 fixations), $p = .16$, with a significantly longer duration (331 ms), $p < .001$ and significantly increased saccade amplitudes (4.47° of visual angle), $p < .01$ than in controls (number of fixations: 5.83, fixation duration: 222 ms, saccade amplitude: 3.79° of visual angle). Searchers with the peripheral scotoma, in contrast, showed a significant increase in fixation numbers (7.06 fixations), $p < .01$, comparable fixation durations (220 ms), $p = 1$, and significantly decreased saccade amplitudes (3.27° of visual angle), $p < .05$.

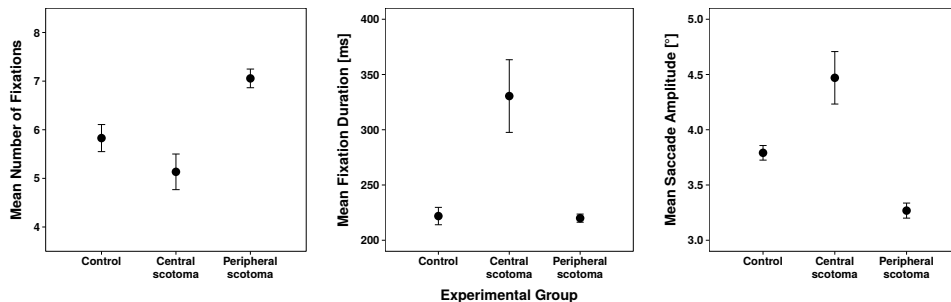


Figure 7.3.: Averaged number of fixations (left), fixation duration (middle), and saccade amplitude (right) of novel configurations in the last epoch of the learning phase as a function of experimental group. Error bars depict the standard error of the mean.

7.5. Discussion

We recently reported that central vision loss severely interferes with contextual cueing during visual search. The lack of contextual cueing was observed using central scotoma simulations (Geringswald et al., 2012) as well as in patients suffering from naturally occurring scotomata due to age-related macular degeneration (Geringswald, Herbig, Hoffmann, & Pollmann, 2013). A central question of the current study was to investigate whether central vision loss interferes with the incidental learning of spatial contextual cues or, alternatively, whether spatial contexts can still be learned, but not used for efficient search guidance in learned displays. Another central question was if foveal vision loss interfered with contextual cueing in a specific way that was different from peripheral vision loss. To investigate these questions, normal-sighted young observers completed visual search with a simulated gaze-contingent

scotoma – either central or peripheral – during an initial learning phase, analogous to our previous study (Geringswald et al., 2012). Critically, the scotoma was removed in a subsequent test phase. Data of the scotoma group were compared with a control group that completed both learning and test phases without any visual restriction.

Contextual cueing was, as expected, intact in the control group, manifested in faster search times in repeated compared to random stimulus configurations. This contextual cueing was not observed when search was impaired by the central scotoma in the learning phase, replicating our previous findings (Geringswald et al., 2012; Geringswald, Herbig, Hoffmann, & Pollmann, 2013). When the central scotoma was removed in the test phase, however, a reliable benefit for repeated configurations emerged. The magnitude of this contextual cueing was not significantly different from that of controls. Furthermore, it was larger than the magnitude of contextual cueing of non-scotomized search in the first epoch of the experiment, making it unlikely to be a result of new learning in the test phase. When observers had to carry out search with a simulated peripheral scotoma, analogous to search with the central scotoma, repeated contexts failed to improve search efficiency during the learning phase. In contrast to the central scotoma condition, however, no contextual cueing was observed when the peripheral scotoma was removed to allow unimpaired search in the test phase.

Thus, visual search in the presence of a simulated central scotoma led to deficits in the expression of learning, that is, incidentally learned spatial distractor configurations could not be used for the efficient guidance of search in repeated displays as long as the central scotoma was present. The reinstatement of contextual cueing after the central scotoma was removed, however, showed that the target-distractor configurations had been learned during search with the gaze-contingent central scotoma simulation. In contrast, simulation of an annular peripheral scotoma (the reverse of the central scotoma) leading to tunnel vision, abolished contextual cueing not only in the presence of the scotoma, but also after its removal, indicating that tunnel vision prevented the learning of repeated target-distractor configurations.

7.5.1. Central vision loss selectively impairs the expression of contextual learning

We had hypothesized that a central scotoma might interfere with contextual cueing in two different ways. One intuitively plausible hypothesis was that the local distractor pattern in the vicinity of the target was incidentally learned at the end of a successful search trial, when the observer foveates the trial. A central scotoma was expected to interfere with this learning more than a peripheral scotoma, by preventing foveation of the target and its environs. Although plausible, this hypothesis was not supported by the data. Learning of contextual cues was still possible in the presence of a central scotoma, that is, when only the peripheral visual field could be used. It has previously been reported that repeated contexts can be learned if attention is diverted away from the repeated distractors (Jiang & Leung, 2005). However, the study by Jiang and Leung differed from the present study in that attention was drawn to differently colored, but spatially intermixed subsets of distractors. The current experiment adds to this finding in that incidental learning of target-distractor patterns does not need to rely on the foveation of the target and its surround which in normal search accompanies the deployment of attention towards the target region (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995).

While incidental learning of spatial contexts was still possible, the use of learned displays for the efficient guidance of visual search was severely disrupted in search with a central scotoma. We have argued that the normally effortless exploration of the environment becomes more strongly top-down controlled in the presence of a scotoma (Geringswald et al., 2012). Patients with foveal vision loss will quickly learn to shift their gaze to view a target with a part of their extrafoveal retina that has remained intact. However, it may take years until an extrafoveal location becomes a reference point for saccades, that is, that saccades are programmed such that the saccade target does fall into this extrafoveal area instead of the fovea (von Noorden & Mackensensen, 1962; White & Bedell, 1990; Whittaker et al., 1991). Even in young normal-sighted observers, learning to rereference a saccade to an extrafoveal non-

scotomized spot on the retina takes a few hours of visual search training with simulated gaze-contingent central scotoma, even when learning is facilitated by making the extent of the scotoma clearly visible, in contrast to our scotoma simulation, that made stimuli disappear into the background (Kwon et al., 2013; Walsh & Liu, 2014).

It might be argued that a lack of saccadic rereferencing alone may be enough to explain the contextual cueing deficit with a central scotoma, because a saccade towards the target that is facilitated by a learned spatial pattern in a repeated display will land the target within the scotoma, making one or several corrective saccades necessary to bring it into a visible part of the visual field. We think, however, that this explanation is unlikely to account for the loss of contextual cueing, because the more efficient scan path in repeated displays (Brockmole & Henderson, 2006; Geringswald et al., 2012; Manginelli & Pollmann, 2009; Peterson & Kramer, 2001; Tseng & Li, 2004) should still enable shorter search times compared with random search in a display, because corrective saccades will also be necessary after every saccade during random search in a novel display. It might even lead to an added disadvantage in novel displays, because more saccades to non-target locations will be carried out on average, each requiring corrective saccades to bring the saccade target location into vision. The perhaps strongest argument against this scenario is that we did not observe more fixations for search with a central scotoma than without. Instead, the gaze data show a somewhat reduced number of fixations of longer duration (Figure 7.3). This pattern is more compatible with a top-down controlled, rather slow search, perhaps with a larger attentional focus than in unimpaired search. An increased attentional focus would be compatible with the increased saccade length that we observed in the central scotoma group.

Top-down controlled search has been shown to reduce contextual cueing (Lleras & Von Mühlenen, 2004). This may simply be due to following a fixed search path (for example, a reading pattern: line by line from top left to bottom right) that eliminates any search advantage that could be gained by knowing the target location. However, those of our participants who reported a systematic search strategy were excluded from analysis.

Another reason for the reduction of contextual cueing by top-down controlled search may be that top-down controlled search goes along with higher visuospatial working memory load. It has been shown that the expression of spatial context learning depends on the available attentional and visuospatial working memory resources (Manginelli et al., 2012; Manginelli, Langer, et al., 2013; Travis et al., 2013; Vickery et al., 2010). Whereas learning was not dependent on attending the informative distractor subset in the study by Jiang and Leung (2005), the later search guidance by learned spatial patterns did depend on attending the informative subset. Likewise, adding a visuospatial working memory load during search did not prevent contextual learning but interfered with using learned patterns for search guidance (Annac et al., 2013; Manginelli et al., 2012; Manginelli, Langer, et al., 2013). Top-down controlled scanning of the environment affords keeping the already scanned parts of the environment in working memory. This may very quickly compete with the retrieval and maintenance of the learned search pattern and its comparison with the current display that is necessary to obtain the context-guided search advantage in repeated displays. Moreover, brain activation has been found during expression of learning – but not during learning itself – in brain areas whose activation in a separate delayed matching task reflected visual working memory capacity (Manginelli, Baumgartner, & Pollmann, 2013). Taken together, the behavioral and brain imaging data suggest quite strongly an important role for working memory-dependent processes in the guidance of visual search by learned contexts. Thus, loading visuospatial working memory by top-down controlled search may be at least one factor contributing to the loss of contextual cueing in search with a central scotoma simulation.

Does such a more top-down controlled search strategy lead to more explicit learning of spatial configurations? The data do not support this assumption. The recognition test did not provide any reliable evidence that central scotoma search led to explicit memory of repeated displays. In fact, only the peripheral scotoma group placed the target slightly closer to its actual position in repeated configurations. However, this difference was very small (0.91° of visual angle) given that the target was, on average, placed 6.03° of visual angle away in repeated configurations. Furthermore, the advantage in repeated

configurations was not correlated with the size of contextual cueing in any group.

7.5.2. Peripheral vision loss impairs the learning of spatial contexts

We contrasted the impact of central vision loss with a reverse scotoma simulation, in which the area covered by the central scotoma was visible but the more peripheral parts of the visual field were made invisible. The resulting tunnel vision obviously compromises exploration of the search display, but in a different way than a central scotoma. Thus, for much the same reasons as for the central scotoma simulation, we expected that visual search with a peripheral scotoma would lead to increased demands on visuospatial working memory which in turn would reduce the expression of contextual learning.

However, we observed that the peripheral scotoma simulation even prevented the learning of spatial contexts. At first sight, it may appear odd that incidental spatial configuration learning is possible in the periphery – with central scotoma simulation – but not with foveal vision, when the periphery is blocked out. Previous reports have emphasized the dominant role of the local configuration in the vicinity of the target for contextual cueing. In contrast, the elimination of contextual learning in the peripheral scotoma condition emphasizes the role of the global context for contextual cueing. As outlined in the introduction, this was not completely unexpected. Contextual cueing was eliminated when only the target quadrant contained repeated distractor configurations and this quadrant was allowed to switch positions with the other quadrants between trials (Brady & Chun, 2007; Experiment 4). In the model by Brady and Chun, absolute locations in the configuration are encoded, not relative locations to the target. Such an encoding scheme could explain two aspects of our data. On the one hand, it could explain why the peripheral scotoma prevents efficient location coding, because the borders of the configuration are not visible respectively they change from each saccade to the next, making location coding in a common display configuration impossible. On the other hand, the model predicts that encoding of local configurations relative to the target – for example, when foveating the target at the successful completion of search – is not important for contextual cueing. In agreement with the model, we found no evidence that foveation of the target is necessary for contextual cueing, as discussed in the previous section.

In previous studies of local versus global contributions towards contextual cueing, the informativeness of local versus global context was varied. However, even if only a fraction of display items near the target was repeated and all other items were randomly assigned to their positions within the display, contextual cueing only occurred if the local configuration roughly kept its position within the whole display (for example, remained in the same quadrant, Brady & Chun, 2007; Olson & Chun, 2002). Our data may imply that for repeated configurations to be learned as instances of the same display, the display as a whole must be visible, at least for a brief moment, as shown by the benefit of a brief preview of the periphery before tunnel vision simulation in the recent study by Zang et al. (2014). This brief preview enabled contextual cueing that was not observed without this preview of the periphery.

It may be argued that learning was absent with the peripheral scotoma because this search was most difficult, leading to the longest search times. However, when we compared the peripheral scotoma group with the slowest observers in the central scotoma group, the difference between absent versus present contextual cueing during the test phase was still present, although overall search times were comparable.

Our data agree with a recent study of contextual cueing with gaze-contingent tunnel vision simulation (Zang et al., 2014). In their experimental condition most similar to ours, tunnel vision with a visible diameter of 8° of visual angle prevented contextual cueing, whereas a larger tunnel of 12° of visual angle diameter did not do so. This comparison shows that contextual cueing can occur if the remaining tunnel vision is sufficiently wide. Zang et al. (2014) also found that contextual cueing was reinstated after search with the 8° of visual angle diameter tunnel in a subsequent non-scotomatous test phase, in contradistinction to our data. As both display size and tunnel diameter were very similar in the present study and that of Zang et al. (2014) there must be a more subtle distinction between these studies, such as the probability of target occurrences in the center or periphery that may have caused this difference.

One interesting question is in how far adverse effects of central and peripheral scotomization on contextual cueing could be reduced by training. It appears that patients with a central scotoma may profit more from a training regime than patients with tunnel vision, because spatial configuration learning is still intact and automatization of peripheral exploration strategies may reduce the burden of top-down controlled scene exploration on visual attention and visuospatial working memory capacity. While adaptation of exploration strategies to scotomatous vision has been reported to be slow in many patients, recent scotoma simulation experiments with young normal-sighted observers reported efficient use of a preferred peripheral retinal location after only few hours of training (Kwon et al., 2013).

7.5.3. Conclusion

Using gaze contingent scotoma simulation techniques, we have shown that both central and peripheral scotomata can lead to impaired contextual cueing in visual search, affecting, however, very different processes. Central scotoma simulation left the incidental learning of repeated spatial configurations intact, but interfered with the expression of learning for efficient search guidance in learnt displays. This is most likely due to the more top-down controlled search with central scotoma simulation interfering with visual working memory dependent processes needed for memory-guided search in contextual cueing. In contrast, tunnel vision induced by peripheral scotoma simulation disrupted already the learning of spatial configurations, due to the inability to link the visible local configurations to the larger layout of the display.

While we have previously shown that foveal vision loss in patients suffering from AMD leads to reduced contextual cueing, the current data suggest that patients with tunnel vision, for example, caused by retinitis pigmentosa or glaucoma, may be even more at risk to suffer from contextual cueing deficits. The contextual cueing deficit already observed in AMD patients and potentially also in patients with retinal diseases affecting peripheral vision demonstrates the need for scientific exchange between researchers investigating high-level vision and related cognitive processes, such as visual learning and memory, on the one hand and ophthalmologists on the other hand.

8 General Discussion

Does the loss of central vision impair higher-level visual memory functions that depend on the efficient deployment of attention? This question was at the core of the experiments presented in this thesis. Because intelligent interaction with our environment requires selection, impaired deployment of visual attention would severely compromise adaptive behavior. The research question addressed by this thesis is therefore highly relevant to patients suffering from central vision loss (age-related macular degeneration, AMD). A potential impairment in higher-level visual function that depends on attentive selection would be an additional burden, beyond basic visual deficits that go along with the disease (Hogg & Chakravarthy, 2006; Neelam et al., 2009).

In normal viewing, attentive stimulus processing is carried out with high-resolution foveal vision. Attentional selection is therefore closely tied to eye movements (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995). Attentive foveation leads to encoding of detailed object representations into visual long-term memory (VLTm, Hollingworth, 2006) and when predictive contexts that have been learned during past experience are encountered in the future guidance of attention and gaze speeds up the detection of target objects (Chun, 2000; Chun & Jiang, 1998). The close tie between the allocation of attention and subsequent foveation in normal viewing becomes a problem for patients who suffer from central vision loss. Attentive processing has to be carried out with the remaining peripheral vision. In addition to difficulties imposed by reduced spatial resolution and interference by crowding, a new oculomotor reference that can be used to fixate objects eccentrically needs to be established (preferred retinal locus, PRL). Although a PRL can develop in patients with a central scotoma within a short period of time (Crossland et al., 2005), efficient eye movement control remains a challenge for most patients (Crossland et al., 2004; White & Bedell, 1990). The impact of reduced eye movement control has been documented across different tasks in vision research. For instance, reading rates are slowed due to fixation instability and the need for additional saccades (Crossland et al., 2004; Falkenberg et al., 2007; McMahan et al., 1991; Rayner & Bertera, 1979), and visual search becomes more cumbersome due to inefficient scan paths (Cornelissen et al., 2005; Van der Stigchel et al., 2013). But even when eye movement requirements are minimized, reading rates remain inferior (Cheong et al., 2008; Legge et al., 2007; Legge et al., 2001). Furthermore, deficits in word and face recognition, tasks that depend on the integration of individual features, are correlated (Bullimore & Bailey, 1995) indicating that the efficient allocation of attention to a stimulus may suffer in AMD.

The experiments presented in this thesis investigated whether central vision loss may impair efficient encoding of natural objects into VLTm (Experiments 1 and 2) or facilitation of visual search for a target in repeated invariant contexts (Experiments 3, 4, and 5). These processes critically depend on the efficient allocation of attention in normal vision. Performance was compared between patients with AMD and age-matched healthy controls. Complementary experiments compared performance under gaze-contingent central scotoma simulation to unimpaired vision in younger observers who were unexperienced with central vision loss.

8.1. Summary and results

Experiments 1 and 2 investigated attentive memory encoding of every-day objects, embedded within complex computer-generated natural scenes, with a change detection task. The main question was whether encoding of objects into VLTm, which has been shown to depend on attentive foveation in normal vision (Hollingworth, 2006), can be efficiently relocated to peripheral vision. Participants were asked to memorize all objects within a scene during a period of free scene exploration. At the end of this period, a salient onset cue was used to capture attention to a non-target location in half of the trials, to ensure that change detection in a subsequent test scene had to rely on memory. In the test scene, a post-cue was used to indicate the test object, minimizing retrieval and comparison demands. Target objects were replaced with a similar object from the same semantic category (token change) in half of the trials. Eye movements were measured throughout all experimental sessions.

