Coupling of attention and saccades when viewing scenes with central and peripheral degradation

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Degrading real-world scenes in the central or the peripheral visual field yields a characteristic pattern: Mean saccade amplitudes increase with central and decrease with peripheral degradation. Does this pattern reflect corresponding modulations of selective attention? If so, the observed saccade amplitude pattern should reflect more focused attention in the central region with peripheral degradation and an attentional bias toward the periphery with central degradation. To investigate this hypothesis, we measured the detectability of peripheral (Experiment 1) or central targets (Experiment 2) during scene viewing when low or high spatial frequencies were gaze-contingently filtered in the central or the peripheral visual field. Relative to an unfiltered control condition, peripheral filtering induced a decrease of the detection probability for peripheral but not for central targets (tunnel vision). Central filtering decreased the detectability of central but not of peripheral targets. Additional post hoc analyses are compatible with the interpretation that saccade amplitudes and direction are computed in partial independence. Our experimental results indicate that task-induced modulations of saccade amplitudes reflect attentional modulations.

Introduction

Visual acuity and spatial resolution are highest at the point of gaze, the fovea, and fall off dramatically to the periphery (see Strasburger, Rentschler, & Jüttner, 2011). Consequently, we have to move our eyes in a sequence of high-velocity saccadic eye movements with intermittent fixations on regions of interest for the exploration of visual detail. During each fixation, the foveal region is analyzed and the next saccade target is selected among competing peripheral locations. More precisely, the visual field is typically divided into three regions: the foveal, the parafoveal, and the peripheral regions. Foveal vision extends to 1° retinal eccentricity, and parafoveal vision extends from 1° to 5° eccentricity; the union of both regions is usually referred to as central vision. Peripheral vision comprises the remaining part of the visual field beyond 5° eccentricity (see Larson & Loschky, 2009). How central and peripheral vision interact represents a key problem in scene perception research.

Gaze-contingent filtering of visual information is a powerful experimental tool for investigating the specific contributions of central and peripheral vision to the processing of natural scenes. The moving-window technique, first introduced in reading research (McConkie & Rayner, 1975; Rayner & Bertera, 1979), aligns a window of arbitrary size to the current gaze position of the viewer. In general, the window is centered at the point of gaze and moves with the gaze position in real time. Visual information inside or outside the window can then be altered to manipulate vision in the central or the peripheral visual field, respectively.

Previous research on gaze-contingent scene degradation consistently shows characteristic patterns of mean saccade amplitudes with central versus peripheral filtering. Saccade amplitudes decrease with peripheral filtering (Foulsham, Teszka, & Kingstone, 2011; Laubrock, Cajar, & Engbert, 2013; Loschky & McConkie, 2002; Loschky, McConkie, Yang, & Miller,

2005; Nuthmann, 2013, 2014; Nuthmann & Malcolm, 2016; Reingold & Loschky, 2002; Shioiri & Ikeda, 1989; van Diepen & Wampers, 1998) and increase with central filtering (Laubrock et al., 2013; Nuthmann, 2014; Nuthmann & Malcolm, 2016; van Diepen, 2001). These patterns are typically caused by a higher proportion of short saccades with peripheral filtering and a higher proportion of long saccades with central filtering (e.g., see Laubrock et al., 2013). The effects get stronger with increasing filter level (Cajar, Engbert, & Laubrock, 2016; Loschky & McConkie, 2002) and filter size (Cajar et al., 2016; Loschky & McConkie, 2002; Nuthmann, 2013, 2014). A straightforward interpretation of the results is a viewing strategy of avoiding filtered scene regions as saccade targets. With central filtering, viewers make fewer short inspection saccades in the filtered central region; instead, they program more long saccades that target unfiltered peripheral scene regions. With peripheral filtering, the reverse pattern is obtained: Viewers avoid the filtered periphery and tend to keep their gaze in the unfiltered central region, thus making more short saccades.

These modulations of saccade amplitudes have often been linked to attention (Loschky & McConkie, 2002; Nuthmann, 2013; Reingold & Loschky, 2002); for example, Reingold and Loschky (2002) showed that saccade latencies to peripheral targets in short movie clips and static scenes increase when peripheral information is blurred. However, so far, it has not been directly tested if changes of saccade amplitudes due to varying central or peripheral processing difficulty in scenes indeed reflect corresponding attentional modulations. This is the purpose of the present study.

For the interpretation of eye-movement behavior, the tight coupling between saccades and attention is an important theoretical constraint. Several studies have demonstrated that (a) attention precedes a saccade to an intended target location, and (b) stimulus detection and identification are facilitated at intended saccade target locations compared to other locations in the visual field, at least in simple, reduced task environments (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995). Deubel and Schneider (1996) also showed that it is impossible to discriminate a target at one location while preparing a saccade to another location. Due to this coupling between attention and saccades, saccade amplitudes and direction are thought to reflect attentional selection and thus the spatial extent of parafoveal processing (Greene, Pollatsek, Masserang, Lee, & Rayner, 2010; Loschky & McConkie, 2002; Nuthmann, 2013). Following this notion, the aforementioned effects of central and peripheral scene degradation on saccade amplitudes suggest more focused attention on the unfiltered central region with peripheral filtering and a stronger attentional bias toward the periphery with central filtering.

However, attention and eye movements can also be partly decoupled as indicated by covert attention shifts. Covert attention shifts can be several times faster than overt eye movements (Nakayama & MacKeben, 1989). Well-known metaphors for attention include the spotlight (Posner, Snyder, & Davidson, 1980), zoom lens (Eriksen & James, 1986), and the attentional-gradient model (LaBerge & Brown, 1989). In the spotlight model, covert attention moves in an analog fashion across the visual field using disengage, shift, and engage operations. The zoom-lens model extends the spotlight by a variable-sized focus. Several aspects of the spotlight metaphor have been questioned by later work. For example, the movement of covert attention is probably digital rather than analog, meaning that the spotlight is turned off at one location and turned on at the next without passing over intermediate locations (Chastain, 1992a, 1992b; Gersch, Kowler, & Dosher, 2004). Furthermore, the time to move attention between two locations is rather independent of the distance between the two locations (Eriksen & Webb, 1989; Sagi & Julesz, 1985). Although additional effects of object-based selection have been demonstrated in simple tasks (Duncan, 1984; Egly, Driver, & Rafal, 1994) as well as in scene perception (Malcolm & Shomstein, 2015), one critical feature of the spotlight model that has remained valid is that attentional selection is based on location, mirroring the importance of topological maps in the visuospatial processing stream. The attentional-gradient model emphasizes that the size and the concentration of attention can vary according to task demands. A further innovative feature is the possibility of several peaks, so that independent locations can be enhanced in parallel (e.g., see Engbert, Trukenbrod, Barthelmé, & Wichmann, 2015, for a computational implementation in scene viewing). This also includes the possibility of a ring-shaped allocation of attention as has been experimentally demonstrated (Egly & Homa, 1984; Juola, Bouwhuis, Cooper, & Warner, 1991). When the attention field gets large compared to the size of the target, introducing target location uncertainty, one observes a performance decrement with invalid cues (i.e., withdrawal of attention) but no enhancement with valid cues (Herrmann, Montaser-Kouhsari, Carrasco, & Heeger, 2010). In summary, covert attention can obviously be distinguished from overt attention as indicated by eye-movement execution, but it might still be related or equivalent to eye-movement planning.