In Experiment 1 (Chapter 3), change detection accuracy and eye movements of AMD patients performing the task with their worse eye and under binocular vision was compared with healthy age-matched controls. In both viewing conditions, patients' sensitivity to object changes was comparable to controls and did not correlate with visual acuity. This pattern did not change after removing trials with less than four intervening fixations, ensuring that performance had to rely on VLTm, and efficient attentional capture by the salient onset was confirmed via eye movement analysis. Normal VLTm performance furthermore went along with normal eye movement parameters. In general, the number and duration of fixations was comparable between patients and controls, and this was equally the case specifically for the target region. Visual acuity, however, correlated negatively with fixation number and positively with fixation duration. More severely impaired patients may therefore have adapted their exploration behavior to sustain efficient VLTm encoding.

The first experiment suggested that when viewing natural scenes, AMD patients were able to successfully adapt their exploration behavior. Efficient rereferencing of eye movements may have allowed to use an extrafoveal PRL as a focus of attention for efficient object encoding into VLTm. Intact VLTm encoding in AMD patients may, however, simply have been due to the fact that attentive encoding of objects into VLTm does not require foveation, as long as observers have sufficient time to allocate attention to the periphery. To rule out this alternative explanation, Experiment 2 (Chapter 4) investigated VLTm encoding with the same paradigm in young healthy observers who were unexperienced with central vision loss. Memory performance under gaze-contingent central scotoma simulation was compared to unimpaired young observers. Three different scotoma types were tested. We implemented a fully opaque scotoma and a more subtle warp scotoma extending across foveal and parafoveal vision and a smaller fully opaque scotoma diminishing specifically foveal vision. Change detection performance was significantly impaired in the simulations with the larger scotomata and the foveal scotoma led to a marginally significant decrease of VLTm performance. Overall, however, change detection performance remained well above chance with all three scotoma simulations. All three scotoma types lead to significantly increased saccade amplitudes and there was a tendency for decreased fixation number and increased fixation duration in the simulations with the larger scotomata, reflecting the need to adapt exploration in the presence of central vision loss. The results suggest that foveation is not a necessity to encode objects into VLTm, but that the quality of VLTm under central vision loss suffers as long as successful saccadic rereferencing has not yet developed.

Experiments 3, 4, and 5 investigated incidental learning of contextual regularities and attentional guidance during visual search with the standard spatial contextual cueing paradigm (Chun & Jiang, 1998). Observers had to search for a target T-shape under L-shape distractors and, unbeknownst to the observers, half of the search displays were repeated throughout the experiment. The main question was whether efficient guidance of attention, going along with more efficient exploration of the displays with eye movements, becomes impaired when central vision is lost. Eye movements were measured during all experimental sessions. In all three experiments, we replicated the expected pattern of search facilitation

in repeated displays in younger observers under normal viewing and in healthy older controls.

In Experiment 3 (Chapter 5), we had healthy younger observers perform the contextual cueing task once under free viewing and once with a gaze-contingent central scotoma. Under free viewing, efficient attentional guidance by repeated displays lead to reduced search times, fixation numbers and shorter scan paths compared to random search arrays. The simulated central scotoma abolished these effects completely and made eye movement control less efficient. Surprisingly, observers with the simulated scotoma did not increase the number of fixations when exploring the search displays. Inefficient exploration was reflected by longer scan paths, suggesting that fixations were placed more strategically. Such strategic eye movement planning may well have interfered with stimulus-driven attentional guidance in repeated contexts, preventing the emergence of contextual cueing.

Could adaptation of visual exploration to central vision loss in more experienced AMD patients compensate for the contextual cueing deficits observed in unexperienced controls? Experiment 4 (Chapter 6) was set out to investigate this question. The same visual search experiment was carried out with the patients under monocular vision with their worse eye as well as under binocular vision. Performance was compared with healthy age-matched controls. In contrast to VLTm encoding of natural objects, contextual cueing deficits could not fully be compensated for in AMD patients. Impairment was most evident when only the more severely affected eye was used for search and the magnitude of contextual cueing was correlated with visual acuity. When both eyes could be used for visual search, the better eye could compensate to some degree, allowing for some residual contextual cueing, but effects were still smaller than in healthy controls.

Experiments 3 and 4 indicated that central vision loss interferes with attentional guidance in contextual cueing. However, it is not clear whether the learning of repeated displays becomes impaired, for example because critical parts of the displays are not perceived (Brady & Chun, 2007; Olson & Chun, 2002; Song & Jiang, 2005), or whether attentional guidance by learned displays fails under central vision loss, for example because search is more top-down driven (Lleras & Von Mühlenen, 2004). To investigate this question, we again simulated a central scotoma in healthy young observers and compared their performance with unimpaired controls in Experiment 5 (Chapter 7). However, we extended the contextual cueing paradigm with an additional test phase in which the simulated scotoma was removed. To test whether the encoding of the local context in the vicinity of the target suffices for contextual learning (Brady & Chun, 2007), we added a second experimental group that searched with a simulated annular peripheral scotoma during the learning phase, allowing only the centrally fixated part of the display to be visible. Behavioral and eye movement data from the learning phase of the central scotoma group replicated the results from Experiment 3 in that contextual cueing was completely abolished during the learning phase. When the central scotoma was removed, however, contextual cueing reinstated immediately. Search with the central scotoma did thus not prevent incidental learning of the contexts but severely interfered with attentional guidance, that is the use of learned contextual cues. In contrast, the peripheral scotoma eliminated contextual cueing during learning but when it was later removed in the test phase, contextual cueing remained absent. The peripheral scotoma thus prevented learning of the repeated displays altogether, suggesting that unimpaired perception of the global context in a search display is indispensable to integrate the perceived local contexts for contextual learning.

8.2. Discussion and implications

Age-related macular degeneration is becoming an increasingly important condition world wide (W. L. Wong et al., 2014). Damage to the photoreceptors in the macula gradually leads to irreversible central vision impairment, imposing a considerable burden on the patients that are often restricted in their capacity to accomplish many daily tasks. In the last decades, extensive efforts have been made to address the underlying causes of impaired reading ability (for review, see Chung, 2010) and face recognition (Bernard & Chung, 2016; Bullimore et al., 1991; He et al., 2015; Seiple et al., 2013) to eventually

help patients to compensate their difficulties with adapted stimulus material (Bernard et al., 2016; Peli et al., 1991) or eye movement training (Crossland et al., 2004; Nilsson et al., 1998, 2003; Seiple et al., 2005; Tarita-Nistor et al., 2009). The studies presented in this thesis enrich this research by asking the question whether higher-level cognitive memory function that depend on the efficient allocation of attention, may become impaired under central vision loss.

Memory for natural objects

A major finding of the experiments presented in this thesis is that encoding of natural objects into VLTM remains intact in patients with AMD (Experiment 1, Chapter 3). Attentive object encoding was as efficient in AMD patients, using their remaining peripheral vision, as in matched healthy controls who could use foveal vision to carry out the task. Our results therefore provide further evidence for the notion that previously attended objects can form rich representations in VLTM (Hollingworth, 2004, 2005) and do not support the view that the representation of a previously attended object is lost as soon as focused attention is withdrawn (for example, O'Regan & Noë, 2001; Rensink, 2002; Simons & Levin, 1997). In addition, our results extend these findings by showing that encoding of such memory representations can also be supported by peripheral vision. Based on the literature, this finding is quite surprising. Typically, only objects that are attended within foveal vision may form detailed memory representations (Hollingworth et al., 2001; Nelson & Loftus, 1980) whereas objects that are not foveated lead to chance performance in subsequent memory tests (Hollingworth, 2006; Hollingworth & Henderson, 2002). Furthermore, peripheral vision is usually involved in stimulus processing that is very different from such detailed attentive object encoding. Peripheral vision is specialized in texture segmentation (Joffe & Scialfa, 1995; Kehrer, 1989), scene gist recognition (Larson & Loschky, 2009), or object detection (Thorpe, Gegenfurtner, Fabre-Thorpe, & Bühlhoff, 2001), providing a rapid, but rather coarse representation of a visual scene. This rapid peripheral analysis subserves the guidance of foveal vision to potential target regions for detailed attentive stimulus processing (Rosenholtz, Huang, Raj, Balas, & Ilie, 2012; Torralba, Oliva, Castelano, & Henderson, 2006). In line with this view, the verification of the target identity in visual search in natural scenes, but not its localization, is slowed under central scotoma simulation in healthy observers (Miellet et al., 2010; Nuthmann, 2014). There is thus good reason to expect at least impairment to some degree in VLTM performance when attentive object encoding has to be relocated to peripheral vision. The data presented in Experiment 2 (Chapter 4) provides evidence in support of this hypothesis. The necessity of attentive foveation for object encoding in normal vision was clearly shown in young observers who were unexperienced with central vision loss. Even a small foveal scotoma lead to a numerical drop in change detection performance and VLTM encoding clearly suffered when parafoveal vision was diminished in addition. Attentive encoding of objects into VLTM was, however, not completely eliminated under simulated central vision loss. This residual memory encoding under scotoma simulation and the finding that attentive VLTM encoding remains intact in AMD patients (Experiment 1, Chapter 3) highlights the potential of our visual system to adapt efficient visual behavior when foveal vision becomes compromised. The results presented in our experiments show that the capability of peripheral vision can go far beyond the coarse representation of a visual scene. These findings are of considerable importance to patients suffering from AMD. They demonstrate that VLTM function that normally depends on foveal vision can be compensated when the efficient use of an extrafoveal PRL allows for the allocation of attentive object processing to peripheral vision.

The success of attentive object encoding with an extrafoveal PRL will likely be limited with increasing vision loss. A steady decrease of visual resolution and increase of crowding, going hand in hand with complicated use of a PRL, will make scene exploration more and more difficult, and eventually impair efficient allocation of attention for object encoding in the periphery. For example, substantial problems in face recognition tasks have repeatedly been demonstrated (Barnes et al., 2011; Bernard & Chung, 2016; Bullimore et al., 1991). It has been suggested that face recognition, in particular face identity

recognition that requires encoding of fine differences such as the distance of the eyes or the shape of the nose and mouth, may be limited by crowding of internal facial features (Bernard & Chung, 2016; He et al., 2015). AMD patients may show similar impairments in object encoding when perception of the object becomes more difficult with progression of the disease. Future research should therefore investigate the limits of attentive object encoding under central vision loss in more severely affected patients. These experiments could be complemented by scotoma simulation in healthy observers. Recently, powerful training regimes have been developed that allow for efficient rereferencing of eye movements to a PRL after only five hours of training (Kwon et al., 2013; Walsh & Liu, 2014) and training has been shown to improve letter recognition, reading speed and the deployment of spatial attention at the trained PRL location (Liu & Kwon, 2016). Such training could allow to test attentive object encoding at different PRL eccentricities to map out the potential of peripheral vision to compensate for central vision loss in more detail.

Incidental memory for spatial regularities in contextual cueing

The second major finding of the experiments presented in this thesis is that loss of central vision significantly impairs the efficient guidance of attention by contextual memory. This deficit was demonstrated consistently under simulated central vision loss in unexperienced observers (Experiment 3, Chapter 5; Experiment 5, Chapter 7), but also under naturally occurring central vision impairment in AMD patients in whom contextual cueing deficits were especially pronounced in more severely affected patients. (Experiment 4, Chapter 6). In Experiment 5 (Chapter 7) we extended these findings by demonstrating that the lack of contextual cueing was in particular due to the inefficient use of contextual cues.

These result fit in well with the literature on contextual cueing. Converging evidence suggests that the guidance of attention by learned invariant environments may not be as automatic as initially assumed (Chun & Jiang, 1998). In particular, selective attention to the predictive search items (Jiang & Chun, 2001; Jiang & Leung, 2005), the availability of visuospatial working memory (WM) resources (Annac et al., 2013; Manginelli, Baumgartner, & Pollmann, 2013; Manginelli et al., 2012; Manginelli, Langer, et al., 2013; Zhang et al., 2011; for review, see Pollmann, 2019), and search strategies that are not controlled in a voluntary manner (Lleras & Von Mühlenen, 2004) are fundamental for the efficient expression of contextual cueing. We expand these findings by showing that central vision impairment also compromises the efficient use of contextual cues, very likely by an interaction of these factors. First, in the scotoma simulation studies reported in this thesis, inefficient exploration behavior very likely reflects a top-down controlled search strategy. Second, because search with a simulated scotoma is more cumbersome, observers may actively inhibit saccades to stimuli in the periphery, thus impairing attentional processing of predictive search items at the inhibited location (Dhawan et al., 2013). Third, visuospatial WM may be occupied by maintaining recently inspected locations (for example, B. S. Gibson et al., 2000; R. M. Klein, 1988; Kristjánsson, 2000; Müller & von Mühlenen, 2000; Takeda & Yagi, 2000) or become disrupted by the voluntary planning of fixation locations (Postle, Idzikowski, Sala, Logie, & Baddeley, 2006; Theeuwes, Belopolsky, & Olivers, 2009), leaving not enough resources to match the current search display with learned repeated configurations.

Learning of the repeated contexts, on the other hand, was unimpaired in search with a simulated central scotoma (Experiment 5 Chapter 7). This strongly suggests that learning of spatial context does neither depend on the availability foveal vision nor on efficient automatic eye movement control. These results support the notion that contextual learning is a genuine form of incidental learning that does not require selective attention (Jiang & Leung, 2005) or visuospatial WM (Annac et al., 2013; Manginelli, Langer, et al., 2013; Vickery et al., 2010). This learning may even survive rough disturbance of the context as may be experienced during search with a central scotoma, as long as individual distractors can become associated with the target location. When distractor locations can not be associated with target position, however, learning of contextual cues becomes impossible as indicated by the tunnel vision simulation.

In patients suffering from AMD, visual exploration has become more automatic and efficient rereferencing of eye movements to an extrafoveal PRL may allow for the residual contextual cueing observed in Experiment 4 (Chapter 6). However, the exploration of artificial arbitrary search displays may remain cumbersome (Van der Stigchel et al., 2013) and impair efficient attentional guidance. It has been hypothesized that PRL usage depends on the demands of the specific visual task (Lingnau et al., 2014; Lingnau et al., 2008, 2010). Because searching for tilted T-shapes is likely an unusual activity for AMD patients, patients may have used an inefficient PRL for the contextual cueing task, especially when they were restricted to their worse eye. It will thus remain an interesting question for future research whether longer exposure to the search task or the use of stimuli that correspond more closely to our natural environment will allow for efficient contextual cueing in AMD patients.

Based on the result that learning of contextual cues was successful in unexperienced younger observers who had considerable difficulties with visual exploration of the displays with the simulated central scotoma (Chapter 7), it seems very likely that AMD patients who showed residual contextual cueing (Experiment 4, Chapter 6) also acquired contextual memory during search. A careful investigation of this issue remains to be carried out, however. For example, patients with large interocular differences in disease progression could perform a learning phase with their more severely affected eye and switch to the better eye during a test phase. The literature suggests that contextual cueing is mediated by higher-level top-down memory-enhancement of the allocation of attention during search (Chaumon, Hasboun, Baulac, Adam, & Tallon-Baudry, 2009; Giesbrecht, Sy, & Guerin, 2013; Johnson, Woodman, Braun, & Luck, 2007; Olson, Chun, & Allison, 2001) and transfers to perceptually modified search displays (Chun & Jiang, 1998; Jiang & Song, 2005; Jiang & Wagner, 2004). Contextual learning should therefore be transferable between both eyes, allowing to test whether the results from the simulation studies can be generalized to the patient population.

In addition to the theoretical contributions that are provided by the contextual cueing experiments presented in this thesis, the results are also highly important for patients suffering from AMD. Attentional guidance by contextual memory is an adaptive behavior that enables efficient interaction with our environment. When guidance by contextual cues is impaired, the cognitive system has to allocate additional resources to find a target object and the search process becomes more cumbersome. This may well affect daily actions in the patients' life that involve visual search. Reduced visual acuity and crowding can make object identification more difficult. Relying on efficient guidance by incidental memory should therefore be even more beneficial for the patients. Future research should thus address the question, in how far the reported deficits in contextual memory guidance can be compensated, for example by the development of effective training regimes. Eye movement training has substantial effects in reading speed, especially when training targeted fixation stability and saccade control (Crossland et al., 2004; Nilsson et al., 1998, 2003; Seiple et al., 2005; Tarita-Nistor et al., 2009). Contextual cueing could be used as an additional outcome measure in training studies to investigate whether training of eye movement control generalizes to efficient guidance of attention in learned contexts, potentially by reducing competition for visuospatial working memory capacity.

8.2.1. Conclusion

The experiments presented in this thesis provide evidence that loss of central vision can affect higher-level visual memory processes that depend on attentive foveation in normal vision in different ways. While encoding of objects into visual long-term memory can be compensated, automatic guidance of attention in familiar environments is impaired. A major factor for the successful use of remaining peripheral vision is the efficient rereferencing of eye movements to an extrafoveal retinal location as a focus of attention. In observers unexperienced with central vision loss, efficient rereferencing has not yet developed and VLTM encoding as well as search facilitation in repeated invariant contexts is impaired. In patients with age-related macular degeneration, rereferencing may require more top-down controlled visual exploration when the resolution of remaining vision becomes a limiting factor. This does not

impair attentive object encoding into memory. Potential competition for visuospatial working memory capacity, however, reduces efficient guidance of attention by learned contextual cues. These results may contribute to improve training regimes that help patients to better cope with their visual deficits in everyday life. In addition, the results may raise awareness in clinicians and researchers that impairment of higher-level visual processes which are more subtle and may therefore not be reported by the patients may suffer in AMD and should be subject to further research.