To investigate whether modulations of saccade lengths during scene viewing correspond to the spatial extent of attention, we here measured in two experiments how the perceptibility of central or peripheral target objects is affected by gaze-contingent central or peripheral filtering of spatial frequencies. High spatial frequencies carry the fine-grained information of an image whereas low spatial frequencies carry the coarse-

grained information of an image. Although the fovea is very sensitive to medium and high spatial frequencies, which are critical for object identification and the analysis of details, the visual periphery is mostly sensitive to low spatial frequencies (Hilz & Cavonius, 1974; Robson & Graham, 1981). Based on this different specialization of central and peripheral vision and on results from a previous study (Laubrock et al., 2013), we assume that high spatial frequencies are more important than low spatial frequencies for processing central information whereas low spatial frequencies are more important than high spatial frequencies for processing peripheral information. We applied low-pass or high-pass filters, which attenuate high or low spatial frequencies, respectively, either to the central or to the peripheral part of the visual field. Such gaze-contingent, spatial-frequency filtering systematically alters scene-viewing behavior. In Laubrock et al. (2013), we applied central or peripheral low-pass or high-pass filters to colored scenes with a gaze-contingent window radius of 2.8°. Replicating the aforementioned effects on saccade amplitudes, amplitudes increased with central and decreased with peripheral filtering compared to an unfiltered control condition. Opposite to our hypotheses, fixation durations increased with central high-pass and peripheral low-pass filtering (the latter replicating Loschky & McConkie, 2002; Loschky et al., 2005; Nuthmann, 2013, 2014; Parkhurst, Culurciello, & Niebur, 2000; Shioiri & Ikeda, 1989; van Diepen & Wampers, 1998) but were similar to the unfiltered control with central low-pass and peripheral high-pass filtering. We concluded that fixation durations prolong with increased processing difficulty due to central or peripheral filtering as long as the filter leaves at least a part of the critical information intact (i.e., low spatial frequencies in the peripheral and high spatial frequencies in the central visual field). If most of the critical information is removed, fixation durations can return to the baseline (Laubrock et al., 2013).

In both experiments of the present study, high or low spatial frequencies were filtered either in the central or the peripheral visual field during real-world scene viewing. Participants had the dual tasks of inspecting the scenes carefully in expectation of difficult memory questions and simultaneously indicating the presence of a green circle in the scene whenever detected. This target stimulus only appeared during randomly chosen fixations in either peripheral (Experiment 1) or central vision (Experiment 2) but always with an offset from the point of fixation. Thus, viewers could only detect the target using covert attention. Consistent with previous findings, we expected mean saccade amplitudes in both experiments to shorten with peripheral filtering and to lengthen with central filtering relative to an unfiltered control condition. If saccadic amplitude modulations are coupled to attention, target detection

probability should change in accordance with the effects on saccade amplitudes. Shorter saccade amplitudes with peripheral filtering would therefore reflect tunnel vision (Mackworth, 1965; Williams, 1988) with a shrinkage of the attentional focus, meaning that attention is withdrawn from the filtered periphery. Consequently, the detection of peripheral targets should be impaired whereas the detection of central targets should be unaffected. On the other hand, longer saccade amplitudes with central filtering would reflect a wider attentional focus or more frequent attention shifts to the undegraded periphery as attention is withdrawn from the filtered center. Consequently, the detection of central targets should be impaired with central filtering whereas the detection of peripheral targets should be unaffected.

The hypothesis that central filtering does not impair the detection of peripheral targets challenges previous research showing that an increased foveal load interferes with performance in peripheral detection tasks (Crundall, Underwood, & Chapman, 1999; Holmes, Cohen, Haith, & Morrison, 1977; Ikeda & Takeuchi, 1975; Williams, 1985, 1989, 1995). This deterioration in performance has been attributed to a reduction of the functional field of view due to the increased foveal processing demands. Holmes et al. (1977) showed that even the mere presence of a foveal stimulus that subjects were asked to ignore decreased peripheral target detection. In contrast, we hypothesize here that if modulations of saccade amplitudes reflect modulations of attention, peripheral target detection should not deteriorate with central filtering although processing demands in the central visual field are increased. Thus, we predicted perceptual costs in the peripheral detection task with peripheral filtering but not with central filtering.

Experiment 1

High or low spatial frequencies were filtered either in the central or the peripheral visual field during scene viewing. Viewers explored the scene in preparation for a memory task while simultaneously detecting targets in the visual periphery. Saccade amplitudes were expected to increase with central filtering and to decrease with peripheral filtering relative to an unfiltered control condition with the effects being stronger when filters attenuate more useful spatial frequencies (i.e., central low-pass and peripheral high-pass filtering). If saccade amplitudes reflect attentional selection, peripheral filtering should deteriorate target detection and slow down target response times whereas central filtering should not interfere with detection performance.

Method

Participants

Thirty students from the University of Potsdam (four male, mean age: 23 years) with normal or corrected-to-normal vision and normal color discrimination were tested. They received course credit or 12 Euro for participation and were naive as to the purpose of the experiment. The experiment conformed to the Declaration of Helsinki. Participants gave their written informed consent prior to the experiment.

Apparatus

Stimuli were presented on a 20-in. Mitsubishi DiamondPro 2070 CRT monitor at a resolution of $1,024 \times 768$ pixels and a refresh rate of 150 Hz. A head and chin rest ensured stability of the head and a constant viewing distance of 60 cm (23.6 in.). During binocular viewing, gaze position of the right eye was recorded with an EyeLink 1000 tower mount system (SR Research, Ontario, Canada) at a sampling rate of 1000 Hz. Stimulus presentation and response collection were implemented in MATLAB® (The Mathworks, Natick, MA) using the OpenGL-based Psychophysics Toolbox (PTB3; Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) and the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002).

Stimuli and design

Stimuli were 85 grayscale photographs (1024×768 pixels) of outdoor, real-world scenes that subtended a visual angle of $38.2° \times 28.6°$. For each scene, low-pass and high-pass filtered versions were prepared in advance via Fourier analysis. Low-pass filtering attenuated spatial frequencies above 1 c/° and high-pass filtering attenuated spatial frequencies below 10 c/°. For gaze-contingent filtering in the central or the peripheral visual field, a foreground and a background image were merged in real time using alpha blending. With peripheral low-pass filtering, for example, the foreground image was the original scene and the background image was the low-pass filtered version of the scene. A 2-D hyperbolic tangent with a slope of 0.06 served as a blending function for creating the alpha mask. The inflection point of the function corresponded to the radius of the gaze-contingent window, which was 5° and thus divided central from peripheral vision. The alpha mask was centered at the current gaze position and defined the transparency value, that is, the weighting of the central foreground image at each point. At the point of fixation, only the foreground image was visible; with increasing eccentricity, the peripheral background image was weighted more strongly until it was fully visible.

Two filter locations (central/peripheral visual field) were crossed with two filter types (low-pass/high-pass filtering), yielding four experimental conditions: central low-pass, central high-pass, peripheral low-pass, and peripheral high-pass filtering. A control condition without filtering served as a baseline (for example stimuli, see Figure 1). A Latin square design assured counterbalancing of condition–scene assignments across participants. Scenes were presented in random order.

The target stimulus was a medium-green circle with a diameter of 0.26°; it appeared several times in each trial at a random location 7.5° away from the current gaze position of the viewer. Thus, the circle always appeared in the visual periphery beyond the boundary of the gaze-contingent window and was located on a completely filtered background with peripheral filtering or on a completely unfiltered background with central filtering and the control condition. The target appeared during randomly chosen fixations (every sixth to 10th fixation) about two or three times per scene (mean: 2.8). Online velocity detection in the raw time series of gaze positions was used to identify fixations and saccades during each trial; for a saccade to be detected, the average eye velocity across five consecutive samples (i.e., 5 ms) had to exceed a threshold of 100°/s, and fixations were designated as periods during which the threshold was not exceeded. Target onset coincided with the beginning of the critical fixation, and target offset coincided with termination of the critical fixation by the viewer or after a maximum presentation time of 300 ms.[1] This means that subjects had to detect the target using peripheral vision (i.e., covert attention) as the target was already removed from the scene when the eyes landed after the next saccade. Target detectability was set to 75% independently for each peripheral scene background (unfiltered, low-pass filtered, high-pass filtered) and individually for each participant using the adaptive QUEST procedure (King-Smith, Grigsby, Vingrys, Benes, & Supowit, 1994; Watson & Pelli, 1983).

A colored circle was chosen as target stimulus because it was independent from the grayscale scene due to its color feature. It is better suited as a target than, for example, a Gabor stimulus, which shares all its features with the scene (spatial frequency, contrast, color, orientation) and therefore interacts strongly with the background; thus, its detectability can range from very easy to very difficult, depending on the scene patch on which it is located. The colored circle promised more consistent visibility across different scene patches. Medium green was chosen over other colors that appeared too salient on the grayscale scenes.
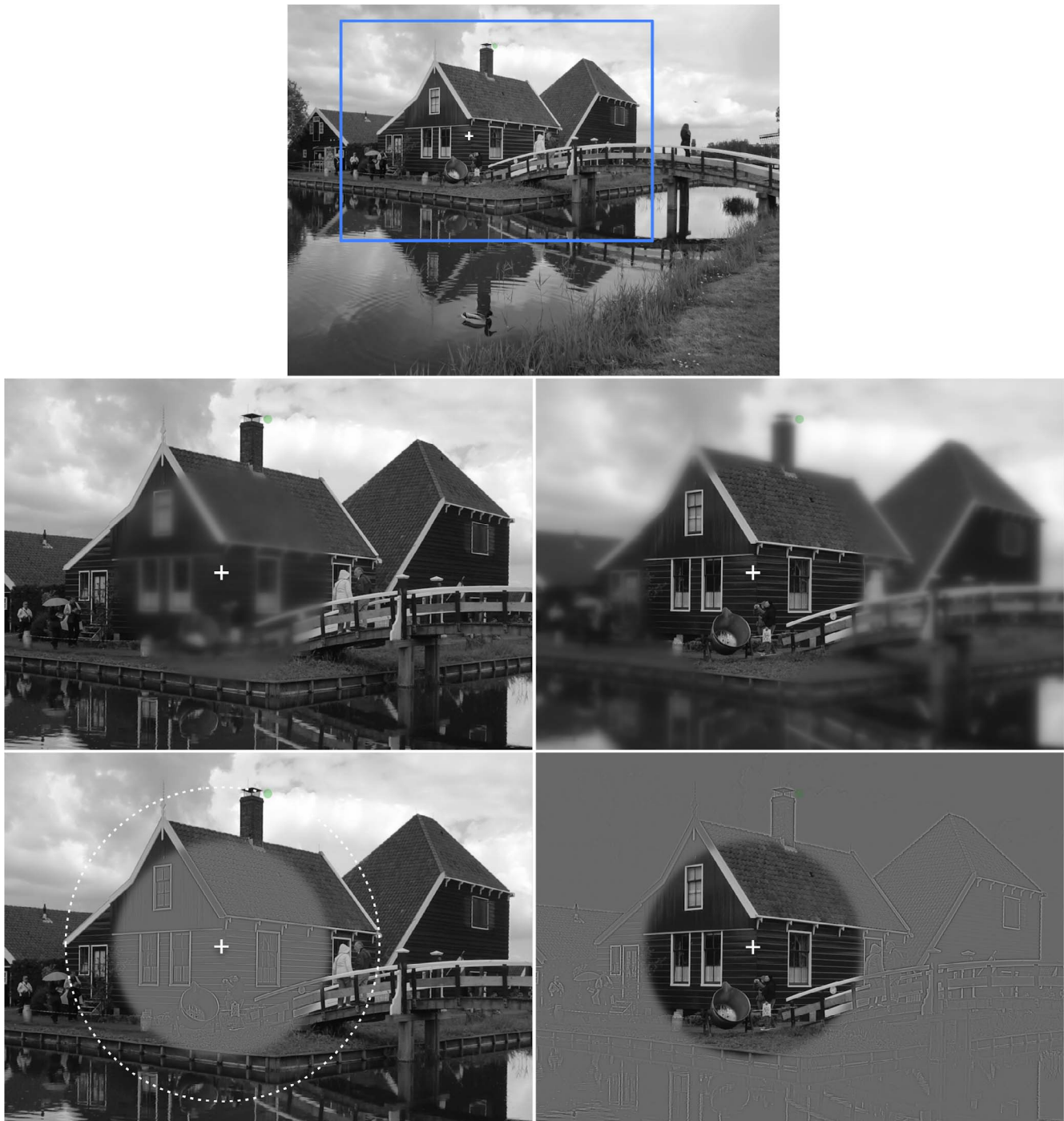
Figure 1. Illustration of the five conditions and the peripheral target stimulus in Experiment 1. The white cross indicates the current gaze position, and the dashed-line circle (see lower left image) indicates the possible target positions around the gaze at 7.5° eccentricity. In this example, the green target is located above the gaze. Target visibility varies with unfiltered, low-pass filtered, and high-pass filtered backgrounds because target detectability was set to 75% on each background (see Procedure). The top panel shows the original stimulus in the unfiltered control condition. Below, the four filter conditions are illustrated with cropped and zoomed-in versions of the original stimulus (indicated by the blue frame) to better illustrate the filter effects: (second row, left) central low-pass filtering, (second row, right) peripheral low-pass filtering, (third row, left) central high-pass filtering, (third row, right) peripheral high-pass filtering. Note that these images serve as illustrations; because of resampling in reproduction and because the illustrated scenes are at a smaller scale than presented in the experiment, they do not faithfully reproduce the filters actually used in the experiment.

Procedure

Data from each participant were collected in two sessions. In the first session, individual transparency thresholds for 75% target detection on unfiltered, low-pass filtered, and high-pass filtered backgrounds were determined. Each participant viewed three blocks of either unfiltered, completely low-pass filtered, or completely high-pass filtered scenes. The eye tracker was calibrated at the beginning of each block and after every 15 trials. Each trial started with a gray screen showing a central fixation point. If the point was fixated for at least 50 ms within 1 s from trial start, the scene was revealed; otherwise, a recalibration was initiated. Each scene was presented for 12 s. Participants were instructed to explore the scene and memorize the scene content. In addition, they were told to indicate the presence of the target stimulus by pressing the computer mouse button as quickly as possible. The response deadline for the target was reached after 1.5 s; later responses were labeled as misses. The transparency (alpha channel) of the target was adjusted using the QUEST algorithm, a Bayesian adaptive method for measuring psychometric thresholds. The QUEST staircase adjusted the transparency of the target on the scene between zero and one—smaller alpha values indicate a higher transparency of the target and thereby impede its segregation from the scene background. The individual transparency thresholds determined by QUEST then served as fixed target transparencies for unfiltered, low-pass filtered, and high-pass filtered peripheral backgrounds in the second session (i.e., the main experiment).