References

- Abramson, D. H., & Abramson, H. S. (2002). High-dose supplements for age-related macular degeneration: Did you leave out centrum? *Archives of Ophthalmology*, *120*(11), 1602.
- Altpeter, E., Mackeben, M., & Trauzettel-Klosinski, S. (2000). The importance of sustained attention for patients with maculopathies. *Vision Research*, *40*(10-12), 1539–1547.
- Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science*, *15*(2), 106–111.
- Ambati, J., & Ambati, B. K. (2002). Age-related eye disease study caveats. *Archives of Ophthalmology*, *120*(7), 997, author reply 997–997, author reply 999.
- Ambati, J., Ambati, B. K., Yoo, S. H., Ianchulev, S., & Adamis, A. P. (2003). Age-related macular degeneration: Etiology, pathogenesis, and therapeutic strategies. *Survey of Ophthalmology*, *48*(3), 257–293.
- Ambati, J., Atkinson, J. P., & Gelfand, B. D. (2013). Immunology of age-related macular degeneration. *Nature Reviews. Immunology*, *13*(6), 438–451.
- Ambati, J., & Fowler, B. J. (2012). Mechanisms of age-related macular degeneration. *Neuron*, *75*(1), 26–39.
- Annac, E., Manginelli, A. A., Pollmann, S., Shi, Z., Müller, H. J., & Geyer, T. (2013). Memory under pressure: Secondary-task effects on contextual cueing of visual search. *Journal of Vision*, *13*(13), 6.
- Anstis, S. M. (1974). Letter: A chart demonstrating variations in acuity with retinal position. *Vision Research*, *14*(7), 589–592.
- AREDS. (2001). A randomized, placebo-controlled, clinical trial of high-dose supplementation with vitamins C and E, beta carotene, and zinc for age-related macular degeneration and vision loss: AREDS report no. 8. *Archives of Ophthalmology*, *119*(10), 1417–1436.
- AREDS2. (2013). Lutein + zeaxanthin and omega-3 fatty acids for age-related macular degeneration: The Age-Related Eye Disease Study 2 (AREDS2) randomized clinical trial. *JAMA*, *309*(19), 2005–2015.
- Arroyo, J. G. (2006). A 76-year-old man with macular degeneration. *Journal of the American Medical Association*, *295*(20), 2394–2406.
- Augood, C. A., Vingerling, J. R., de Jong, P. T. V. M., Chakravarthy, U., Seland, J., Soubrane, G., . . . Fletcher, A. E. (2006). Prevalence of age-related maculopathy in older Europeans: The European Eye Study (EUREYE). *Archives of Ophthalmology*, *124*(4), 529–535.
- Averbach, E., & Coriell, A. S. (1961). Short-term memory in vision. *Bell System Technical Journal*, *40*(1), 309–328.
- Awh, E., Armstrong, K. M., & Moore, T. (2006). Visual and oculomotor selection: Links, causes and implications for spatial attention. *Trends in Cognitive Sciences*, *10*(3), 124–130.
- Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in cognitive sciences*, *16*(8), 437–443.

- Bach, M. (1996). The freiburg visual acuity test—automatic measurement of visual acuity. *Optometry and Vision Science*, *73*(1), 49–53.
- Bach, M. (1997). Anti-aliasing and dithering in the 'freiburg visual acuity test'. *Spatial Vision*, *11*(1), 85–89.
- Bach, M. (2007). The freiburg visual acuity test—variability unchanged by post-hoc re-analysis. *Graefes Archive for Clinical and Experimental Ophthalmology*, *245*(7), 965–971.
- Bach, M., & Kommerell, G. (1998). Sehschärfestimmung nach Europäischer Norm: Wissenschaftliche Grundlagen und Möglichkeiten der automatischen Messung [Determining visual acuity using European normal values: Scientific principles and possibilities for automatic measurement]. *Klinische Monatsblätter für Augenheilkunde*, *212*(4), 190–195.
- Baddeley, A. D. (1986). *Working memory*. Oxford psychology series. Oxford: Clarendon Press.
- Baddeley, A. D. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, *63*, 1–29.
- Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), (Vol. 8, pp. 47–89). *Psychology of Learning and Motivation*. New York: Academic Press.
- Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods*, *37*(3), 379–384.
- Barnes, C. S., De L'Aune, W., & Schuchard, R. A. (2011). A test of face discrimination ability in aging and vision loss. *Optometry and Vision Science*, *88*(2), 188–199.
- Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*, *91*(2), 276–292.
- Beatty, S., Koh, H., Phil, M., Henson, D., & Boulton, M. (2000). The role of oxidative stress in the pathogenesis of age-related macular degeneration. *Survey of Ophthalmology*, *45*(2), 115–134.
- Becker, M. W., & Pashler, H. (2002). Volatile visual representations: Failing to detect changes in recently processed information. *Psychonomic bulletin & review*, *9*(4), 744–750.
- Bedell, H. E., Tong, J., Woo, S. Y., House, J. R., & Nguyen, T. (2009). Orientation discrimination with macular changes associated with early AMD. *Optometry and Vision Science*, *86*(5), 485–491.
- Beesley, T., Vadillo, M. A., Pearson, D., & Shanks, D. R. (2016). Configural learning in contextual cuing of visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(8), 1173–1185.
- Bellaera, L., von Mühlhelen, A., & Watson, D. G. (2014). When being narrow minded is a good thing: Locally biased people show stronger contextual cueing. *Quarterly Journal of Experimental Psychology*, *67*(6), 1242–1248.
- Bellmann, C., Feely, M., Crossland, M. D., Kabanarou, S. A., & Rubin, G. S. (2004). Fixation stability using central and pericentral fixation targets in patients with age-related macular degeneration. *Ophthalmology*, *111*(12), 2265–2270.
- Bellmann, C., Unnebrink, K., Rubin, G. S., Miller, D., & Holz, F. G. (2003). Visual acuity and contrast sensitivity in patients with neovascular age-related macular degeneration. Results from the Radiation Therapy for Age-Related Macular Degeneration (RAD-) study. *Graefes Archive for Clinical and Experimental Ophthalmology*, *241*(12), 968–974.
- Bernard, J.-B., Aguilar, C., & Castet, E. (2016). A new font, specifically designed for peripheral vision, improves peripheral letter and word recognition, but not eye-mediated reading performance. *PLoS one*, *11*(4), e0152506.
- Bernard, J.-B., Arunkumar, A., & Chung, S. T. L. (2012). Can reading-specific training stimuli improve the effect of perceptual learning on peripheral reading speed? *Vision Research*, *66*, 17–25.
- Bernard, J.-B., & Chung, S. T. L. (2016). The role of external features in face recognition with central vision loss. *Optometry & Vision Science*, *93*(5), 510–520.
- Bertera, J. H. (1988). The effect of simulated scotomas on visual search in normal subjects. *Investigative Ophthalmology and Visual Science*, *29*(3), 470–475.

- Bertera, J. H., & Rayner, K. (2000). Eye movements and the span of the effective stimulus in visual search. *Perception and Psychophysics*, *62*(3), 576–585.
- Bethlehem, R. A. I., Dumoulin, S. O., Dalmaijer, E. S., Smit, M., Berendschot, T. T. J. M., Nijboer, T. C. W., & Van der Stigchel, S. (2014). Decreased fixation stability of the preferred retinal location in juvenile macular degeneration. *PLoS One*, *9*(6), e100171.
- Biederman, I. (1972). Perceiving real-world scenes. *Science (New York, N.Y.)* *177*(4043), 77–80.
- Bird, A. C. (2010). Therapeutic targets in age-related macular disease. *The Journal of Clinical Investigation*, *120*(9), 3033–3041.
- Bird, A. C., Bressler, N. M., Bressler, S. B., Chisholm, I. H., Coscas, G., Davis, M. D., . . . Klein, R. (1995). An international classification and grading system for age-related maculopathy and age-related macular degeneration. The International ARM Epidemiological Study Group. *Survey of Ophthalmology*, *39*(5), 367–374.
- Black, J. R. M., & Clark, S. J. (2016). Age-related macular degeneration: Genome-wide association studies to translation. *Genetics in Medicine : Official Journal of the American College of Medical Genetics*, *18*(4), 283–289.
- Boucart, M., Dinon, J.-F., Desprez, P., Desmettre, T., Hladiuk, K., & Oliva, A. (2008). Recognition of facial emotion in low vision: A flexible usage of facial features. *Visual Neuroscience*, *25*(4), 603–609.
- Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*(5241), 177–178.
- Brady, T. F., & Chun, M. M. (2007). Spatial constraints on learning in visual search: Modeling contextual cuing. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(4), 798–815.
- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(38), 14325–14329.
- Brady, T. F., Konkle, T., & Alvarez, G. A. (2011). A review of visual memory capacity: Beyond individual items and toward structured representations. *Journal of Vision*, *11*(5), 4.
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433–436.
- Breitmeyer, B. G., Kropfl, W., & Julesz, B. (1982). The existence and role of retinotopic and spatiotopic forms of visual persistence. *Acta Psychologica*, *52*(3), 175–196.
- Bressler, N. M., Bressler, S. B., & Fine, S. L. (1988). Age-related macular degeneration. *Survey of Ophthalmology*, *32*(6), 375–413.
- Bressler, N. M., Bressler, S. B., West, S. K., Fine, S. L., & Taylor, H. R. (1989). The grading and prevalence of macular degeneration in chesapeake bay watermen. *Archives of Ophthalmology*, *107*(6), 847–852.
- Bridgeman, B., Hendry, D., & Stark, L. (1975). Failure to detect displacement of the visual world during saccadic eye movements. *Vision Research*, *15*(6), 719–722.
- Brockmole, J. R., Hambrick, D. Z., Windisch, D. J., & Henderson, J. M. (2008). The role of meaning in contextual cuing: Evidence from chess expertise. *Quarterly Journal of Experimental Psychology*, *61*(12), 1886–1896.
- Brockmole, J. R., & Henderson, J. M. (2006). Recognition and attention guidance during contextual cuing in real-world scenes: Evidence from eye movements. *Quarterly journal of experimental psychology*, *59*(7), 1177–1187.
- Brown, D. M., Kaiser, P. K., Michels, M., Soubrane, G., Heier, J. S., Kim, R. Y., . . . Group, A. S. (2006). Ranibizumab versus verteporfin for neovascular age-related macular degeneration. *The New England Journal of Medicine*, *355*(14), 1432–1444.
- Bullimore, M. A., & Bailey, I. L. (1995). Reading and eye movements in age-related maculopathy. *Optometry and Vision Science*, *72*(2), 125–138.
- Bullimore, M. A., Bailey, I. L., & Wacker, R. T. (1991). Face recognition in age-related maculopathy. *Investigative Ophthalmology and Visual Science*, *32*(7), 2020–2029.

- Burr, D. C., Morrone, M. C., & Ross, J. (1994). Selective suppression of the magnocellular visual pathway during saccadic eye movements. *Nature*, *371*(6497), 511–513.
- Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525.
- Chakravarthy, U., Wong, T. Y., Fletcher, A. E., Piau, E., Evans, C., Zlateva, G., . . . Mitchell, P. (2010). Clinical risk factors for age-related macular degeneration: A systematic review and meta-analysis. *BMC Ophthalmology*, *10*, 31.
- Chaumon, M., Hasboun, D., Baulac, M., Adam, C., & Tallon-Baudry, C. (2009). Unconscious contextual memory affects early responses in the anterior temporal lobe. *Brain Research*, *1285*, 77–87.
- Cheong, A. M. Y., Legge, G. E., Lawrence, M. G., Cheung, S.-H., & Ruff, M. A. (2008). Relationship between visual span and reading performance in age-related macular degeneration. *Vision Research*, *48*(4), 577–588.
- Cheung, S.-H., & Legge, G. E. (2005). Functional and cortical adaptations to central vision loss. *Visual Neuroscience*, *22*(2), 187–201.
- Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in cognitive sciences*, *4*(5), 170–178.
- Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology*, *36*(1), 28–71.
- Chun, M. M., & Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychological Science*, *10*(4), 360–365.
- Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*(2), 224–234.
- Chun, M. M., & Phelps, E. A. (1999). Memory deficits for implicit contextual information in amnesic subjects with hippocampal damage. *Nature Neuroscience*, *2*(9), 844–847.
- Chun, M. M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across scenes. *Visual Cognition*, *7*(1-3), 65–81.
- Chung, S. T. L. (2002). The effect of letter spacing on reading speed in central and peripheral vision. *Investigative Ophthalmology & Visual Science*, *43*(4), 1270–1276.
- Chung, S. T. L. (2007). Learning to identify crowded letters: Does it improve reading speed? *Vision Research*, *47*(25), 3150–3159.
- Chung, S. T. L. (2010). Enhancing visual performance for people with central vision loss. *Optometry & Vision Science*, *87*(4), 276.
- Chung, S. T. L. (2012). Dependence of reading speed on letter spacing in central vision loss. *Optometry and Vision Science*, *89*(9), 1288–1298.
- Chung, S. T. L., Legge, G. E., & Cheung, S.-h. (2004). Letter-recognition and reading speed in peripheral vision benefit from perceptual learning. *Vision Research*, *44*(7), 695–709.
- Chung, S. T. L., Mansfield, J. S., & Legge, G. E. (1998). Psychophysics of reading. xviii. the effect of print size on reading speed in normal peripheral vision. *Vision Research*, *38*(19), 2949–2962.
- Colagiuri, B., & Livesey, E. (2016). Contextual cuing as a form of nonconscious learning: Theoretical and empirical analysis in large and very large samples. *Psychonomic bulletin & review*, *23*(6), 1996–2009.
- Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics*, *27*(3), 183–228.
- Conci, M., Sun, L., & Müller, H. J. (2011). Contextual remapping in visual search after predictable target-location changes. *Psychological Research*, *75*(4), 279–289.
- Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., . . . Shulman, G. L. (1998). A common network of functional areas for attention and eye movements. *Neuron*, *21*(4), 761–773.
- Corbetta, M., & Shulman, G. L. (1998). Human cortical mechanisms of visual attention during orienting and search. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *353*(1373), 1353–1362.

- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature reviews neuroscience*, *3*(3), 201.
- Cornelissen, F. W., Bruin, K. J., & Kooijman, A. C. (2005). The influence of artificial scotomas on eye movements during visual search. *Optometry and Vision Science*, *82*(1), 27–35.
- Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The eyelink toolbox: Eye tracking with matlab and the psychophysics toolbox. *Behavior Research Methods, Instruments, and Computers*, *34*(4), 613–617.
- Cowan, N. (2008). What are the differences between long-term, short-term, and working memory? *Progress in Brain Research*, *169*, 323–338.
- Crossland, M. D., Crabb, D. P., & Rubin, G. S. (2011). Task-specific fixation behavior in macular disease. *Investigative Ophthalmology and Visual Science*, *52*(1), 411–416.
- Crossland, M. D., Culham, L. E., Kabanarou, S. A., & Rubin, G. S. (2005). Preferred retinal locus development in patients with macular disease. *Ophthalmology*, *112*(9), 1579–1585.
- Crossland, M. D., Culham, L. E., & Rubin, G. S. (2004). Fixation stability and reading speed in patients with newly developed macular disease. *Ophthalmic and Physiological Optics*, *24*(4), 327–333.
- Crossland, M. D., & Rubin, G. S. (2006). Eye movements and reading in macular disease: Further support for the shrinking perceptual span hypothesis. *Vision Research*, *46*(4), 590–597.
- 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*(12), 833–843.
- Curcio, C. A., & Allen, K. A. (1990). Topography of ganglion cells in human retina. *The Journal of Comparative Neurology*, *300*(1), 5–25.
- D’Amore, P. A. (1994). Mechanisms of retinal and choroidal neovascularization. *Investigative Ophthalmology & Visual Science*, *35*(12), 3974–3979.
- Daniel, P. M., & Whitteridge, D. (1961). The representation of the visual field on the cerebral cortex in monkeys. *The Journal of Physiology*, *159*, 203–221.
- Davidson, M. L., Fox, M.-J., & Dick, A. (1973). Effect of eye movements on backward masking and perceived location. *Perception & Psychophysics*, *14*(1), 110–116.
- de Jong, P. T. V. M. (2006). Age-related macular degeneration. *The New England Journal of Medicine*, *355*(14), 1474–1485.
- Déruaz, A., Matter, M., Whatham, A. R., Goldschmidt, M., Duret, F., Issenhuth, M., & Safran, A. B. (2004). Can fixation instability improve text perception during eccentric fixation in patients with central scotomas? *The British Journal of Ophthalmology*, *88*(4), 461–463.
- Déruaz, A., Whatham, A. R., Mermoud, C., & Safran, A. B. (2002). Reading with multiple preferred retinal loci: Implications for training a more efficient reading strategy. *Vision Research*, *42*(27), 2947–2957.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual review of neuroscience*, *18*(1), 193–222.
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*(12), 1827–1837.
- Dhawan, S., Deubel, H., & Jonikaitis, D. (2013). Inhibition of saccades elicits attentional suppression. *Journal of Vision*, *13*(6).
- Di Lollo, V. (1980). Temporal integration in visual memory. *Journal of Experimental Psychology: General*, *109*(1), 75–97.
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168.
- Dixon, M. L., Zelazo, P. D., & De Rosa, E. (2010). Evidence for intact memory-guided attention in school-aged children. *Developmental Science*, *13*(1), 161–169.
- Doris, N., Hart, P. M., Chakravarthy, U., McClelland, J., Stevenson, M., Hudson, C., & Jackson, J. (2001). Relation between macular morphology and visual function in patients with choroidal