The main experiment presented scenes with gaze-contingent spatial frequency filtering. The eye tracker was calibrated at the beginning of the experiment and after every 15 trials. Two practice trials were given to acquaint participants with the gaze-contingent display and the tasks. As in the first session, each trial started with a central fixation trigger. Participants viewed 85 scenes that were each presented for 12 s. Varying from trial to trial, scenes were either presented unfiltered or with central or peripheral low-pass or high-pass filtering. For each of the five conditions, 17 scenes were presented. Participants were confronted with two tasks. First, they were instructed to inspect the scenes carefully in preparation for questions about the scene content. Additionally, they were asked to indicate the presence of a green circle as quickly as possible whenever detected by pressing the computer mouse button. To ensure that viewers actually engaged in processing the scene and not merely focused on target detection on a scene background, they were asked to answer a three-alternative question about the scene content after a randomly chosen 50% of the scenes. Questions typically asked about the presence or absence of certain objects in the scene (e.g., "Which

object was seen behind the car?"), about the location of objects (e.g., "Where in the scene was the Ferris wheel standing?"), or about the number of certain objects (e.g., "How many people were present in the scene?"). The memory question for the scene in Figure 1, for example, was "Which object was not present in the scene?" with the response alternatives "duck," "street lamp," or "other bird" (correct answer: "street lamp"). As each scene was presented for a long time, scenes were fairly rich in detail, and questions were constructed to be rather difficult to ensure that viewers would carefully explore each scene until the end of the trial. In a previous study (Cajar et al., 2016) in which we applied central and peripheral spatial-frequency filters to a similar stimulus set, including a majority of the present scenes, viewers answered the memory questions correctly in about 70%–75% of the cases although they had no other task. Because viewers in the present experiments were simultaneously confronted with target detection as a second task, we expected somewhat worse memory performance.

Data preparation

Saccades were detected in the raw time series of gaze positions using a velocity-based algorithm (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006) with a relative velocity threshold of 5 *SD* and a minimum duration of six data samples. A total of 28 trials (1.1%) were removed owing to poor calibration or too much data loss. Single fixations and saccades were removed if they neighbored eye blinks or if they were the first or last event of a trial and therefore associated with scene onset or offset. Overall, 80,647 fixations and 83,762 saccades remained for general eye-movement analyses, and 7,150 valid critical fixations during which the target stimulus was presented were left for analyses.

Data analyses

Dependent variables were analyzed using linear mixed-effects models (LMMs) and generalized linear mixed-effects models (GLMMs) as implemented in the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015) of the *R* system for statistical computing (version 3.2.3; R Core Team, 2015). In addition to the fixed effects for experimental conditions, mixed-effects models simultaneously account for random effects due to differences between subjects and items (i.e., scenes). (G)LMMs can account for the variance between subjects and items (a) in the mean of the dependent variable (random intercepts), (b) for all experimental conditions (random slopes), and (c) for correlations between intercepts and slopes. To identify the proper random-effects structure for each model, we applied the algorithm suggested by Bates, Kliegl, Vasishth, and

Baayen (2015). For fixed effects, GLMMs yield regression coefficients, standard errors, z values, and p values. LMMs only yield regression coefficients, standard errors, and t values because the degrees of freedom are not known exactly for LMMs. For large data sets as in the present experiment, however, the t distribution converges to the standard normal distribution for all practical purposes; consequently, t statistics of an absolute value of 1.96 or larger are considered significant on the two-tailed 5% level (Baayen, Davidson, & Bates, 2008, note 1). All (G)LMMs for Experiment 1 are provided in the online supplements to this article.

Results

Eye-movement behavior

Fixation durations and saccade amplitudes were analyzed using LMMs. Fixed effects were estimated using contrast coding that tested for (a) a difference between the control condition and all experimental conditions, (b) a main effect of filter type (low-pass vs. high-pass), (c) a main effect of filter location (periphery vs. center), and (d) an interaction between filter type and filter location. As distributions of fixation durations and saccade amplitudes were positively skewed, variables were transformed before model fitting to approximate normally distributed model residuals. To find a suitable transformation, the optimal λ-coefficient for the Box-Cox power transformation (Box & Cox, 1964) was estimated using the *boxcox* function of the *MASS* package (Venables & Ripley, 2002) with $y(\lambda) = (y^\lambda - 1)/\lambda$ if $\lambda \neq 0$ and $log(y)$ if $\lambda = 0$. For fixation durations, the log-transformation was optimal ($\lambda = -0.10$), and for saccade amplitudes, the transformation with $\lambda = 0.30$ was optimal. Critical fixations (during which the target was presented) and saccades that followed these critical fixations were excluded from the analyses because they likely reflect different eye-movement behavior in response to the target stimulus.

Saccade amplitudes: Mean saccade amplitudes are illustrated in Figure 2a. As expected from previous research, mean amplitudes lengthened with central and shortened with peripheral filtering relative to the unfiltered control condition. This is indicated by a strong main effect of filter region ($b = 1.78 \times 10^{-1}$, $SE = 1.07 \times 10^{-2}$, $t = 16.66$). Thus, viewers preferred unfiltered scene regions as saccade targets. The effect is also reflected in the distributions of saccade amplitudes (Figure 2c); with peripheral filtering, viewers placed more short saccades in the unfiltered central region and fewer long saccades in the filtered periphery compared with the unfiltered control. With central filtering, on the other hand, a higher proportion of long saccades and a lower proportion of short saccades were observed. The effects were stronger when critical spatial frequencies in

the central or the peripheral visual field were missing (i.e., with central low-pass filtering and peripheral high-pass filtering). Low-pass filtering therefore caused longer saccades than high-pass filtering with both filter locations, which is indicated by a main effect of filter type ($b = 5.36 \times 10^{-2}$, $SE = 4.67 \times 10^{-3}$, $t = 11.49$). For foveal analysis, low spatial frequencies are less important than high spatial frequencies; this led to fewer short inspection saccades with central low-pass filtering than with central high-pass filtering. High spatial frequencies, on the other hand, are of little use for peripheral target selection. Viewers therefore targeted the filtered periphery less often with peripheral high-pass filtering than with low-pass filtering and instead placed a higher proportion of short saccades in the unfiltered central region. The LMM also revealed an interaction between filter type and filter region ($b = 2.34 \times 10^{-2}$, $SE = 5.98 \times 10^{-3}$, $t = 3.92$) as the difference between filter types was slightly greater with central filtering than with peripheral filtering.

Fixation durations: Mean fixation durations are illustrated in Figure 2b. Fixation duration averaged across the four filter conditions significantly increased relative to unfiltered scene viewing ($b = 3.51 \times 10^{-2}$, $SE = 7.62 \times 10^{-3}$, $t = 4.60$). Mean fixation duration was longer with central filtering than with peripheral filtering ($b = 5.64 \times 10^{-2}$, $SE = 9.20 \times 10^{-3}$, $t = 6.13$). There was no main effect of filter type ($b = 1.19 \times 10^{-2}$, $SE = 8.89 \times 10^{-3}$, $t = 1.34$). However, an interaction between filter type and filter region occurred ($b = -7.17 \times 10^{-2}$, $SE = 8.58 \times 10^{-3}$, $t = -8.36$). With central filtering fixation durations were longer with high-pass filtering than with low-pass filtering, but with peripheral filtering fixation durations were longer with low-pass filtering than with high-pass filtering. Mean fixation duration even numerically dropped below the baseline with peripheral high-pass filtering (see Figure 2b). The effects replicate our results from a previous study (Laubrock et al., 2013) and indicate that fixations were prolonged more markedly when critical spatial frequencies were still available (center: high frequencies; periphery: low frequencies).