- neovascularisation of age related macular degeneration. *The British Journal of Ophthalmology*, 85(2), 184–188.
- Dowling, J. (2009). Current and future prospects for optoelectronic retinal prostheses. *Eye (London, England)*, 23(10), 1999–2005.
- Drasdo, N., Millican, C. L., Katholi, C. R., & Curcio, C. A. (2007). The length of henle fibers in the human retina and a model of ganglion receptive field density in the visual field. *Vision Research*, 47(22), 2901–2911.
- Drewes, J., Masson, G. S., & Montagnini, A. (2012). Shifts in reported gaze position due to changes in pupil size: Ground truth and compensation. In *Proceedings of the 2012 symposium on eye tracking research and applications* (pp. 209–212). ETRA '12. ACM. Santa Barbara, California: Association for Computing Machinery.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, 96(3), 433–458.
- Duret, F., Issenhuth, M., & Safran, A. B. (1999). Combined use of several preferred retinal loci in patients with macular disorders when reading single words. *Vision Research*, 39(4), 873–879.
- Endo, N., & Takeda, Y. (2004). Selective learning of spatial configuration and object identity in visual search. *Perception & Psychophysics*, 66(2), 293–302.
- Endo, N., & Takeda, Y. (2005). Use of spatial context is restricted by relative position in implicit learning. *Psychonomic Bulletin & Review*, 12(5), 880–885.
- Evans, J. R. (2001). Risk factors for age-related macular degeneration. *Progress in Retinal and Eye Research*, 20(2), 227–253.
- Falkenberg, H. K., Rubin, G. S., & Bex, P. J. (2007). Acuity, crowding, reading and fixation stability. *Vision Research*, 47(1), 126–135.
- Faubert, J., & Overbury, O. (2000). Binocular vision in older people with adventitious visual impairment: Sometimes one eye is better than two. *Journal of the American Geriatrics Society*, 48(4), 375–380.
- Ferris, F. L., Davis, M. D., Clemons, T. E., Lee, L.-Y., Chew, E. Y., Lindblad, A. S., . . . the Age-Related Eye Disease Study Research Group. (2005). A simplified severity scale for age-related macular degeneration: AREDS report no. 18. *Archives of Ophthalmology*, 123(11), 1570–1574.
- Ferris, F. L., Wilkinson, C. P., Bird, A. C., Chakravarthy, U., Chew, E., Csaky, K., . . . for Macular Research Classification Committee, B. I. (2013). Clinical classification of age-related macular degeneration. *Ophthalmology*, 120(4), 844–851.
- Findlay, J. M. (2004). Eye scanning and visual search. In J. M. Henderson & F. Ferreira (Eds.), *The interface of language, vision, and action: Eye movements and the visual world* (pp. 135–159). New York: Psychology Press.
- Findlay, J. M., & Gilchrist, I. D. (2003). *Active vision: The psychology of looking and seeing*. Oxford: Oxford University Press.
- Fine, E. M., & Rubin, G. S. (1999). The effects of simulated cataract on reading with normal vision and simulated central scotoma. *Vision Research*, 39(25), 4274–4285.
- Fine, S. L., Berger, J. W., Maguire, M. G., & Ho, A. C. (2000). Age-related macular degeneration. *The New England Journal of Medicine*, 342(7), 483–492.
- Fiske, S., & Sanocki, T. (2011). Does crowding obscure the presence of attentional guidance in contextual cueing? [Abstract]. *Journal of Vision*, 11(11), 1296.
- Fletcher, D. C., & Schuchard, R. A. (1997). Preferred retinal loci relationship to macular scotomas in a low-vision population. *Ophthalmology*, 104(4), 632–638.
- Fletcher, D. C., Schuchard, R. A., & Renninger, L. W. (2012). Patient awareness of binocular central scotoma in age-related macular degeneration. *Optometry and Vision Science*, 89(9), 1395–1398.
- Friedman, D. S., O'Colmain, B. J., Muñoz, B., Tomany, S. C., McCarty, C., de Jong, P. T. V. M., . . . Group, E. D. P. R. (2004). Prevalence of age-related macular degeneration in the united states. *Archives of Ophthalmology*, 122(4), 564–572.

- Fritsche, L. G., Igl, W., Bailey, J. N. C., Grassmann, F., Sengupta, S., Bragg-Gresham, J. L., . . . Heid, I. M. (2016). A large genome-wide association study of age-related macular degeneration highlights contributions of rare and common variants. *Nature Genetics*, *48*(2), 134–143.
- Gandhi, N. J., & Katnani, H. A. (2011). Motor functions of the superior colliculus. *Annual review of neuroscience*, *34*, 205–231.
- Gass, J. D. (1973). Drusen and disciform macular detachment and degeneration. *Archives of Ophthalmology*, *90*(3), 206–217.
- Geng, J. J., & Behrmann, M. (2002). Probability cuing of target location facilitates visual search implicitly in normal participants and patients with hemispatial neglect. *Psychological Science*, *13*(6), 520–525.
- Geringswald, F., Baumgartner, F. J., & Pollmann, S. (2013). A behavioral task for the validation of a gaze-contingent simulated scotoma. *Behavior Research Methods*, *45*(4), 1313–1321.
- Geringswald, F., Baumgartner, F., & Pollmann, S. (2012). Simulated loss of foveal vision eliminates visual search advantage in repeated displays. *Frontiers in Human Neuroscience*, *6*, 134.
- Geringswald, F., Herbig, A., Hoffmann, M. B., & Pollmann, S. (2013). Contextual cueing impairment in patients with age-related macular degeneration. *Journal of Vision*, *13*(3).
- Geringswald, F., Herbig, A., Hofmüller, W., Hoffmann, M. B., & Pollmann, S. (2015). Visual memory for objects following foveal vision loss. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(5), 1471–1484.
- Geringswald, F., & Pollmann, S. (2015). Central and peripheral vision loss differentially affects contextual cueing in visual search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *41*(5), 1485–1496.
- Geringswald, F., Porracin, E., & Pollmann, S. (2016). Impairment of visual memory for objects in natural scenes by simulated central scotomata. *Journal of Vision*, *16*(2), 6.
- Geyer, T., Baumgartner, F., Müller, H. J., & Pollmann, S. (2012). Medial temporal lobe-dependent repetition suppression and enhancement due to implicit vs. explicit processing of individual repeated search displays. *Frontiers in human neuroscience*, *6*, 272.
- Geyer, T., Shi, Z., & Müller, H. J. (2010). Contextual cueing in multiconjunction visual search is dependent on color- and configuration-based intertrial contingencies. *J Exp Psychol Hum Percept Perform*, *36*(3), 515–532.
- Geyer, T., Zehetleitner, M., & Müller, H. J. (2010). Contextual cueing of pop-out visual search: When context guides the deployment of attention. *Journal of Vision*, *10*(5), 20.
- Gibson, B. S., Li, L., Skow, E., Brown, K., & Cooke, L. (2000). Searching for one versus two identical targets: When visual search has a memory. *Psychological Science*, *11*(4), 324–327.
- Gibson, B. M., Leber, A. B., & Mehlman, M. L. (2015). Spatial context learning in pigeons (*columba livia*). *Journal of Experimental Psychology: Animal Learning and Cognition*, *41*(4), 336–342.
- Giesbrecht, B., Sy, J. L., & Guerin, S. A. (2013). Both memory and attention systems contribute to visual search for targets cued by implicitly learned context. *Vision Research*, *85*, 80–89.
- Goujon, A., Didierjean, A., & Marmèche, E. (2007). Contextual cueing based on specific and categorical properties of the environment. *Visual Cognition*, *15*(3), 257–275.
- Goujon, A., Didierjean, A., & Marmèche, E. (2009). Semantic contextual cueing and visual attention. *Journal of Experimental Psychology. Human Perception and Performance*, *35*(1), 50–71.
- Goujon, A., Didierjean, A., & Thorpe, S. (2015). Investigating implicit statistical learning mechanisms through contextual cueing. *Trends in Cognitive Sciences*, *19*(9), 524–533.
- Goujon, A., & Fagot, J. (2013). Learning of spatial statistics in nonhuman primates: Contextual cueing in baboons (*papio papio*). *Behavioural Brain Research*, *247*, 101–109.
- Gralla, V. (2007). *Peripheres Sehen im Sport—Möglichkeiten und Grenzen dargestellt am Beispiel der synchronoptischen Wahrnehmung* (Doctoral dissertation, Ruhr-Universität Bochum, Bochum).
- Granholtm, E., Asarnow, R. F., Sarkin, A. J., & Dykes, K. L. (1996). Pupillary responses index cognitive resource limitations. *Psychophysiology*, *33*(4), 457–461.

- Green, D. G. (1970). Regional variations in the visual acuity for interference fringes on the retina. *The Journal of physiology*, *207*(2), 351–356.
- Greene, A. J., Gross, W. L., Elsinger, C. L., & Rao, S. M. (2007). Hippocampal differentiation without recognition: An fmri analysis of the contextual cueing task. *Learning & Memory*, *14*(8), 548–553.
- Grimes, J. (1996). On the failure to detect changes in scenes across saccades. In K. Akins (Ed.), *Perception (vancouver studies in cognitive science)* (Vol. 5, 2, pp. 89–110). New York: Oxford University Press.
- Guez, J. E., Le Gargasson, J. F., Rigaudiere, F., & O'Regan, J. K. (1993). Is there a systematic location for the pseudo-fovea in patients with central scotoma? *Vision Research*, *33*(9), 1271–1279.
- Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research*, *18*(10), 1279–1296.
- Halpern, S. D., Andrews, T. J., & Purves, D. (1999). Interindividual variation in human visual performance. *Journal of Cognitive Neuroscience*, *11*(5), 521–534.
- Hawkins, B. S., Bird, A., Klein, R., & West, S. K. (1999). Epidemiology of age-related macular degeneration. *Molecular Vision*, *5*, 26.
- He, Y., Scholz, J. M., Gage, R., Kallie, C. S., Liu, T., & Legge, G. E. (2015). Comparing the visual spans for faces and letters. *Journal of Vision*, *15*(8), 7.
- Henderson, J. M., McClure, K. K., Pierce, S., & Schrock, G. (1997). Object identification without foveal vision: Evidence from an artificial scotoma paradigm. *Perception and Psychophysics*, *59*(3), 323–346.
- Henderson, J. M., & Hollingworth, A. (2003). Global transsaccadic change blindness during scene perception. *Psychological Science*, *14*(5), 493–497.
- Henderson, J. M., & Hollingworth, A. (1999). The role of fixation position in detecting scene changes across saccades. *Psychological Science*, *10*(5), 438–443.
- Henson, D. (1993). *Visual Fields*. Oxford medical publications. Oxford: Oxford University Press.
- Hess, E. H., & Polt, J. M. (1964). Pupil size in relation to mental activity during simple problem-solving. *Science*, *143*(3611), 1190–1192.
- Hoffman, J. E., & Subramaniam, B. (1995). The role of visual attention in saccadic eye movements. *Perception and Psychophysics*, *57*(6), 787–795.
- Hogg, R. E., & Chakravarthy, U. (2006). Visual function and dysfunction in early and late age-related maculopathy. *Progress in Retinal and Eye Research*, *25*(3), 249–276.
- Holladay, J. T. (1997). Proper method for calculating average visual acuity. *Journal of Refractive Surgery*, *13*(4), 388–391.
- Holliday, E. G., Smith, A. V., Cornes, B. K., Buitendijk, G. H. S., Jensen, R. A., Sim, X., . . . Wang, J. J. (2013). Insights into the genetic architecture of early stage age-related macular degeneration: A genome-wide association study meta-analysis. *PloS one*, *8*(1), e53830.
- Hollingworth, A. (2003). Failures of retrieval and comparison constrain change detection in natural scenes. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(2), 388–403.
- Hollingworth, A. (2004). Constructing visual representations of natural scenes: The roles of short- and long-term visual memory. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(3), 519–537.
- Hollingworth, A. (2005). The relationship between online visual representation of a scene and long-term scene memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(3), 396–411.
- Hollingworth, A. (2006). Visual memory for natural scenes: Evidence from change detection and visual search. *Visual Cognition*, *14*(4-8), 781–807. cited By (since 1996) 31.
- Hollingworth, A., & Henderson, J. M. (2002). Accurate visual memory for previously attended objects in natural scenes. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(1), 113.

- Hollingworth, A., Matsukura, M., & Luck, S. J. (2013). Visual working memory modulates rapid eye movements to simple onset targets. *Psychological Science*, *24*(5), 790–796.
- Hollingworth, A., Richard, A. M., & Luck, S. J. (2008). Understanding the function of visual short-term memory: Transsaccadic memory, object correspondence, and gaze correction. *Journal of Experimental Psychology: General*, *137*(1), 163–181.
- Hollingworth, A., Schrock, G., & Henderson, J. M. (2001). Change detection in the flicker paradigm: The role of fixation position within the scene. *Memory and Cognition*, *29*(2), 296–304.
- Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, *6*(2), 65–70.
- Horton, J. C., & Hoyt, W. F. (1991). The representation of the visual field in human striate cortex. a revision of the classic holmes map. *Archives of Ophthalmology (Chicago, Ill. : 1960)*, *109*(6), 816–824.
- Howard, J. H., Jr, Howard, D. V., Dennis, N. A., Yankovich, H., & Vaidya, C. J. (2004). Implicit spatial contextual learning in healthy aging. *Neuropsychology*, *18*(1), 124–134.
- Humayun, M. S., Dorn, J. D., da Cruz, L., Dagnelie, G., Sahel, J.-A., Stanga, P. E., . . . Group, A. I. S. (2012). Interim results from the international trial of second sight’s visual prosthesis. *Ophthalmology*, *119*(4), 779–788.
- Inhoff, A. W., Starr, M., Liu, W., & Wang, J. (1998). Eye-movement-contingent display changes are not compromised by flicker and phosphor persistence. *Psychonomic Bulletin & Review*, *5*(1), 101–106.
- International Organization for Standardization. (2009). *Ophthalmic optics - visual acuity testing - standard optotype and its presentation* (Norm No. ISO 8596:2009). Geneva, Switzerland. Retrieved from http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=52487
- Irwin, D. E. (1992). Memory for position and identity across eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(2), 307–317.
- Irwin, D. E. (2004). Fixation location and fixation duration as indices of cognitive processing. In J. M. Henderson & F. Ferreira (Eds.), *The interface of language, vision, and action: Eye movements and the visual world* (pp. 105–133). New York: Psychology Press.
- Irwin, D. E., Yantis, S., & Jonides, J. (1983). Evidence against visual integration across saccadic eye movements. *Perception & Psychophysics*, *34*(1), 49–57.
- Irwin, D. E., & Yeomans, J. M. (1986). Sensory registration and informational persistence. *Journal of Experimental Psychology: Human Perception and Performance*, *12*(3), 343–360.
- Irwin, D. E., & Zelinsky, G. J. (2002). Eye movements and scene perception: Memory for things observed. *Perception and Psychophysics*, *64*(6), 882–895.
- Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision research*, *40*(10-12), 1489–1506.
- James, W. (1890). *The Principles of Psychology* (Volume 1). New York: Henry Holt and Company.
- Jiang, Y., & Chun, M. M. (2001). Selective attention modulates implicit learning. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *54*(4), 1105–1124.
- Jiang, Y., & Leung, A. W. (2005). Implicit learning of ignored visual context. *Psychonomic bulletin & review*, *12*(1), 100–106.
- Jiang, Y., & Song, J.-H. (2005). Hyperspecificity in visual implicit learning: Learning of spatial layout is contingent on item identity. *Journal of Experimental Psychology. Human Perception and Performance*, *31*(6), 1439–1448.
- Jiang, Y., Song, J.-H., & Rigas, A. (2005). High-capacity spatial contextual memory. *Psychonomic Bulletin & Review*, *12*(3), 524–529.
- Jiang, Y., & Wagner, L. C. (2004). What is learned in spatial contextual cuing—configuration or individual locations? *Perception & Psychophysics*, *66*(3), 454–463.
- Joffe, K. M., & Scialfa, C. T. (1995). Texture segmentation as a function of eccentricity, spatial frequency and target size. *Spatial Vision*, *9*(3), 325–342.

- Johnson, J. S., Woodman, G. F., Braun, E., & Luck, S. J. (2007). Implicit memory influences the allocation of attention in visual cortex. *Psychonomic Bulletin & Review*, *14*(5), 834–839.
- Jonides, J., Irwin, D. E., & Yantis, S. (1982). Integrating visual information from successive fixations. *Science*, *215*(4529), 192–194.
- Kabanarou, S. A., Crossland, M. D., Bellmann, C., Rees, A., Culham, L. E., & Rubin, G. S. (2006). Gaze changes with binocular versus monocular viewing in age-related macular degeneration. *Ophthalmology*, *113*(12), 2251–2258.
- Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual review of neuroscience*, *23*(1), 315–341.
- Kehrer, L. (1989). Central performance drop on perceptual segregation tasks. *Spatial Vision*, *4*(1), 45–62.
- Klein, M. L., Ferris, F. L., Armstrong, J., Hwang, T. S., Chew, E. Y., Bressler, S. B., . . . the Age-Related Eye Disease Study Research Group. (2008). Retinal precursors and the development of geographic atrophy in age-related macular degeneration. *Ophthalmology*, *115*(6), 1026–1031.
- Klein, R. M. (1988). Inhibitory tagging system facilitates visual search. *Nature*, *334*(6181), 430–431.
- Klein, R., Klein, B. E., Jensen, S. C., & Meuer, S. M. (1997). The five-year incidence and progression of age-related maculopathy: The beaver dam eye study. *Ophthalmology*, *104*(1), 7–21.
- Klein, R., Klein, B. E., & Linton, K. L. (1992). Prevalence of age-related maculopathy. the beaver dam eye study. *Ophthalmology*, *99*(6), 933–943.
- Klein, R., Myers, C. E., Lee, K. E., Gangnon, R. E., Sivakumaran, T. A., Iyengar, S. K., & Klein, B. E. K. (2015). Small drusen and age-related macular degeneration: The Beaver Dam Eye Study. *Journal of Clinical Medicine*, *4*(3), 424–440.
- Klein, R., Wang, Q., Klein, B. E., Moss, S. E., & Meuer, S. M. (1995). The relationship of age-related maculopathy, cataract, and glaucoma to visual acuity. *Investigative Ophthalmology & Visual Science*, *36*(1), 182–191.
- Kleiner, R. C., Enger, C., Alexander, M. F., & Fine, S. L. (1988). Contrast sensitivity in age-related macular degeneration. *Archives of Ophthalmology*, *106*(1), 55–57.
- Kliffen, M., Sharma, H. S., Mooy, C. M., Kerkvliet, S., & de Jong, P. T. (1997). Increased expression of angiogenic growth factors in age-related maculopathy. *The British Journal of Ophthalmology*, *81*(2), 154–162.
- Kowler, E., Anderson, E., Doshier, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, *35*(13), 1897–1916.
- Krauzlis, R. J., Lovejoy, L. P., & Zénon, A. (2013). Superior colliculus and visual spatial attention. *Annual review of neuroscience*, *36*, 165–182.
- Kristjánsson, A. (2000). In search of remembrance: Evidence for memory in visual search. *Psychological Science*, *11*(4), 328–332.
- Kristjánsson, A., & Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception & Psychophysics*, *72*(1), 5–18.
- Kristjánsson, A., & Driver, J. (2008). Priming in visual search: Separating the effects of target repetition, distractor repetition and role-reversal. *Vision Research*, *48*(10), 1217–1232.
- Kumar, G., & Chung, S. T. L. (2014). Characteristics of fixational eye movements in people with macular disease. *Investigative Ophthalmology & Visual Science*, *55*(8), 5125–5133.
- Kunar, M. A., Flusberg, S. J., & Wolfe, J. M. (2008). Time to guide: Evidence for delayed attentional guidance in contextual cueing. *Visual Cognition*, *16*(6), 804–825.
- Kunar, M. A., Flusberg, S. J., & Wolfe, J. M. (2006). Contextual cuing by global features. *Perception & Psychophysics*, *68*(7), 1204–1216.
- Kunar, M. A., Flusberg, S., Horowitz, T. S., & Wolfe, J. M. (2007). Does contextual cuing guide the deployment of attention? *Journal of Experimental Psychology: Human Perception and Performance*, *33*(4), 816–828.

- Kwon, M., Nandy, A. S., & Tjan, B. S. (2013). Rapid and persistent adaptability of human oculomotor control in response to simulated central vision loss. *Current Biology*, *23*(17), 1663–1669.
- Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and anovas. *Front Psychol*, *4*, 863.
- Larson, A. M., & Loschky, L. C. (2009). The contributions of central versus peripheral vision to scene gist recognition. *Journal of Vision*, *9*(10), 6.1–6.16.
- Latham, K., & Whitaker, D. (1996). A comparison of word recognition and reading performance in foveal and peripheral vision. *Vision Research*, *36*(17), 2665–2674.
- Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133*(3), 339–354.
- Lee, H.-W., Legge, G. E., & Ortiz, A. (2003). Is word recognition different in central and peripheral vision? *Vision Research*, *43*(26), 2837–2846.
- Legge, G. E., Cheung, S.-H., Yu, D., Chung, S. T. L., Lee, H.-W., & Owens, D. P. (2007). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision*, *7*(2), 9.1–9.15.
- Legge, G. E., Mansfield, J. S., & Chung, S. T. L. (2001). Psychophysics of reading. xx. linking letter recognition to reading speed in central and peripheral vision. *Vision Research*, *41*(6), 725–743.
- Lim, L. S., Mitchell, P., Seddon, J. M., Holz, F. G., & Wong, T. Y. (2012). Age-related macular degeneration. *Lancet*, *379*(9827), 1728–1738.
- Lindblad, A. S., Lloyd, P. C., Clemons, T. E., Gensler, G. R., Ferris, F. L., III, Klein, M. L., . . . the Age-Related Eye Disease Study Research Group. (2009). Change in area of geographic atrophy in the Age-Related Eye Disease Study: AREDS report number 26. *Archives of Ophthalmology*, *127*(9), 1168–1174.
- Lingnau, A., Albrecht, T., Schwarzbach, J., & Vorberg, D. (2014). Visual search without central vision—no single pseudofovea location is best. *Journal of Eye Movement Research*, *7*(2).
- Lingnau, A., Schwarzbach, J., & Vorberg, D. (2008). Adaptive strategies for reading with a forced retinal location. *Journal of Vision*, *8*(5), 6.1–6.18.
- Lingnau, A., Schwarzbach, J., & Vorberg, D. (2010). (un-) coupling gaze and attention outside central vision. *Journal of Vision*, *10*(11), 13.
- Liu, R., & Kwon, M. (2016). Integrating oculomotor and perceptual training to induce a pseudofovea: A model system for studying central vision loss. *Journal of Vision*, *16*(6), 10.
- Lleras, A., & Von Mühlenen, A. (2004). Spatial context and top-down strategies in visual search. *Spatial Vision*, *17*(4-5), 465–482.
- Loschky, L. C., & McConkie, G. W. (2000). User performance with gaze contingent multiresolutional displays. In *Proceedings of the 2000 symposium on eye tracking research and applications* (pp. 97–103). ETRA '00. Palm Beach Gardens, Florida, USA. Palm Beach Gardens, Florida, USA: Association for Computing Machinery.
- Loschky, L. C., & Wolverton, G. S. (2007). How late can you update gaze-contingent multiresolutional displays without detection? *ACM Transactions on Multimedia Computing, Communications, and Applications*, *3*(4), 1–10.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281.
- Luck, S. J., & Vogel, E. K. (2013). Visual working memory capacity: From psychophysics and neurobiology to individual differences. *Trends in Cognitive Sciences*, *17*(8), 391–400.
- Luck, S. J., & Hollingworth, A. (2008). *Visual memory*. OUP USA.
- Luo, Y. H.-L., & da Cruz, L. (2014). A review and update on the current status of retinal prostheses (bionic eye). *British Medical Bulletin*, *109*, 31–44.
- Mack, A., & Rock, I. (1998). *Inattention blindness*. MIT press Cambridge, MA.
- Makovski, T., & Jiang, Y. (2010). Contextual cost: When a visual-search target is not where it should be. *Quarterly Journal of Experimental Psychology*, *63*(2), 216–225.

- Malcolm, G. L., & Henderson, J. M. (2009). The effects of target template specificity on visual search in real-world scenes: Evidence from eye movements. *Journal of Vision, 9*(11), 8.1–813.
- Manginelli, A. A., Baumgartner, F., & Pollmann, S. (2013). Dorsal and ventral working memory-related brain areas support distinct processes in contextual cueing. *Neuroimage, 67*, 363–374.
- Manginelli, A. A., Geringswald, F., & Pollmann, S. (2012). Visual search facilitation in repeated displays depends on visuospatial working memory. *Experimental Psychology, 59*(1), 47–54.
- Manginelli, A. A., Langer, N., Klose, D., & Pollmann, S. (2013). Contextual cueing under working memory load: Selective interference of visuospatial load with expression of learning. *Attention, Perception & Psychophysics, 75*(6), 1103–1117.
- Manginelli, A. A., & Pollmann, S. (2009). Misleading contextual cues: How do they affect visual search? *Psychological Research, 73*(2), 212–221.
- Mangione, C. M., Berry, S., Spritzer, K., Janz, N. K., Klein, R., Owsley, C., & Lee, P. P. (1998). Identifying the content area for the 51-item national eye institute visual function questionnaire: Results from focus groups with visually impaired persons. *Archives of Ophthalmology, 116*(2), 227–233.
- Marmor, D. J., & Marmor, M. F. (2010). Simulating vision with and without macular disease. *Archives of Ophthalmology, 128*(1), 117–125.
- Martin, D. F., Maguire, M. G., Ying, G.-s., Grunwald, J. E., Fine, S. L., & Jaffe, G. J. (2011). Ranibizumab and bevacizumab for neovascular age-related macular degeneration. *The New England journal of medicine, 364*(20), 1897–1908.
- Martin, E. (1974). Saccadic suppression: A review and an analysis. *Psychological Bulletin, 81*(12), 899–917.
- McConkie, G. W., & Loschky, L. C. (2002). Perception onset time during fixations in free viewing. *Behavior Research Methods, Instruments, and Computers, 34*(4), 481–490.
- McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*(6), 578–586.
- McConkie, G. W., & Rayner, K. (1976). Asymmetry of the perceptual span in reading. *Bulletin of the Psychonomic Society, 8*(5), 365–368.
- McIlreavy, L., Fiser, J., & Bex, P. J. (2012). Impact of simulated central scotomas on visual search in natural scenes. *Optometry and Vision Science, 89*(9), 1385–1394.
- McMahon, T. T., Hansen, M., & Viana, M. (1991). Fixation characteristics in macular disease. relationship between saccadic frequency, sequencing, and reading rate. *Investigative Ophthalmology and Visual Science, 32*(3), 567–574.
- Merikle, P. M., & Reingold, E. M. (1992). Measuring unconscious perceptual processes. In R. Bornstein & T. Pittman (Eds.), *Perception without awareness* (pp. 55–80). New York: Guilford Press.
- Merrill, E. C., Conners, F. A., Roskos, B., Klinger, M. R., & Klinger, L. G. (2013). Contextual cueing effects across the lifespan. *The Journal of Genetic Psychology, 174*(4), 387–402.
- Midena, E., & Vujosevic, S. (2015). Metamorphopsia: An overlooked visual symptom. *Ophthalmic Research, 55*(1), 26–36.
- Miellet, S., O'Donnell, P. J., & Sereno, S. C. (2009). Parafoveal magnification: Visual acuity does not modulate the perceptual span in reading. *Psychological Science, 20*(6), 721–728.
- Miellet, S., Zhou, X., He, L., Rodger, H., & Caldara, R. (2010). Investigating cultural diversity for extrafoveal information use in visual scenes. *Journal of Vision, 10*(6), 21.
- Mitchell, J., & Bradley, C. (2006). Quality of life in age-related macular degeneration: A review of the literature. *Health and Quality of Life Outcomes, 4*, 97.
- Monés, J., & Rubin, G. S. (2005). Contrast sensitivity as an outcome measure in patients with subfoveal choroidal neovascularisation due to age-related macular degeneration. *Eye, 19*(11), 1142–1150.
- Morand, S. M., Grosbras, M.-H., Caldara, R., & Harvey, M. (2010). Looking away from faces: Influence of high-level visual processes on saccade programming. *Journal of Vision, 10*(3), 16.1–1610.

- Müller, H. J., & von Mühlenen, A. (2000). Probing distractor inhibition in visual search: Inhibition of return. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(5), 1591–1605.
- Munoz, D. P., & Everling, S. (2004). Look away: The anti-saccade task and the voluntary control of eye movement. *Nature Reviews Neuroscience*, *5*(3), 218–228.
- Murphy, K. S., & Foley-Fisher, J. A. (1988). Visual search with non-foveal vision. *Ophthalmic and Physiological Optics*, *8*(3), 345–348.
- Nazemi, P. P., Fink, W., Lim, J. I., & Sadun, A. A. (2005). Scotomas of age-related macular degeneration detected and characterized by means of a novel three-dimensional computer-automated visual field test. *Retina*, *25*(4), 446–453.
- Neelam, K., Nolan, J., Chakravarthy, U., & Beatty, S. (2009). Psychophysical function in age-related maculopathy. *Survey of Ophthalmology*, *54*(2), 167–210.
- Nelson, W. W., & Loftus, G. R. (1980). The functional visual field during picture viewing. *Journal of experimental psychology: Human learning and memory*, *6*(4), 391–399.
- Nilsson, U. L., Frennesson, C., & Nilsson, S. E. G. (1998). Location and stability of a newly established eccentric retinal locus suitable for reading, achieved through training of patients with a dense central scotoma. *Optometry and Vision Science*, *75*(12), 873–878.
- Nilsson, U. L., Frennesson, 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*(16), 1777–1787.
- Nobre, A. C., Gitelman, D. R., Dias, E. C., & Mesulam, M. M. (2000). Covert visual spatial orienting and saccades: Overlapping neural systems. *NeuroImage*, *11*(3), 210–216.
- Noë, A., Pessoa, L., & Thompson, E. (2000). Beyond the grand illusion: What change blindness really teaches us about vision. *Visual Cognition*, *7*(1-3), 93–106.
- Nuthmann, A. (2014). How do the regions of the visual field contribute to object search in real-world scenes? evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 342–360.
- Nyström, M., & Holmqvist, K. (2010). An adaptive algorithm for fixation, saccade, and glissade detection in eyetracking data. *Behavior Research Methods*, *42*(1), 188–204.
- O'Regan, J. K. (1992). Solving the "real" mysteries of visual perception: The world as an outside memory. *Canadian journal of psychology*, *46*(3), 461–488.
- O'Regan, J. K., & Lévy-Schoen, A. (1983). Integrating visual information from successive fixations: Does trans-saccadic fusion exist? *Vision Research*, *23*(8), 765–768.
- O'Regan, J. K., Lévy-Schoen, A., & Jacobs, A. M. (1983). The effect of visibility on eye-movement parameters in reading. *Perception & Psychophysics*, *34*(5), 457–464.
- O'Regan, J. K., & Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *The Behavioral and Brain Sciences*, *24*(5), 939–73, discussion 973–1031.
- O'Regan, J. K., Deubel, H., Clark, J. J., & Rensink, R. A. (2000). Picture changes during blinks: Looking without seeing and seeing without looking. *Visual Cognition*, *7*(1-3), 191–211.
- Ogawa, H., Watanabe, K., & Yagi, A. (2009). Contextual cueing in multiple object tracking. *Visual Cognition*, *17*(8), 1244–1258.
- Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: Measures of effect size for some common research designs. *Psychological Methods*, *8*(4), 434–447.
- Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, *15*(7), 327–334.
- Olson, I. R., Chun, M. M., & Allison, T. (2001). Contextual guidance of attention: Human intracranial event-related potential evidence for feedback modulation in anatomically early temporally late stages of visual processing. *Brain*, *124* (Pt 7), 1417–1425.

- Olson, I. R., & Chun, M. M. (2001). Temporal contextual cuing of visual attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*(5), 1299–1313.
- Olson, I. R., & Chun, M. M. (2002). Perceptual constraints on implicit learning of spatial context. *Visual Cognition*, *9*(3), 273–302.
- Pashler, H. (1988). Familiarity and visual change detection. *Perception and Psychophysics*, *44*(4), 369–378.
- Pashler, H., Johnston, J. C., & Ruthruff, E. (2001). Attention and performance. *Annual Review of Psychology*, *52*(1), 629–651.
- Peli, E., Goldstein, R. B., Young, G. M., Trempe, C. L., & Buzney, S. M. (1991). Image enhancement for the visually impaired. simulations and experimental results. *Investigative Ophthalmology & Visual Science*, *32*(8), 2337–2350.
- Pelli, D. G. (1997). The videotoolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*(4), 437–442.
- Pelli, D. G., & Tillman, K. A. (2008). The uncrowded window of object recognition. *Nature Neuroscience*, *11*(10), 1129–1135.
- Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision*, *7*(2), 20.1–2036.
- Perry, J. S., & Geisler, W. S. (2002). Gaze-contingent real-time simulation of arbitrary visual fields. In B. E. Rogowitz & T. N. Pappas (Eds.), *Human vision and electronic imaging vii, spie proceedings* (Vol. 4662, pp. 57–69). San Jose, CA: SPIE - International Society for Optical Engineering.
- Pertsov, Y., Avidan, G., & Zohary, E. (2009). Accumulation of visual information across multiple fixations. *Journal of Vision*, *9*(10), 2.1–212.
- Peterson, M. S., & Kramer, A. F. (2001). Attentional guidance of the eyes by contextual information and abrupt onsets. *Perception and Psychophysics*, *63*(7), 1239–1249.
- Peterson, M. S., Kramer, A. F., & Irwin, D. E. (2004). Covert shifts of attention precede involuntary eye movements. *Perception & Psychophysics*, *66*(3), 398–405.
- Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics*, *16*(2), 283–290.
- Pollmann, S. (2019). Working memory dependence of spatial contextual cueing for visual search. *British Journal of Psychology*, *110*(2), 372–380.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.
- Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology*, *109*(2), 160–174.
- Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual review of neuroscience*, *13*(1), 25–42.
- Postle, B. R., Idzikowski, C., Sala, S. D., Logie, R. H., & Baddeley, A. D. (2006). The selective disruption of spatial working memory by eye movements. *The Quarterly Journal of Experimental Psychology*, *59*(1), 100–120.
- Pratt, J. D., Ohara, J. M., Woo, S. Y., & Bedell, H. E. (2014). Fixation locus in patients with bilateral central scotomas for targets that perceptually fill in. *Optometry and Vision Science*, *91*(3), 312–321.
- Prins, N. (2007). Phase spectrum scrambling [Electronic mailing list message]. Retrieved June 16, 2010, from <http://visionscience.com/pipermail/visionlist/2007/002181.html>
- Putnam, N. M., Hofer, H. J., Doble, N., Chen, L., Carroll, J., & Williams, D. R. (2005). The locus of fixation and the foveal cone mosaic. *Journal of Vision*, *5*(7), 632–639.
- Qiu, F., & Leat, S. J. (2009). Functional deficits in early stage age-related maculopathy. *Clin Exp Optom*, *92*(2), 90–98.
- Quillen, D. A. (2001). Effect of unilateral exudative age-related macular degeneration on binocular visual function. *Archives of Ophthalmology*, *119*(11), 1725–1726.