Task performance

Correct answer probability for the memory questions and target detection probability were analyzed using GLMMs with a logit link function. Reaction times to the target were analyzed with an LMM. Because the reaction time distribution was positively skewed, reaction times were transformed with $\lambda = -0.42$. Reaction times shorter than 260 ms ($N = 25$) and longer than 1200 ms ($N = 25$) were identified as clear outliers based on the raw reaction time distribution and were therefore excluded from the analysis. Fixed effects for all three dependent variables were estimated with
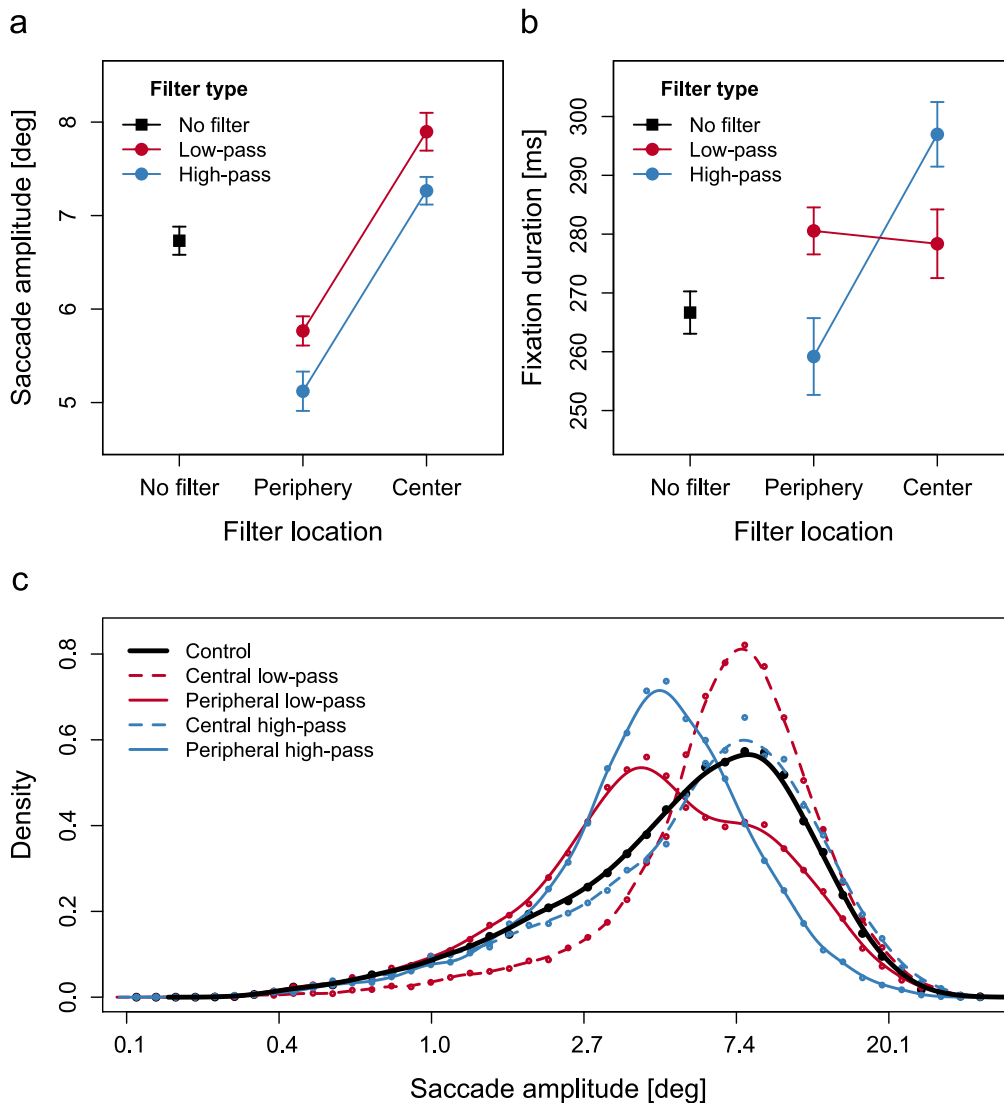
Figure 2. Eye-movement behavior in Experiment 1. Mean saccade amplitudes (a) and mean fixation durations (b). Error bars are 95% within-subject confidence intervals with the Cousineau-Morey correction applied (Cousineau, 2005; Morey, 2008). (c) Distributions of saccade amplitudes. The logarithmic scaling of the abscissa emphasizes the effects for short saccades. Lines represent kernel density estimates using a Gaussian kernel as implemented in the *R* function *density*; the bandwidth was chosen according to Silverman (1986), equation 3.31 with a weight of 1.2. The area under each curve adds up to one.

treatment contrasts as implemented in *R* that tested for differences between each filter condition and the unfiltered control condition.

Memory questions: Mean proportions of correct answers to memory questions about the scene content were 69.6% for the unfiltered control condition, 59.1% for central low-pass filtering, 66.0% for central high-pass filtering, 65.1% for peripheral low-pass filtering, and 63.4% for peripheral high-pass filtering. These values are far above the guessing probability and not far below the proportion of 70%–75% correct that we observed in a previous study (Cajar et al., 2016) using the same stimuli and scene encoding as a single task. We are therefore assured that viewers in the present experiment engaged in scene processing and did not disregard scene encoding

in favor of target detection. The GLMM showed that only central low-pass filtering significantly differed from the control condition in the proportion of correct answers ($b = -0.45$, $SE = 0.21$, $z = -2.16$, $p = 0.031$).

Target detection: Transparency thresholds for 75% target detection across participants were 0.36 ($SD = 0.07$) for unfiltered backgrounds, 0.24 ($SD = 0.07$) for low-pass filtered backgrounds, and 0.17 ($SD = 0.04$) for high-pass filtered backgrounds; the target was therefore most transparent on high-pass filtered backgrounds and least transparent on unfiltered backgrounds with low-pass filtered backgrounds in between.

Overall target detection probability was 72%. Mean probabilities for the five conditions are shown in Figure 3a. Target detection probability with central filtering
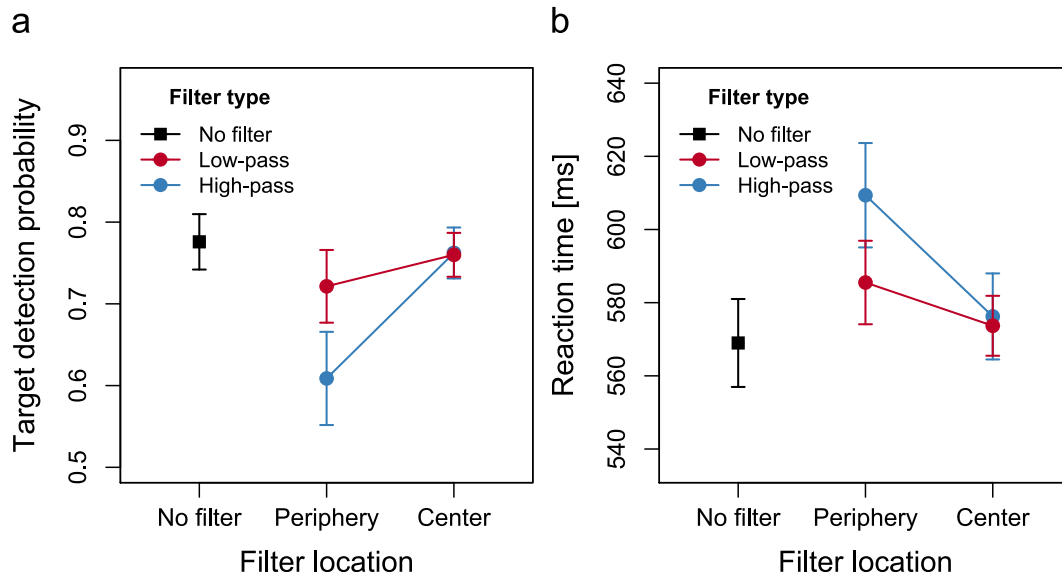
Figure 3. Task performance in Experiment 1. Mean target detection probability (a) and mean reaction time to the target (b). Error bars are 95% within-subject confidence intervals with the Cousineau-Morey correction applied (Cousineau, 2005; Morey, 2008).

did not differ from the control condition for either filter type ($b = -9.15 \times 10^{-2}$, $SE = 1.02 \times 10^{-1}$, $z = -0.90$, $p = 0.369$ for central low-pass filtering and $b = -4.21 \times 10^{-2}$, $SE = 1.12 \times 10^{-1}$, $z = -0.38$, $p = 0.707$ for central high-pass filtering). Peripheral filtering, on the other hand, decreased target detection probability relative to the control condition ($b = -3.09 \times 10^{-1}$, $SE = 9.08 \times 10^{-2}$, $z = -3.40$, $p < 0.001$ for peripheral low-pass filtering and $b = -8.09 \times 10^{-1}$, $SE = 1.83 \times 10^{-1}$, $z = -4.42$, $p < 0.001$ for peripheral high-pass filtering).