- R Core Team. (2012). *R: A language and environment for statistical computing*. ISBN 3-900051-07-0. R Foundation for Statistical Computing. Vienna, Austria. Retrieved October 4, 2012, from <http://www.R-project.org/>
- R Core Team. (2013). *R: A language and environment for statistical computing [Computer software and manual]*. R Foundation for Statistical Computing. Vienna, Austria. Retrieved October 8, 2013, from <http://www.R-project.org/>
- R Core Team. (2015). *R: A language and environment for statistical computing [Computer software and manual]*. R Foundation for Statistical Computing. Vienna, Austria. Retrieved December 10, 2015, from <http://www.R-project.org/>
- Ramachandran, V. S., & Gregory, R. L. (1991). Perceptual filling in of artificially induced scotomas in human vision. *Nature*, *350*(6320), 699–702.
- Rattner, A., & Nathans, J. (2006). Macular degeneration: Recent advances and therapeutic opportunities. *Nature Reviews Neuroscience*, *7*(11), 860–872.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422.
- Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, *7*(1), 65–81.
- Rayner, K., & Bertera, J. H. (1979). Reading without a fovea. *Science*, *206*(4417), 468–469.
- Rayner, K., & Pollatsek, A. (1983). Is visual information integrated across saccades? *Perception & Psychophysics*, *34*(1), 39–48.
- Remington, L. A. (2012). *Clinical anatomy and physiology of the visual system* (Third Edition). Saint Louis, MO: Butterworth-Heinemann.
- Rensink, R. A. (2000). The dynamic representation of scenes. *Visual Cognition*, *7*(1-3), 17–42.
- Rensink, R. A. (2002). Change detection. *Annual Review of Psychology*, *53*, 245–277.
- Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological science*, *8*(5), 368–373.
- Rosenfeld, P. J., Brown, D. M., Heier, J. S., Boyer, D. S., Kaiser, P. K., Chung, C. Y., . . . Group, M. S. (2006). Ranibizumab for neovascular age-related macular degeneration. *The New England Journal of Medicine*, *355*(14), 1419–1431.
- Rosenholtz, R., Huang, J., Raj, A., Balas, B. J., & Ilie, L. (2012). A summary statistic representation in peripheral vision explains visual search. *Journal of Vision*, *12*(4).
- Sarks, S. H. (1982). Drusen patterns predisposing to geographic atrophy of the retinal pigment epithelium. *Australian Journal of Ophthalmology*, *10*(2), 91–97.
- Sarks, S. H., Arnold, J. J., Killingsworth, M. C., & Sarks, J. P. (1999). Early drusen formation in the normal and aging eye and their relation to age related maculopathy: A clinicopathological study. *The British Journal of Ophthalmology*, *83*(3), 358–368.
- Savitzky, A., & Golay, M. (1964). Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry*, *36*(8), 1627–1639. cited By (since 1996) 3585.
- Schankin, A., & Schubö, A. (2009). Cognitive processes facilitated by contextual cueing: Evidence from event-related brain potentials. *Psychophysiology*, *46*(3), 668–679.
- Schankin, A., & Schubö, A. (2010). Contextual cueing effects despite spatially cued target locations. *Psychophysiology*, *47*(4), 717–727.
- Scherlen, A.-C., Bernard, J.-B., Calabrese, A., & Castet, E. (2008). Page mode reading with simulated scotomas: Oculo-motor patterns. *Vision Research*, *48*(18), 1870–1878.
- Schlagbauer, B., Müller, H. J., Zehetleitner, M., & Geyer, T. (2012). Awareness in contextual cueing of visual search as measured with concurrent access- and phenomenal-consciousness tasks. *Journal of Vision*, *12*(11).
- Schneider, W. X., & Deubel, H. (2002). Selection-for-perception and selection-for-spatial-motor-action are coupled by visual attention: A review of recent findings and new evidence from stimulus-driven

- saccade control. In W. Prinz & B. Hommel (Eds.), *Attention and performance xix: Common mechanisms in perception and action* (pp. 609–627). Oxford: Oxford University Press.
- Schuchard, R. A. (2005). Preferred retinal loci and macular scotoma characteristics in patients with age-related macular degeneration. *Canadian Journal of Ophthalmology*, *40*(3), 303–312.
- Schuchard, R. A., Naseer, S., & de Castro, K. (1999). Characteristics of AMD patients with low vision receiving visual rehabilitation. *Journal of Rehabilitation Research and Development*, *36*(4), 294–302.
- Seigel, D. (2002). AREDS investigators distort findings. *Archives of Ophthalmology*, *120*(1), 100–101.
- Seiple, W., Rosen, R. B., & Garcia, P. M. T. (2013). Abnormal fixation in individuals with age-related macular degeneration when viewing an image of a face. *Optometry and Vision Science*, *90*(1), 45–56.
- Seiple, W., Szyk, J. P., McMahon, T., Pulido, J., & Fishman, G. A. (2005). Eye-movement training for reading in patients with age-related macular degeneration. *Investigative Ophthalmology & Visual Science*, *46*(8), 2886–2896.
- Shen, J., Reingold, E. M., Pomplun, M., & Williams, D. (2003). Saccadic selectivity during visual search: The influence of central processing difficulty. In J. Hyona, R. Radach, & H. Deubel (Eds.), *The mind's eye: Cognitive and applied aspects of eye movement research* (pp. 65–88). Amsterdam: Elsevier.
- Simons, D. J. (2000). Current approaches to change blindness. *Visual Cognition*, *7*(1-3), 1–15.
- Simons, D. J., & Levin, D. T. (1997). Change blindness. *Trends in cognitive sciences*, *1*(7), 261–267.
- Simons, D. J., & Levin, D. T. (1998). Failure to detect changes to people during a real-world interaction. *Psychonomic Bulletin & Review*, *5*(4), 644–649.
- Simons, D. J., & Rensink, R. A. (2005). Change blindness: Past, present, and future. *Trends in cognitive sciences*, *9*(1), 16–20.
- Sjöstrand, J., Olsson, V., Popovic, Z., & Conradi, N. (1999). Quantitative estimations of foveal and extra-foveal retinal circuitry in humans. *Vision Research*, *39*(18), 2987–2998.
- Smyth, A. C., & Shanks, D. R. (2008). Awareness in contextual cuing with extended and concurrent explicit tests. *Memory & Cognition*, *36*(2), 403–415.
- Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: Applications to dementia and amnesia. *Journal of Experimental Psychology: General*, *117*(1), 34–50.
- Song, J.-H., & Jiang, Y. (2005). Connecting the past with the present: How do humans match an incoming visual display with visual memory? *Journal of Vision*, *5*(4), 322–330.
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological monographs: General and applied*, *74*(11), 1.
- Stampe, D. M. (1993). Heuristic filtering and reliable calibration methods for video-based pupil-tracking systems. *Behavior Research Methods, Instruments, and Computers*, *25*(2), 137–142.
- Standing, L. (1973). Learning 10,000 pictures. *Quarterly Journal of Experimental Psychology*, *25*(2), 207–222.
- Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, and Computers*, *31*(1), 137–149.
- Stone, E. M., Sheffield, V. C., & Hageman, G. S. (2001). Molecular genetics of age-related macular degeneration. *Human Molecular Genetics*, *10*(20), 2285–2292.
- 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*(9), 1458–1466.
- Sunness, J. S., Gonzalez-Baron, J., Applegate, C. A., Bressler, N. M., Tian, Y., Hawkins, B., ... Bergman, A. (1999). Enlargement of atrophy and visual acuity loss in the geographic atrophy form of age-related macular degeneration. *Ophthalmology*, *106*(9), 1768–1779.

- Sunness, J. S., Gonzalez-Baron, J., Bressler, N. M., Hawkins, B., & Applegate, C. A. (1999). The development of choroidal neovascularization in eyes with the geographic atrophy form of age-related macular degeneration. *Ophthalmology*, *106*(5), 910–919.
- Sunness, J. S., & Applegate, C. A. (2005). Long-term follow-up of fixation patterns in eyes with central scotomas from geographic atrophy that is associated with age-related macular degeneration. *American Journal of Ophthalmology*, *140*(6), 1085–1093.
- Takeda, Y., & Yagi, A. (2000). Inhibitory tagging in visual search can be found if search stimuli remain visible. *Perception & Psychophysics*, *62*(5), 927–934.
- Tarita-Nistor, L., Brent, M. H., Markowitz, S. N., Steinbach, M. J., & González, E. G. (2013). Maximum reading speed and binocular summation in patients with central vision loss. *Canadian Journal of Ophthalmology*, *48*(5), 443–449.
- Tarita-Nistor, L., González, E. G., Markowitz, S. N., & Steinbach, M. J. (2008). Fixation characteristics of patients with macular degeneration recorded with the mp-1 microperimeter. *Retina*, *28*(1), 125–133.
- Tarita-Nistor, L., González, E. G., Markowitz, S. N., & Steinbach, M. J. (2009). Plasticity of fixation in patients with central vision loss. *Visual Neuroscience*, *26*(5-6), 487–494.
- Tatler, B. W., Gilchrist, I. D., & Land, M. F. (2005). Visual memory for objects in natural scenes: From fixations to object files. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *58*(5), 931–960.
- Tejeria, L., Harper, R. A., Artes, P. H., & Dickinson, C. M. (2002). Face recognition in age related macular degeneration: Perceived disability, measured disability, and performance with a bioptic device. *The British Journal of Ophthalmology*, *86*(9), 1019–1026.
- Theeuwes, J., Kramer, A. F., Hahn, S., & Irwin, D. E. (1998). Our eyes do not always go where we want them to go: Capture of the eyes by new objects. *Psychological Science*, *9*(5), 379–385.
- Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta psychologica*, *135*(2), 77–99.
- Theeuwes, J., Belopolsky, A., & Olivers, C. N. (2009). Interactions between working memory, attention and eye movements. *Acta psychologica*, *132*(2), 106–114.
- Thornton, J., Edwards, R., Mitchell, P., Harrison, R. A., Buchan, I., & Kelly, S. P. (2005). Smoking and age-related macular degeneration: A review of association. *Eye*, *19*(9), 935–944.
- Thorpe, S. J., Gegenfurtner, K. R., Fabre-Thorpe, M., & Bülthoff, H. H. (2001). Detection of animals in natural images using far peripheral vision. *The European Journal of Neuroscience*, *14*(5), 869–876.
- 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 and Visual Science*, *27*(7), 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 & Visual Science*, *28*(8), 1268–1274.
- Timberlake, G. T., Sharma, M. K., Grose, S. A., Gobert, D. V., Gauch, J. M., & Maino, J. H. (2005). Retinal location of the preferred retinal locus relative to the fovea in scanning laser ophthalmoscope images. *Optometry and Vision Science*, *82*(3), 177–185.
- Torralba, A., Oliva, A., Castelano, M. S., & Henderson, J. M. (2006). Contextual guidance of eye movements and attention in real-world scenes: The role of global features in object search. *Psychological Review*, *113*(4), 766–786.
- Travis, S. L., Mattingley, J. B., & Dux, P. E. (2013). On the role of working memory in spatial contextual cueing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(1), 208–219.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136.
- Tseng, Y.-C., & Li, C.-S. R. (2004). Oculomotor correlates of context-guided learning in visual search. *Perception and Psychophysics*, *66*(8), 1363–1378.

- Vadillo, M. A., Konstantinidis, E., & Shanks, D. R. (2016). Underpowered samples, false negatives, and unconscious learning. *Psychonomic Bulletin & Review*, *23*(1), 87–102.
- Valberg, A., & Fosse, P. (2002). Binocular contrast inhibition in subjects with age-related macular degeneration. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, *19*(1), 223–228.
- van Asselen, M., & Castelo-Branco, M. (2009). The role of peripheral vision in implicit contextual cuing. *Attention, perception & psychophysics*, *71*(1), 76–81.
- Van der Stigchel, S., Bethlehem, R. A. I., Klein, B. P., Berendschot, T. T. J. M., Nijboer, T. C. W., & Dumoulin, S. O. (2013). Macular degeneration affects eye movement behavior during visual search. *Frontiers in Psychology*, *4*, 579.
- van Diepen, P. M., Ruelens, L., & d’Ydewalle, G. (1999). Brief foveal masking during scene perception. *Acta psychologica*, *101*(1), 91–103.
- Van Selst, M., & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier elimination. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, *47*(3), 631–650.
- van Asselen, M., Sampaio, J., Pina, A., & Castelo-Branco, M. (2011). Object based implicit contextual learning: A study of eye movements. *Attention, Perception & Psychophysics*, *73*(2), 297–302.
- Velilla, S., García-Medina, J. J., García-Layana, A., Dolz-Marco, R., Pons-Vázquez, S., Pinazo-Durán, M. D., . . . Gallego-Pinazo, R. (2013). Smoking and age-related macular degeneration: Review and update. *Journal of Ophthalmology*, *2013*, 895147.
- Vickery, T. J., Sussman, R. S., & Jiang, Y. (2010). Spatial context learning survives interference from working memory load. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(6), 1358–1371.
- Vickery, T. J., King, L.-W., & Jiang, Y. (2005). Setting up the target template in visual search. *Journal of Vision*, *5*(1), 81–92.
- Vingerling, J. R., Dielemans, I., Hofman, A., Grobbee, D. E., Hijmering, M., Kramer, C. F., & de Jong, P. T. (1995). The prevalence of age-related maculopathy in the rotterdam study. *Ophthalmology*, *102*(2), 205–210.
- Vinnikov, M., Allison, R. S., & Swierad, D. (2008). Real-time simulation of visual defects with gaze-contingent display. In *Proceedings of the 2008 symposium on eye tracking research and applications* (pp. 127–130). ETRA '08. Savannah, Georgia. New York, NY, USA: Association for Computing Machinery.
- Vogt, S., & Magnussen, S. (2007). Long-term memory for 400 pictures on a common theme. *Experimental Psychology*, *54*(4), 298–303.
- von Noorden, G. K., & Mackensensen, G. (1962). Phenomenology of eccentric fixation. *American Journal of Ophthalmology*, *53*, 642–660.
- Voss, J. L. (2009). Long-term associative memory capacity in man. *Psychonomic Bulletin & Review*, *16*(6), 1076–1081.
- Walsh, D. V., & Liu, L. (2014). Adaptation to a simulated central scotoma during visual search training. *Vision Research*, *96*, 75–86.
- Wandell, B. A. (1995). Useful quantities in vision science. In *Foundations of vision* (Chap. Inner cover pages). Sunderland, MA: Sinauer Associates.
- Wang, Y.-Z., Wilson, E., Locke, K. G., & Edwards, A. O. (2002). Shape discrimination in age-related macular degeneration. *Investigative Ophthalmology and Visual Science*, *43*(6), 2055–2062.
- Warburg, O. (1928). Über die klassifizierung tierischer gewebe nach ihrem stoffwechsel. In O. Warburg (Ed.), *Über die katalytischen wirkungen der lebendigen substanz: Arbeiten aus dem kaiser wilhelm-institut für biologie · berlin-dahlem* (pp. 510–514). Berlin, Heidelberg: Springer Berlin Heidelberg.
- Wertheim, T. (1894). Über die indirekte Sehschärfe. *Zeitschrift für Psychologie & Physiologie der Sinnesorgane*, (7), 172–187.

- Wertheim, T. (1980). Peripheral visual acuity: Th. wertheim. *American Journal of Optometry and Physiological Optics*, *57*(12), 915–924.
- Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, *131*(1), 48–64.
- White, J. M., & Bedell, H. E. (1990). The oculomotor reference in humans with bilateral macular disease. *Investigative Ophthalmology and Visual Science*, *31*(6), 1149–1161.
- Whitney, D., & Levi, D. M. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences*, *15*(4), 160–168.
- Whittaker, S. G., Budd, J., & Cummings, R. W. (1988). Eccentric fixation with macular scotoma. *Investigative Ophthalmology and Visual Science*, *29*(2), 268–278.
- Whittaker, S. G., Cummings, R. W., & Swieson, L. R. (1991). Saccade control without a fovea. *Vision Research*, *31*(12), 2209–2218.
- Wiens, S. (2007). Concepts of visual consciousness and their measurement. *Advances in cognitive psychology*, *3*(1-2), 349–359.
- Williams, C. C., Henderson, J. M., & Zacks, R. T. (2005). Incidental visual memory for targets and distractors in visual search. *Perception & Psychophysics*, *67*(5), 816–827.
- Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human perception and performance*, *15*(3), 419.
- Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience*, *5*(6), 495–501.
- Wolfe, J. M., Horowitz, T. S., Kenner, N., Hyle, M., & Vasan, N. (2004). How fast can you change your mind? the speed of top-down guidance in visual search. *Vision Research*, *44*(12), 1411–1426.
- Wong, T. Y., Wong, T., Chakravarthy, U., Klein, R., Mitchell, P., Zlateva, G., . . . Sledge, I. (2008). The natural history and prognosis of neovascular age-related macular degeneration: A systematic review of the literature and meta-analysis. *Ophthalmology*, *115*(1), 116–126.
- Wong, W. L., Su, X., Li, X., Cheung, C. M. G., Klein, R., Cheng, C.-Y., & Wong, T. Y. (2014). Global prevalence of age-related macular degeneration and disease burden projection for 2020 and 2040: A systematic review and meta-analysis. *The Lancet Global Health*, *2*(2), e106–e116.
- Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 121–138.
- Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review*, *11*(2), 269–274.
- World Medical Association. (2000). Declaration of helsinki: Ethical principles for medical research involving human subjects. *Journal of the American Medical Association*, *284*(23), 3043–3045.
- Wyatt, H. J. (2010). The human pupil and the use of video-based eyetrackers. *Vision Research*, *50*(19), 1982–1988.
- Yang, Y., & Merrill, E. C. (2015). Response cost to repeated displays—when previous distractors become targets. *Quarterly Journal of Experimental Psychology*, *68*(4), 625–634.
- Young, R. W. (1988). Solar radiation and age-related macular degeneration. *Survey of Ophthalmology*, *32*(4), 252–269.
- Yu, D., Cheung, S.-H., Legge, G. E., & Chung, S. T. L. (2010). Reading speed in the peripheral visual field of older adults: Does it benefit from perceptual learning? *Vision Research*, *50*(9), 860–869.
- Zang, X., Jia, L., Müller, H. J., & Shi, Z. (2014). Invariant spatial context is learned but not retrieved in gaze-contingent tunnel-view search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.
- Zelinsky, G. J., & Loschky, L. C. (2005). Eye movements serialize memory for objects in scenes. *Perception & Psychophysics*, *67*(4), 676–690.

References

- Zellin, M., Conci, M., von Mühlénen, A., & Müller, H. J. (2011). Two (or three) is one too many: Testing the flexibility of contextual cueing with multiple target locations. *Attention, Perception & Psychophysics*, *73*(7), 2065–2076.
- Zellin, M., von Mühlénen, A., Müller, H. J., & Conci, M. (2013). Statistical learning in the past modulates contextual cueing in the future. *Journal of Vision*, *13*(3).
- Zhang, B., Zhang, J. X., Huang, S., Kong, L., & Wang, S. (2011). Effects of load on the guidance of visual attention from working memory. *Vision Research*, *51*(23-24), 2356–2361.
- Zhao, G., Liu, Q., Jiao, J., Zhou, P., Li, H., & Sun, H.-j. (2012). Dual-state modulation of the contextual cueing effect: Evidence from eye movement recordings. *Journal of Vision*, *12*(6), 11.
- Zur, D., & Ullman, S. (2003). Filling-in of retinal scotomas. *Vision Research*, *43*(9), 971–982.

A A behavioral task for the validation of a gaze-contingent simulated scotoma

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A.1. Abstract

Gaze-contingent displays provide a valuable method in visual research for controlling visual input and investigating its visual and cognitive processing. Although the body of research using gaze-contingent retinal stabilization techniques has grown considerably during the last decade, only few studies have been concerned with the reliability of the specific real-time simulations applied. Using a Landolt ring discrimination task, we present a behavioral validation of gaze-contingent central scotoma simulation in healthy observers. Importantly, behavioral testing is necessary to show whether the simulation impairs foveal processing of visual information. This test becomes even more crucial when researchers are faced with null results in a task performed with the scotoma, as compared with a control condition. It must be ruled out that the lack of behavioral effects results from a Type II error caused by improper implementation before conclusions about foveal contributions to the given task may be drawn. In our experiment, the scotoma effectively prevented foveal processing of the visual stimuli, leading to significantly reduced response accuracies, as compared with unimpaired vision. Moreover, the final fixation at the time of the participants' responses was placed close to the target position in the unimpaired condition, whereas the distance to the target was enhanced with the scotoma, indicating that the observers were not able to discriminate visual target stimuli from distractors, due to the scotoma. The present work presents a validated behavioral testing method for the efficiency of gaze-contingent scotoma simulations, including code for implementation. In addition, solutions for common methodological problems are discussed.

A.2. Introduction

Gaze-contingent paradigms are widely used in visual research to study visual perception and cognitive processes. In gaze-contingent paradigms, the gaze location is monitored with an eye-tracker and is then used to manipulate the visual information the observer is currently looking at. In one variant of such gaze-contingent paradigms, the moving mask technique (Rayner & Bertera, 1979), foveal information is degraded in order to investigate scene and object perception (Henderson et al., 1997; Larson & Loschky, 2009; van Diepen, Ruelens, & d'Ydewalle, 1999), eye movement patterns in visual search (Bertera, 1988;

Bertera & Rayner, 2000; Cornelissen et al., 2005) and reading (E. M. Fine & Rubin, 1999; Scherlen, Bernard, Calabrese, & Castet, 2008), and high-level cognitive functioning such as visual context learning (Geringswald et al., 2012) when the observer is faced with a central scotoma.

The results of studies with simulated scotomata are often interpreted in the light of foveal contribution to specific visual processes or the consequences of impaired foveal vision and may further be related to visual functioning in patients with maculopathies suffering from the loss of central vision. However, it is often not reported whether and how the reliability of the scotoma simulation was tested. In the case of the disruption of an effect of interest in the scotoma, as compared with a control condition, interpretation of the results may be straightforward, indicating that foveal vision is required for a given task. However, in experiments faced with null effects in the scotoma condition the interpretation of the outcome may be flawed if the implementation of the simulation is not tested and reported. The preferable explanation for a null effect in the scotoma condition may be that foveal vision is not necessary for or, for example, a result of adaptation of visual strategies to the task. However, the alternative explanation that needs to be ruled out in order to draw this conclusion is that the simulated scotoma fails in serving its purpose of disrupting foveal perception of visual stimuli, thus resulting in a Type II error caused by the poor quality of the scotoma implementation.

One way of determining the quality of gaze-contingent scotoma simulations may lie in the measurement of the temporal accuracy that concomitantly affects the spatial precision. The end-to-end latency of the system – that is, the temporal delay between the retrieval of the eye position and the corresponding update of the visual stimulus – mainly depends on the inherent properties of the eye-tracker, such as sampling rate and algorithms concerning pupil and corneal reflex detection in video-based eye trackers, data-smoothing, or online saccade detection; on routines used for the rendering of the visual stimulus; and on the refresh rate of the monitor. The total temporal delay of these processes is difficult to measure but may be sufficiently approached by a worst-case estimate if events are synchronized and their individual duration is known. Work on gaze-contingent paradigms suggests that observers do not become aware of display changes when delays up to 12 to 16 ms (Inhoff, Starr, Liu, & Wang, 1998; Loschky & McConkie, 2000), 20 to 30 ms (McConkie & Loschky, 2002), or even 60 ms (Loschky & Wolverton, 2007) in gaze-contingent multiresolutional displays are considered. However, this does not sufficiently answer the critical question of whether the simulated scotoma effectively disrupts foveal processing. In addition to the end-to-end latency of the system, many other factors can influence the spatial accuracy of the simulated scotoma. Oculomotor events such as eye blinks or similar signal distortions may introduce periods in which the position of the scotoma cannot reliably be calculated. Furthermore, the measured eye position may be inaccurate due to unreliable detection of the pupil, especially in video-based eye-trackers, because of occlusion of the eye, low contrasts between pupil and iris or reflections of visual aids such as glasses or lenses.

The interaction of all these factors makes it difficult to estimate the validity of the scotoma simulation even if some of the interfering parameters can be measured or controlled for. Thus, without testing whether a gaze-contingent scotoma actually results in behavioral impairments in tasks that require foveal resolution, interpreting null effects in scotoma simulations may still be flawed. Only if it can be experimentally shown that a foveally demanding task is disrupted by the scotoma simulation while the main task of interest remains unaffected by the scotoma can the conclusion that the main task does not require foveal vision be statistically supported against a possible Type II error. However, if the control task requiring foveal vision produces a null effect in the scotoma condition, a null effect in the main task might be due to improper implementation of the scotoma simulation. Hence, we developed a method for testing the validity of the simulated scotoma behaviorally. Our method consists of a high-acuity visual discrimination task that is performed under free viewing and compared with a scotoma condition within the same observer. If the scotoma simulation prevents foveal processing target detection performance in the scotoma condition should be significantly impaired, as compared with free viewing. In addition, we evaluated the spatial accuracy of the eye movement recording during the experiment and measured the participants' visual acuity after they had completed the search task.

A.3. Method

A.3.1. Experimental Paradigm

The spatial resolution of the visual system decreases with increasing distance from the fovea (for example, Anstis, 1974; Green, 1970; Wertheim, 1980; an overview is provided by Marmor & Marmor, 2010). While the relative visual acuity of foveal vision is equal to 1, acuity of peripheral vision rapidly decreases to 0.1 at a retinal eccentricity of 10° . In order to test the validity of the scotoma, we utilize the Landolt ring as the target stimulus that is the international standard optotype for visual acuity testing (International Organization for Standardization, 2009). According to the international standards, visual acuity is defined as the reciprocal of the smallest resolvable gap width measured in minutes of arc (MAR, "Minimum Angle of Resolution"; visual acuity = gap of Landolt ring [$']^{-1}$). Thus, a visual acuity of 1 is given if an observer is able to discriminate a Landolt ring with a gap size of $1'$. If the Landolt ring needs to be enlarged to a gap width of $2'$, the visual acuity measures 0.5.

Regarding the validation of an artificial scotoma, we can thus calculate the size of a Landolt ring whose identification should be impaired if the scotoma covers the retina to a given extent. Table A.1 represents the relation between eccentricity, visual acuity, and the size of the gap of the Landolt ring that should still be resolvable at the given eccentricity. If, for example, one wants to evaluate a scotoma with a radius of 4° , a gap size smaller than $0.291^{-1} = 3.5'$ should not be resolvable by the observer if visual stimuli are efficiently blocked out. One minute of arc equals one sixtieth of 1° , which leads to a gap size of $3.5'/60' = 0.058^\circ$. The other way around, the minimum sized scotoma necessary to constrict peripheral identification of a given Landolt gap can be calculated. The gap of the Landolt ring should be at least 2 pixels large for accurate presentation (Bach, 1997). Thus, the minimal scotoma size that can be evaluated using this method depends on the size of 2 pixels on the screen in minutes of arc.

Table A.1.: Relation between eccentricity, decimal visual acuity and corresponding size of the resolvable Landolt ring gap.

Eccentricity ($^\circ$ of visual angle)	Decimal visual acuity	MAR (size of the Landolt ring gap)	
		Minutes of arc ($'$)	Degrees of visual angle ($^\circ$)
0.0	1.00	1.0	0.017
0.5	0.67	1.5	0.025
1.0	0.50	2.0	0.033
2.0	0.40	2.5	0.042
3.0	0.33	3.0	0.050
4.0	0.29	3.5	0.058
5.0	0.25	4.0	0.067
10.0	0.10	10.0	0.167
20.0	0.05	20.0	0.333
30.0	0.04	25.0	0.417
40.0	0.03	30.0	0.500

Note: MAR = minimum angle of resolution. The values for Eccentricity and corresponding visual acuity are adapted from Marmor and Marmor (2010).

A.3.2. Participants

Ten healthy participants (2 males, 8 females; 23 years average age) took part in the experiment. All participants were right-handed.

A.3.3. Apparatus

Stimulus presentation and response recording were controlled using the Psychtoolbox (Brainard, 1997; Pelli, 1997) and iViewXToolbox extension based on the EyelinkToolbox (Cornelissen et al., 2002) under Matlab on a PC with a 22-inch Iiyama Vision Master Pro 511 CRT monitor and a MSI NX6200AX-TD512H graphics card. The monitor was 400 mm (1280 pixels) wide and 300 mm (960 pixels) high, and the vertical refresh rate was 100 Hz. Participants viewed stimuli binocularly from a distance of 60 cm, leading to a pixel size of 0.03° of visual angle. Eye position was recorded using an iViewX Hi-Speed eye tracking system (SensoMotoric Instruments GmbH, Teltow, Germany) with a temporal resolution of 240 Hz. Head movements were minimized using a chin and forehead rest. Participants were tested individually in a dimly lit, sound-attenuated chamber. Participants' visual acuity was measured with the Acuity Test implemented in the Freiburg Vision Test (FrACT; Bach, 1996, 1997), using the standard settings implemented in the software. Participants viewed the stimuli on an LCD monitor measuring 340 mm (1280 pixels) \times 270 mm (1024 pixels) at a distance of 3 m. The participants' responses were recorded by the experimenter.

A.3.4. Stimuli and Procedure

The participant's task was to find a Landolt ring under seven closed circles and to indicate the side of its gap that was varied according to the four cardinal positions (bottom, left, top, right) by pressing one of the four arrow keys on the keyboard. All stimuli were black presented on a gray background and placed equidistantly on an imaginary circle with a radius of 9° of visual angle. The position of the Landolt ring and the direction of its gap were randomized and counterbalanced across blocks. An example of a stimulus display is given in Figure A.1.

We used a Landolt ring with the smallest possible gap that could be resolved by our monitor (0.06° of visual angle), reflecting a relative visual acuity of $(0.06 * 60)^{-1} = 0.28$. Given this value, we created a minimum sized scotoma necessary to constrict peripheral identification of the Landolt gap. Using linear interpolation on the values in Table A.1, the gap of the Landolt ring should not be perceptible at retinal eccentricities greater than 4.18° of visual angle. Thus, the scotoma was composed of an opaque area with a radius of 4.18° of visual angle and a transparency gradient following the increasing slope of a Gaussian distribution with a deviation of 0.5° of visual angle leading to a smooth fading out at the edges, resulting in a total scotoma radius of 4.68° of visual angle. On the basis of Landolt acuity norms, participants should thus not be able to resolve Landolt rings outside the scotoma, and potentially resolvable Landolt rings would be occluded by the scotoma. The scotoma was superimposed on the search display and colored the same gray as the background. Its position was updated with the gaze coordinates retrieved from the iViewX Hi-Speed tracking system. Raw gaze coordinates were spatially smoothed by the heuristic filter implemented in the eye-tracking software, adding a latency of one sample to the gaze data. No other additional filter algorithms – for example, for fixation or saccade identification – were implemented. The machine delay of the eye-tracker was estimated to be about 10 ms. The estimated worst-case latency until the update of the display was two frames on the CRT (20 ms), adding up to a total of 30 ms. In case no gaze sample was available – for example, due to eye blinks or signal losses – the scotoma statically remained on the last known valid position until a new gaze sample became available. The timeline of stimulus presentation is illustrated in Figure A.1.

Each trial started with the presentation of a fixation cue for 1000 ms, followed by the search display that remained on screen until the participant responded or for a maximum of 5000 ms. Auditory

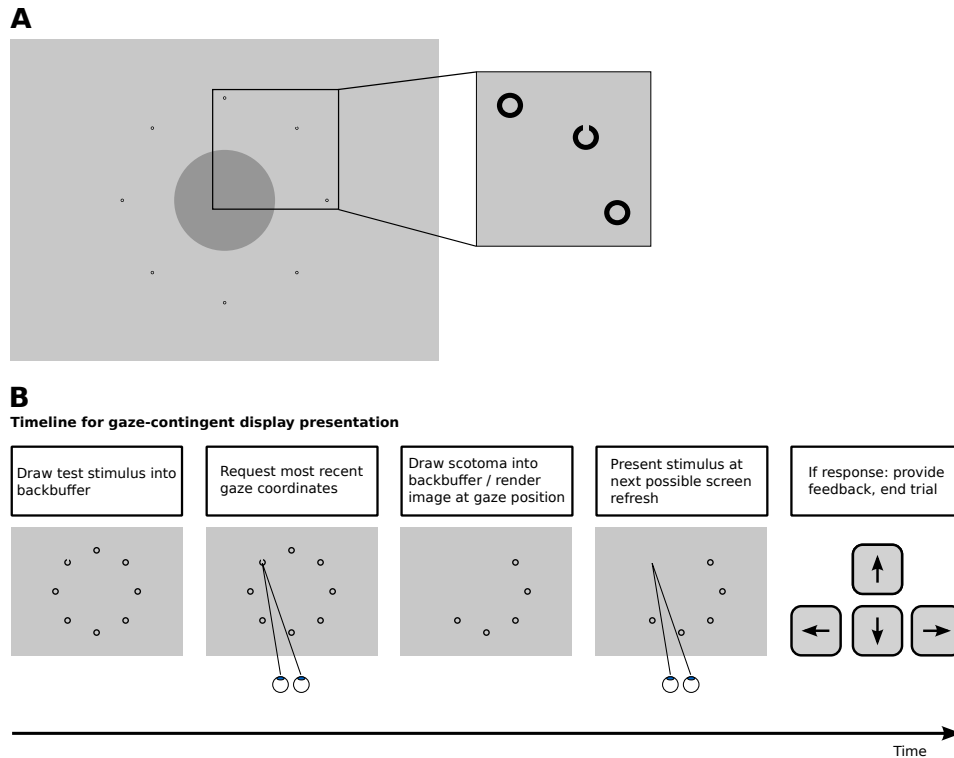


Figure A.1.: Stimulus displays and schematic trial timeline. (A) Search displays were composed of one target Landolt ring and seven closed circles serving as distractors. The simulated scotoma is shaded dark for the purpose of visualization, whereas it was colored the same gray as the background in the experiment. Relations between the size and spatial position of stimuli on the left are the same as in the experiment. The section on the right depicts enlarged stimuli, which do not correspond to displays used in the experiment regarding size and spatial relation. (B) Schematic depiction of the sequence of stimulus presentation. After drawing the search display into the backbuffer, the current gaze coordinates are retrieved from the eye tracker and used to draw the scotoma at the corresponding coordinates. The backbuffer is made visible at the next vertical blank. This procedure is repeated for every screen refresh until a response by the participant has been recorded.

feedback was provided for correct (a 2000 Hz high-pitch tone) and wrong (a 500 Hz low-pitch tone) answers. After the search display, a blank was presented for 500 ms.

Before the start of the experiment, participants were calibrated using a 13-point gaze calibration. Each participant completed six search blocks each including 64 trials. The control and central scotoma viewing conditions were alternated over blocks and counterbalanced across participants for the first block. After each block, we validated the spatial accuracy of the gaze data. Thirteen points of 0.3° of visual angle were presented in succession on an imagery grid covering $23.5^\circ \times 17.6^\circ$ of visual angle for 2s, and participants were asked to fixate them as accurately as possible. Participants' visual acuity was measured after completing the search experiment. One complete experimental session lasted approximately 30 min. The Matlab code for the experiment is provided under <http://link.springer.com/article/10.3758%2Fs13428-013-0321-6#SupplementaryMaterial>.

A.3.5. Gaze Data analysis

Spatial accuracy of the gaze data was determined by calculating mean distances between the physical screen coordinates of search stimuli and the measured eye position, using the intermediate fixation task. Although participants were explicitly instructed to strictly maintain fixation at the dot presented, some participants made several fixations or anticipated the location of the consecutive fixation dot. We thus weighted the fixations by their duration and distance to the fixation dot and chose those fixations that were the longest in duration and the closest to the validation target, with a priority weighting on duration. After determining the Euclidean distances between the selected fixations and the validation points for all 13 trials, we fitted a second-order local polynomial surface to the distances at the given coordinates in order to approximate deviations between physical screen coordinates and measured gaze location across the whole display. Following this procedure, we could estimate the spatial accuracy of the gaze data at the specific positions of the search stimuli. The code for obtaining the deviations between physical screen coordinates and measured gaze location is provided under <http://link.springer.com/article/10.3758%2Fs13428-013-0321-6#SupplementaryMaterial>.

A.3.6. Data exclusion

The first two blocks served as training in order to familiarize participants with the search task and were not included in data analysis. We further removed trials on which more than 20 % of the gaze samples were missing due to signal losses¹.

A.4. Results

One participant's data contained 34.4 % of invalid trials in the unimpaired condition and 17.2 % in the scotoma condition, leading to the exclusion of the participant from all further analysis. The average percentage of data excluded for the remaining 9 participants was 1.7 % ($SD = 2.9\%$) in the control and 0.6 % ($SD = 1.2\%$) in the scotoma conditions. There was no significant difference in the amount of data excluded between viewing conditions, $t(8) = 1.18$, $p = .27$.

A.4.1. Spatial accuracy of the measured gaze data

The mean deviation score across all positions and participants was 0.84° of visual angle ($SD = 0.27^\circ$). The mean deviation scores for the eight stimulus positions ranged from 0.68° to 1.02° , and an ANOVA on deviations did not indicate any significant differences between the stimulus positions, $F(7, 56) = 1.19$, $p = .33$, $\eta_P^2 = .13$, $\eta_G^2 = .083$.