Overall reaction time to the target was 576 ms. Mean reaction times to the target for the five conditions are shown in Figure 3b. With central filtering, reaction times did not differ from the control condition for either filter type ($b = -2.49 \times 10^{-4}$, $SE = 2.62 \times 10^{-4}$, $t = -0.95$ for central low-pass filtering and $b = -3.52 \times 10^{-4}$, $SE = 3.09 \times 10^{-4}$, $t = -1.14$ for central high-pass filtering). Reaction times slowed down, however, with both peripheral filters ($b = -8.17 \times 10^{-4}$, $SE = 2.78 \times 10^{-4}$, $t = -2.94$ for peripheral low-pass filtering and $b = -2.23 \times 10^{-3}$, $SE = 3.96 \times 10^{-4}$, $t = -5.62$ for peripheral high-pass filtering).

As participants were allowed to move their eyes freely during scene viewing, we were also interested in the coupling between eye movements and the distribution of covert attention. We therefore investigated how target detection, which could only be achieved using peripheral vision, was correlated with the size and direction of the saccade that followed the critical fixation. For this purpose, target detection probability was analyzed as a function of the angle between target position and landing position as well as amplitude of the subsequent saccade (see Figure 4a for further

details). A saccade that landed on the former target position corresponds to a target–saccade angle of 0° of arc and a saccade amplitude of 7.5° of visual angle. Figure 4b shows a plot of target detection probability across all five conditions as a function of target–saccade angle (in steps of 45° of arc) and saccade amplitude (divided into three bins). Expectedly, target detection probability was highest when the subsequent saccade landed near the former position of the target, supporting the findings that saccades and attention are tightly coupled (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler et al., 1995). Detection probability appeared worst when saccades longer than 10° of visual angle were made that also landed more than 67° of arc away from the previous target position. Most interestingly, target detection probability was generally best when saccade amplitudes were similar to the target's distance from the fovea rather independent of saccade direction.[2] A GLMM using a logit link function and treatment contrasts tested for differences of target detection probability between the three ranges of saccade amplitude (<5°, 5° to 10°, and >10° of visual angle). The amplitude range from 5° to 10°, which includes the target's distance from the fovea, served as the reference category ($b = 1.61$, $SE = 0.12$, $z = 13.56$, $p < 0.001$). Compared to this amplitude range, target detection probability significantly decreased for saccade amplitudes <5° ($b = -1.24$, $SE = 0.12$, $z = -9.97$, $p < 0.001$) and for amplitudes >10° ($b = -1.59$, $SE = 0.12$, $z = -13.66$, $p < 0.001$). These results might indicate a ring-shaped allocation of covert attention induced by the present task demands with which several peripheral locations
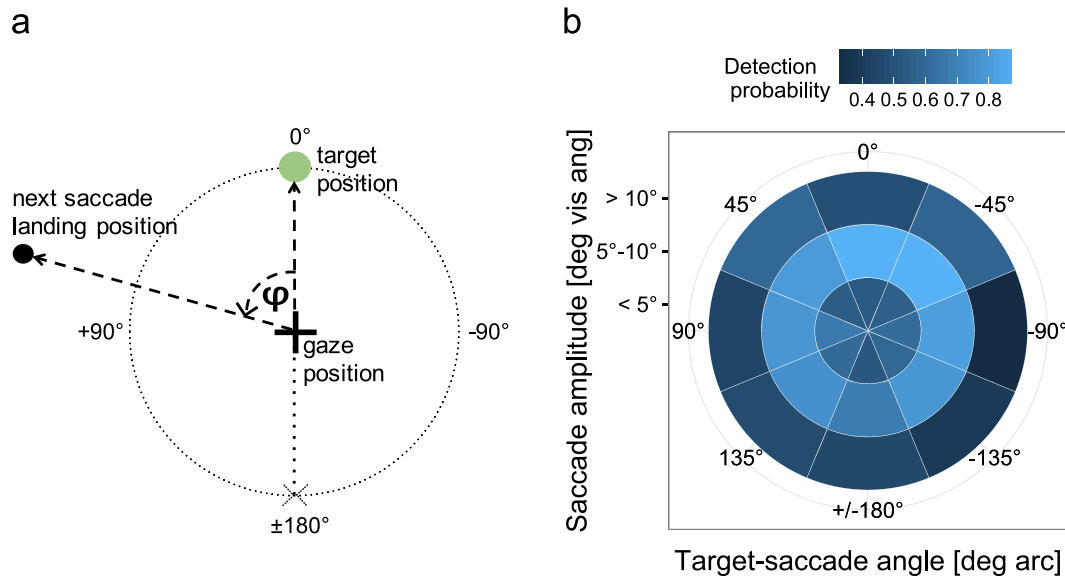
a

b

Figure 4. Target detection probability as a function of target–saccade angle. (a) The target–saccade angle φ was computed as angle of the arc between vectors connecting the gaze position during the critical fixation with the position of the target and the landing position of the subsequent saccade. An angle of 0° of arc corresponds to a saccade in the direction of the target. Positive angles ranging from 0° to +180° correspond to saccade landing positions to the left of the target whereas negative angles ranging from 0° to −180° correspond to saccade landing positions to the right of the target. (b) Target detection probability as a function of target–saccade angle and saccade amplitude in Experiment 1. Probability was computed for target–saccade angles in steps of 45° of arc and for three ranges of saccade amplitude: <5°, 5°–10°, and >10° of visual angle. The medium amplitude range (5°–10°) comprised all possible target positions at 7.5° retinal eccentricity. Lighter colors in the plot correspond to a higher probability to detect the target.

are scanned in parallel for the detection of the target, of which only one is chosen as the next saccade target.

Experiment 2

Experiment 1 found support for the hypothesis that reductions of saccade amplitude due to peripheral filtering involve a corresponding withdrawal of attention from the peripheral visual field. Experiment 2 tested whether increased saccade amplitudes with central filtering reflect a withdrawal of attention from the central visual field. As in Experiment 1, high or low spatial frequencies were filtered either in the central or the peripheral visual field during scene viewing. Viewers explored the scene in preparation for a memory task while simultaneously detecting targets. In contrast to Experiment 1, targets were presented in the central rather than the peripheral visual field. Saccade amplitudes were expected to increase with central filtering and to decrease with peripheral filtering relative to the unfiltered control, especially with central low-pass and peripheral high-pass filtering. If saccade amplitudes reflect attention, central filtering should reduce central target detection and slow down target response times whereas peripheral filtering should not interfere with central target detection.

Method

Participants

Participants were 30 students from the University of Potsdam (three male, mean age: 22 years) with normal or corrected-to-normal vision and normal color discrimination. None of them participated in Experiment 1. They received course credit or 12 Euro for participation and were naive as to the purpose of the experiment. The experiment conformed to the Declaration of Helsinki. Participants gave their written informed consent prior to the experiment.

Apparatus

The apparatus was the same as in Experiment 1.

Stimuli and design

Stimuli and design were the same as in Experiment 1. The only difference was that the target was not presented in the peripheral but in the central visual field at a random location 3.5° away from the current fixation point.

Procedure

The procedure was the same as in Experiment 1.

Data preparation

A total of 27 trials (1.0%) were removed owing to poor calibration or too much data loss. Overall, 75,888 fixations and 79,164 saccades remained for eye-movement analyses. Furthermore, 6,718 valid critical fixations during which the target stimulus was presented were left for analyses.