A.4.2. Response Accuracy

In order to test the validity of the simulated scotoma, we carried out an ANOVA on response accuracy with the factors viewing condition (control vs. scotoma) and target position (1-8). It revealed a significant main effect of viewing condition, $F(1, 8) = 203.86$, $p < .001$, $\eta_P^2 = .96$, $\eta_G^2 = .810$, reflecting a severe impairment in stimulus discrimination when vision was impaired by the artificial scotoma.

¹ Excluding trials with more than 20 % missing gaze samples constitutes a rather liberal criterion. We chose this criterion because we had previously encountered issues concerning the quality of data regarding our experimental setup. We wanted to ensure that the simulation would work reliably under similar circumstances in future experiments in which the number of trials excluded may be critical regarding the power of statistical tests. However, we additionally carried out all analyses reported in the results section using a more stringent criterion of excluding trials containing more than 5 % missing gaze samples. This led to an exclusion of 11.5 % in the control and 9.7 % in the scotoma conditions, respectively. None of the results in this study were affected by this procedure.

Neither the main effect of target position, $F(7, 56) = 1.49$, $p = .19$, $\eta_P^2 = .16$, $\eta_G^2 = .051$, nor the interaction $F(7, 56) = 1.26$, $p = .29$, $\eta_P^2 = .14$, $\eta_G^2 = .039$, was significant. Thus, stimulus discrimination was equally impaired across all eight positions with the scotoma (Figure A.2). The average performance was 96.4% ($SD = 2.7\%$) in the unimpaired condition and dropped to 43.3% ($SD = 12.7\%$) in the scotoma condition.

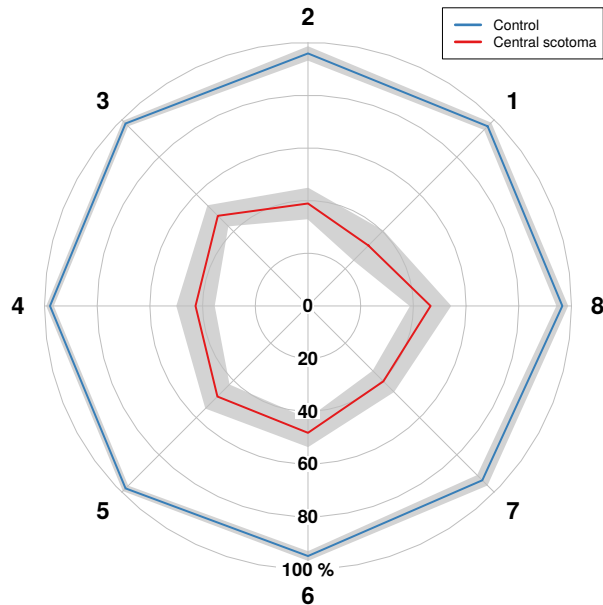


Figure A.2.: Connected radial vectors representing the average response accuracy (grid labels, in percentage) of all participants at the target locations (outer labels). Accuracy was close to 100% in the control condition (blue), in which participants could foveate the target, but dropped significantly below 50% when participants were forced to rely on eccentric viewing due to the central scotoma (red). The shaded area represents the standard error of the mean.

We next investigated whether participants with a higher visual acuity performed better in the discrimination task. The decimal visual acuity measured with the FrACT was converted to the LogMAR (logarithmic "Minimum Angle of Resolution") equivalent to approximate the logarithmic metric of the visual percept corresponding to the arithmetic scale of visual acuity (Bach & Kommerell, 1998; Holladay, 1997). Decimal visual acuities ranged from 1.05 to 2.00, with a reconverted mean of 1.42. Response accuracy in the unimpaired condition did not correlate significantly with logMAR acuity, $r = .26$, $p = .49$. However, we found a significant correlation between response accuracy in the scotoma condition and logMAR acuity, $r = .68$, $p < .05$, indicating that participants with a higher foveal acuity performed better in peripheral stimulus discrimination.

A.4.3. Eye movement patterns

The analysis of the response accuracies clearly shows that the scotoma significantly impaired target identification when observers searched the displays with the scotoma. This should also be apparent in the eye-movement data. If the scotoma prevented observers from foveating the stimuli, visual exploration of the displays should be more difficult and result in unstructured search patterns, as compared with the control condition. We expected the increased difficulty in target detection to be reflected in the

number of fixations as well as the distance of the last fixation to the Landolt ring when the response was given. As compared with unimpaired search, participants were expected to commit more fixations until responding with the scotoma. In order to investigate this question, we selected only trials on which participants responded during the search interval (99.8% of data in the unimpaired and 95.0% in the scotoma conditions). On average, participants made 6.95 fixations ($SD = 0.88$ fixations) in the unimpaired and 8.62 fixations ($SD = 1.39$ fixations) in the scotoma condition. An ANOVA on the number of fixations, with the factors viewing condition (control vs. scotoma) and target position (1-8), confirmed that participants made significantly more fixations under search with the scotoma, main effect of viewing condition, $F(1, 8) = 15.65$, $p < .01$, $\eta_P^2 = .66$, $\eta_G^2 = .244$, independently of the target position, main effect target position, $F(7, 56) = 0.42$, $p = .89$, $\eta_P^2 = .05$, $\eta_G^2 = .015$; interaction, $F(7, 56) = 0.87$, $p = .54$, $\eta_P^2 = .10$, $\eta_G^2 = .018$.

If the scotoma effectively disrupted target identification, the position of the last fixation of the trial should be placed equally often on distractors and the Landolt ring alike, whereas participants should foveate the Landolt ring under unimpaired viewing in order to discriminate the direction of its gap. This should lead to larger distances of the last fixation to the target in the scotoma condition, as compared with the control condition. The analysis of the fixation data revealed that in some cases, observers immediately moved their eyes back to the center of the screen awaiting the following trial during or slightly after pressing the response key. Thus, if the last fixation of the trial was within 3° of the center of the screen and if the distance of this fixation to the center was smaller than that of the second to last fixation, we included the latter as the critical fixation in the analysis. An ANOVA on the median distances to the target with the factors viewing condition (control vs. scotoma) and target position (1-8) revealed a significant main effect of viewing condition, $F(1, 8) = 79.67$, $p < .001$, $\eta_P^2 = .91$, $\eta_G^2 = .727$, indicating that the distance of the last fixation was significantly higher when observers searched with the scotoma. Neither the main effect of target position, $F(7, 56) = 0.54$, $p = .80$, $\eta_P^2 = .06$, $\eta_G^2 = .014$, nor the interaction, $F(7, 56) = 1.22$, $p = .31$, $\eta_P^2 = .13$, $\eta_G^2 = .029$, was significant. Without the scotoma, the median distance was, on average, 1.03° , meaning that the participants foveated the target when making their response. With the scotoma, the average median distance was 9.52° , and last fixations were distributed across the target and distractor positions (Figure A.3).

A.5. Discussion

The goal of this work was to develop and test a visual high-acuity task that can be used to examine the validity of gaze-contingent scotoma simulations behaviorally. The question of whether the scotoma effectively disrupts foveal processing is especially important in the case of null effects in scotoma simulations, since researchers will need to rule out the possibility that such a null effect was due to an improper implementation. Thus, it needs to be shown that the scotoma does have an effect in a secondary task that requires foveal resolution, such as discriminating high-acuity visual targets like the Landolt rings used in our paradigm. To this end, we measured visual discrimination accuracy and eye movement patterns in a visual search task without and with the scotoma.

Response accuracy patterns show that the scotoma severely impaired visual discrimination of the opening of target Landolt rings. Accuracy dropped from almost perfect discrimination in unimpaired viewing to approximately 43% in search with the scotoma. Since the discrimination of the target stimuli required the spatial resolution of those parts of the fovea that were blocked from visual input by the scotoma, we can conclude that the scotoma effectively interfered with foveal processing. Eye movement patterns further support this result. Under unimpaired viewing, participants foveated the Landolt ring to discriminate its gap direction in the great majority of trials. This was not the case when visual input was blocked by the scotoma. The distance of the last fixation to the target of 9.5° and its distribution across distractor positions may indicate that participants misidentified distractors as Landolt rings. Taken together, these results show that visual discrimination of fine targets was significantly reduced

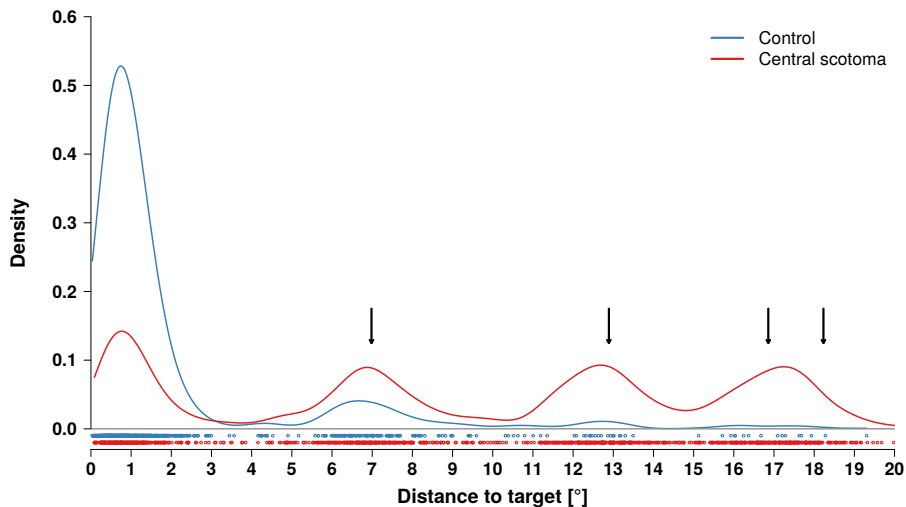


Figure A.3.: Probability density plots of the distance of the last fixation to the target in degrees of visual angle for the control condition (blue) and for the central scotoma condition (red). Plotted are all trials in which the participants responded during the response interval. The arrows show the Euclidean distances of the distractors to the target, which were roughly 7°, 13°, 17°, and 18° of visual angle.

when foveal processing was disrupted by the scotoma. This indicates that the method we developed provides immediate evidence that the scotoma impairs foveal vision and can generally be implemented as described in order to test the effectiveness of the experimental (hard- and software) setup.

A.5.1. Limitations and future directions

It is important to point out that, although the data clearly show a severe disruption of foveal processing of the target Landolt rings with the scotoma, response accuracies were higher than chance performance (25%). Thus, target identification was not completely eliminated in our experiment. Furthermore, participants with a higher foveal acuity performed better at peripheral discrimination of the targets. In order to ensure that the simulated scotoma completely diminishes foveal processing, we suggest considering the following procedures in the construction of the behavioral validation task.

The use of interpolated values of eccentric visual acuity (Marmor & Marmor, 2010) can serve as a well-defined approximation to determine the minimal size of the scotoma necessary to disrupt discrimination of the Landolt rings. However, they may not be an optimal choice for all participants. The interindividual variance in acuity is especially prominent at eccentricities below 10° (Marmor & Marmor, 2010), and similarly, it has been shown that visual performance in a variety of tasks, including orientation discrimination, contrast sensitivity, and vernier acuity, can vary greatly between participants (Halpern, Andrews, & Purves, 1999). We found a positive correlation between detection performance and acuity in the scotoma condition. Thus, testing foveal acuity yielded an indication of detection performance of peripheral targets. While measurement of individual discrimination performance at a given eccentricity with an adaptive threshold protocol is the best way to determine individual test stimuli, standard tests of foveal acuity may at least hint at peripheral discrimination performance. This becomes particularly important for the evaluation of small scotomata, since differences in visual resolution of the retina are largest up to an eccentricity of 5°.

Second, the spatial inaccuracy of the specific eye-tracker model should be taken into account. The average deviation between the measured and the actual gaze position was well below 1° of visual angle

in our setup, indicating a good spatial accuracy of the system. However, the spatial error in eye position measuring can vary greatly within trials depending on physiological and cognitive factors, as well as the participant's compliance during the task. For example, it has been shown that the measured gaze position using video-based eye trackers is influenced by the size of the pupil (Drewes, Masson, & Montagnini, 2012; Wyatt, 2010), which, in turn, depends on the stimulus luminance which might vary between and within trials but can also be influenced by task difficulty or cognitive load (for example, J. Beatty, 1982; Granholm, Asarnow, Sarkin, & Dykes, 1996; Hess & Polt, 1964). The radius of the scotoma should thus be increased by the averaged spatial error of the eye-tracking system, which should be separately measured – for example, via fixation validation, as in our experiment. We note that our method for the selection of fixations used for the calculation of the spatial accuracy may be biased in favor of selecting fixations closer to the validation target, rather than sampling the overall performance of each participant. In order to avoid this problem, participants should be asked to press a button when they are fixating the target, and the fixation temporally associated with the button press should be used in the calculations.

Third, the validation paradigm should be adapted to the specific needs of the intended main experiment. For example, if the filtering or distorting algorithms for the creation of the simulated scotoma are more complex than in our study (for example, Marmor & Marmor, 2010; Perry & Geisler, 2002; Vinnikov, Allison, & Swierad, 2008), the same algorithms should also be used in the validation experiment, since they can introduce an additional temporal delay. Similarly, the presentation of large pictures can introduce delays in display presentation and should be carefully evaluated. We also suggest adapting the position of the test stimuli to corresponding positions important to the intended main experiment, since we have previously observed variable spatial accuracies of our eye-tracking system, particularly close to the corners of the screen.

A.5.2. Conclusion

Gaze-contingent displays offer a promising method for the investigation of visual perception. We would like to stress the merit of behavioral tests of gaze-contingent simulations. Since the scotoma simulation will always meet technical limits, such as the delay between gaze retrieval and scotoma movement or the spatial accuracy of gaze tracking, there will be a need to validate how effectively vision is impaired by the simulation. This is even more the case when additional, sample-specific factors, such as the individual physical attributes of the eye, the influence of vision aids, or individual strategies, come into play. Visual tasks in which the dependent variable is modulated in the scotoma condition, as compared with a control condition, might need a different paradigm to test the simulation, in order to control for the possible influence of other factors, such as inducing saccadic inhibition by global transients during fixation. However, we suggest running a behavioral paradigm such as the one we propose here before carrying out the main experiment, potentially in the scope of a pilot study, since it directly addresses the critical question of whether the scotoma does affect foveal perception and, thus, reduces the costs of investigating confounds post hoc in case of obtaining null effects.

B Ehrenerklärung

Ich versichere hiermit, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe; verwendete fremde und eigene Quellen sind als solche kenntlich gemacht.

Ich habe insbesondere nicht wissentlich:

- Ergebnisse erfunden oder widersprüchlich Ergebnisse verschwiegen,
- statistische Verfahren absichtlich missbraucht, um Daten in ungerechtfertigter Weise zu interpretieren,
- fremde Ergebnisse oder Veröffentlichungen plagiiert,
- fremde Forschungsergebnisse verzerrt wiedergegeben.

Mir ist bekannt, dass Verstöße gegen das Urheberrecht Unterlassungs- und Schadensersatzansprüche des Urhebers sowie eine strafrechtliche Ahndung durch die Strafverfolgungsbehörden begründen kann.

Ich erkläre mich damit einverstanden, dass die Arbeit ggf. mit Mitteln der elektronischen Datenverarbeitung auf Plagiate überprüft werden kann.

Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form als Dissertation eingereicht und ist als Ganzes auch noch nicht veröffentlicht.

Franziska Geringswald

C List of Publications

- Schmidt, A., **Geringswald, F.**, & Pollmann, S. (2018). Spatial contextual cueing, assessed in a computerized task, is not a limiting factor for expert performance in the domain of team sports or action video game playing. *Journal of Cognitive Enhancement*, 1–12.
- Schmidt, A., **Geringswald, F.**, Sharifian, F., & Pollmann, S. (2018). Not scene learning, but attentional processing is superior in team sport athletes and action video game players. *Psychological Research*, 1–11.
- Geringswald, F.**, Herbig, A., Hofmüller, W., Hoffmann, M. B., & Pollmann, S. (2015). Visual memory for objects following foveal vision loss. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 41(5), 1471–1484.
- Geringswald, F.**, & Pollmann, S. (2015). Central and peripheral vision loss differentially affects contextual cueing in visual search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 41(5), 1485–1496.
- Pollmann, S., Zinke, W., Baumgartner, F., **Geringswald, F.**, & Hanke, M. (2014). The right temporo-parietal junction contributes to visual feature binding. *Neuroimage*, 101, 289–297.
- Herbig, A., **Geringswald, F.**, Thieme, H., Pollmann, S., & Hoffmann, M. B. (2014). Prediction of higher visual function in macular degeneration with multifocal electroretinogram and multifocal visual evoked potential. *Ophthalmic and Physiological Optics*, 34(5), 540–551.
- Wendt, M., Kiesel, A., **Geringswald, F.**, Purmann, S., & Fischer, R. (2014). Attentional adjustment to conflict strength: Evidence from the effects of manipulating flanker-target soa on response times and prestimulus pupil size. *Experimental Psychology*, 61(1), 55–67.
- Geringswald, F.**, Baumgartner, F. J., & Pollmann, S. (2013). A behavioral task for the validation of a gaze-contingent simulated scotoma. *Behavior Research Methods*, 45(4), 1313–1321.
- Geringswald, F.**, Herbig, A., Hoffmann, M. B., & Pollmann, S. (2013). Contextual cueing impairment in patients with age-related macular degeneration. *Journal of Vision*, 13(3).
- Baumgartner, F., Hanke, M., **Geringswald, F.**, Zinke, W., Speck, O., & Pollmann, S. (2013). Evidence for feature binding in the superior parietal lobule. *Neuroimage*, 68, 173–180.
- Geringswald, F.**, Baumgartner, F., & Pollmann, S. (2012). Simulated loss of foveal vision eliminates visual search advantage in repeated displays. *Frontiers in Human Neuroscience*, 6, 134.