Data analyses

Data analyses were performed as in Experiment 1. All (G)LMMs for Experiment 2 are provided in the online supplements to this article.

Results

Eye-movement behavior

LMMs were performed as in Experiment 1. Fixation durations were log-transformed before model fitting, and saccade amplitudes were transformed with $\lambda = 0.26$. Critical fixations during which the target was presented and saccades that followed these critical fixations were excluded from the analyses.

Saccade amplitudes: Mean saccade amplitudes are illustrated in Figure 5a. Results parallel those of Experiment 1. Mean saccade amplitudes increased with central filtering and decreased with peripheral filtering, leading to a strong main effect of filter location ($b = 1.72 \times 10^{-1}$, $SE = 8.75 \times 10^{-3}$, $t = 19.67$). Furthermore, a main effect of filter type indicated longer amplitudes with low-pass filtering than with high-pass filtering with both filter locations ($b = 5.53 \times 10^{-2}$, $SE = 5.99 \times 10^{-3}$, $t = 9.23$). The distributions of saccade amplitudes (see Figure 5c) also reflect the same pattern as in Experiment 1. With central filtering, the amount of short saccades decreased whereas the amount of longer saccades increased, particularly with low-pass filtering. With peripheral filtering, on the other hand, the amount of short saccades increased and the amount of long saccades decreased, particularly with high-pass filtering. An interaction of filter type and filter location ($b = 1.86 \times 10^{-2}$, $SE = 7.63 \times 10^{-3}$, $t = 2.44$) occurred because the difference between filter types was greater with central than with peripheral filtering. Note that the distribution of saccade amplitudes in the control condition suggests that participants did not prioritize the target-detection task; otherwise, a pronounced mode of the distribution would be expected at the target eccentricity of 3.5°.

Fixation durations: Mean fixation durations are illustrated in Figure 5b. Fixation duration averaged across the four filter conditions did not increase relative to the unfiltered control ($b = 1.25 \times 10^{-2}$, $SE = 1.02 \times 10^{-2}$, $t = 1.2$). With peripheral high-pass filtering, mean fixation duration was even numerically shorter than in the

control condition (see Figure 5b). Fixations were significantly longer with central than with peripheral filtering ($b = 5.66 \times 10^{-2}$, $SE = 1.12 \times 10^{-2}$, $t = 5.1$). A main effect of filter type also indicated longer fixation durations with low-pass than with high-pass filtering ($b = 3.54 \times 10^{-2}$, $SE = 9.96 \times 10^{-3}$, $t = 3.6$). However, this main effect was qualified by an interaction between filter type and filter location ($b = -3.84 \times 10^{-2}$, $SE = 7.38 \times 10^{-3}$, $t = -5.2$), showing that fixation durations were indeed longer with low-pass filtering than with high-pass filtering in the periphery but that there was no difference between filter types with central filtering.

Task performance

GLMMs and the LMM were performed as in Experiment 1. Reaction times were transformed before model fitting with $\lambda = -0.42$. Reaction times shorter than 240 ms ($N = 17$) were identified as clear outliers based on the raw reaction time distribution and the LMM residuals and were therefore excluded from the analysis.

Memory questions: Mean proportions of correct answers to the memory questions about the scene content were 70.8% for the unfiltered control condition, 60.9% for central low-pass filtering, 63.0% for central high-pass filtering, 66.8% for peripheral low-pass filtering, and 66.3% for peripheral high-pass filtering. These values assured us that viewers in the present experiment actually engaged in scene processing and did not disregard scene encoding in favor of target detection. The decrease in the proportion of correct answers relative to the control condition was significant with central low-pass filtering ($b = -0.52$, $SE = 0.21$, $z = -2.44$, $p = 0.015$) and marginally significant with central high-pass filtering ($b = -0.41$, $SE = 0.21$, $z = -1.91$, $p = 0.056$). The decrease with peripheral filtering was not significant.

Target detection: Transparency thresholds for 75% target detection across participants were 0.21 ($SD = 0.04$) for unfiltered backgrounds, 0.14 ($SD = 0.04$) for low-pass filtered backgrounds, and 0.10 ($SD = 0.02$) for high-pass filtered backgrounds. Thresholds were lower than in Experiment 1 because the target was closer to the fovea and therefore easier to detect.

Overall target detection probability was 67.2%. Mean detection probabilities for the five conditions are shown in Figure 6a. Detection probability with peripheral filtering was similar to the unfiltered control condition for both filter types ($b = -1.30 \times 10^{-1}$, $SE = 1.00 \times 10^{-1}$, $z = -1.30$, $p = 0.195$ for high-pass filtering and $b = 9.01 \times 10^{-3}$, $SE = 9.41 \times 10^{-2}$, $z = 0.10$, $p = 0.924$ for low-pass filtering). With central filtering, on the other hand, target detection probability significantly decreased with both filter types ($b = -3.70 \times 10^{-1}$, $SE = 8.74 \times 10^{-2}$, $z = -4.23$, $p < 0.001$ for low-
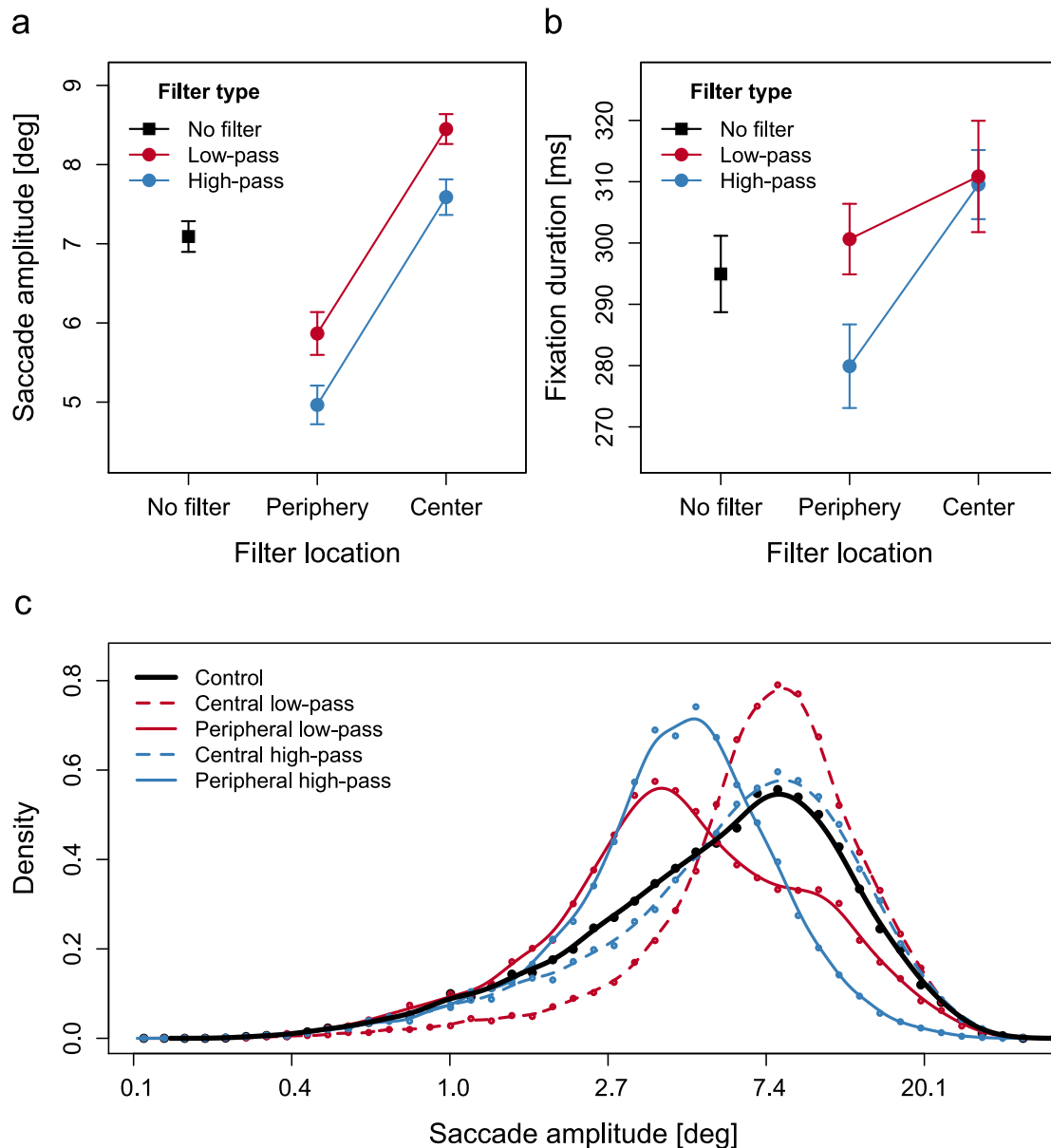
Figure 5. Eye-movement behavior in Experiment 2. Mean saccade amplitudes (a) and mean fixation durations (b). Error bars are 95% within-subject confidence intervals with the Cousineau-Morey correction applied (Cousineau, 2005; Morey, 2008). (c) Distributions of saccade amplitudes. The logarithmic scaling of the abscissa emphasizes the effects for short saccades. Lines represent kernel density estimates using a Gaussian kernel as implemented in the *R* function *density*; the bandwidth was chosen according to Silverman (1986), equation 3.31 with a weight of 1.2. The area under the curve adds up to one.

pass filtering and $b = -1.42$, $SE = 1.75 \times 10^{-1}$, $z = -8.08$, $p < 0.001$ for high-pass filtering). Contrary to our predictions, this decrease was more dramatic with central high-pass filtering.

Overall reaction time to the target was 619 ms. Mean reaction times for the five conditions are illustrated in Figure 6b. Reaction times did not differ from the unfiltered control with peripheral low-pass filtering ($b = -4.09 \times 10^{-4}$, $SE = 2.81 \times 10^{-4}$, $t = -1.45$) but increased with all other filter conditions, especially with central high-pass filtering ($b = -7.35 \times 10^{-4}$, $SE = 3.32 \times 10^{-4}$, t

$= -2.21$ for peripheral high-pass filtering; $b = -7.59 \times 10^{-4}$, $SE = 2.77 \times 10^{-4}$, $t = -2.74$ for central low-pass filtering; and $b = -2.84 \times 10^{-3}$, $SE = 3.64 \times 10^{-4}$, $t = -7.82$ for central high-pass filtering).

As in Experiment 1, we investigated how target detection depended on the size and direction of the saccade following the critical fixation. For this purpose, target detection probability was plotted across all five conditions as a function of target–saccade angle (i.e., the angle between target position and landing position of the subsequent saccade in steps of 45° of arc) and
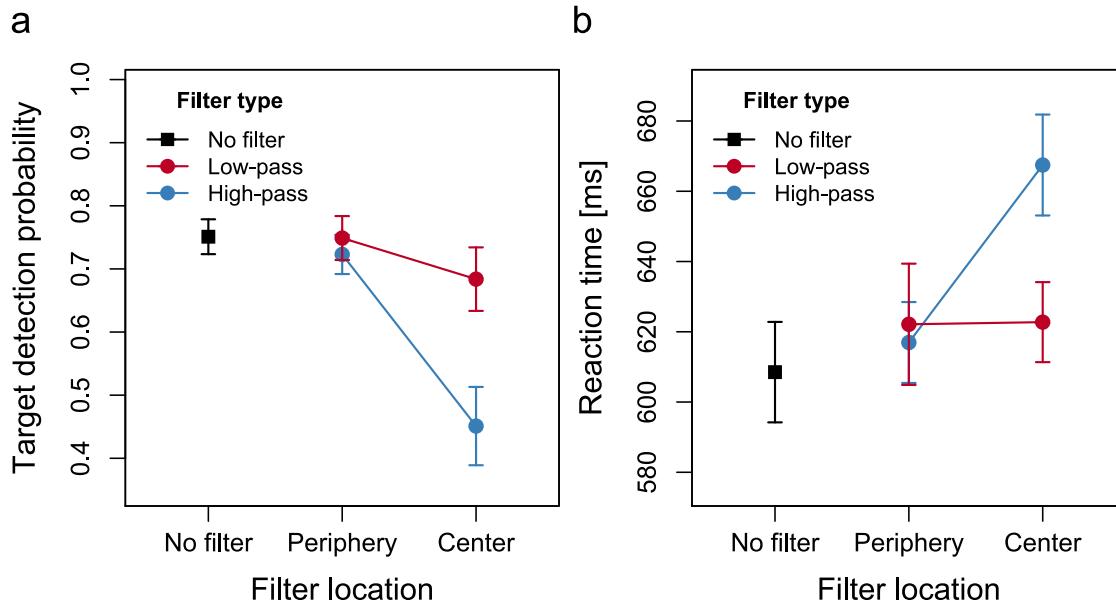
Figure 6. Task performance in Experiment 2. Mean target detection probability (a) and mean reaction time to the target (b). Error bars are 95% within-subject confidence intervals with the Cousineau-Morey correction applied (Cousineau, 2005; Morey, 2008).

saccade amplitude (ranges: <5°, 5° to 10°, >10°) as illustrated in Figure 7. Corresponding to the results of Experiment 1, target detection probability was best when saccade amplitudes were similar to the target's distance from the fovea rather independent of saccade direction. A GLMM with a logit link function and

Figure 7. Target detection probability as a function of target–saccade angle (see Figure 4a for further details) and saccade amplitude in Experiment 2. Probability was computed for target–saccade angles in steps of 45° of arc and for three ranges of saccade amplitude: <5°, 5° to 10°, and >10° of visual angle. The small amplitude range (<5°) comprised all possible target positions at 3.5° retinal eccentricity. Lighter colors in the plot correspond to a higher probability to detect the target.

treatment contrasts tested for differences of target detection probability between the three ranges of saccade amplitude (<5°, 5° to 10°, and >10° of visual angle). The range of amplitudes <5°, which includes the target's distance from the fovea, served as the reference category ($b = 1.37$, $SE = 0.10$, $z = 13.72$, $p < 0.001$). Compared to this amplitude range, target detection probability significantly decreased for saccade amplitudes of 5° to 10° ($b = -1.41$, $SE = 0.11$, $z = -12.70$, $p < 0.001$) and for amplitudes >10° ($b = -1.82$, $SE = 0.11$, $z = -16.86$, $p < 0.001$). As in Experiment 1, the results suggest that target detection probability correlated with the amplitude rather than the direction of the planned saccade.
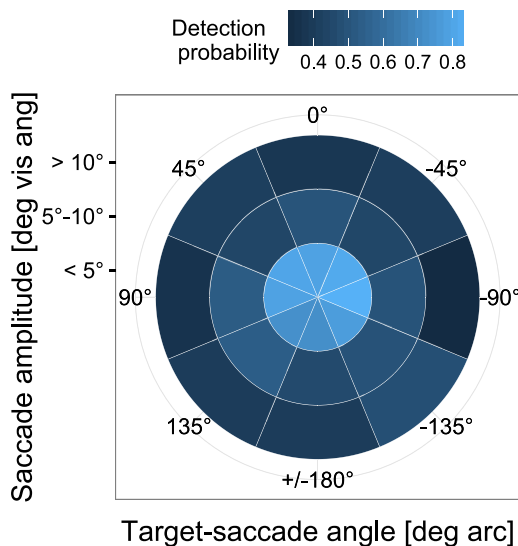
Discussion

In two experiments, we investigated how the degradation of complex natural scenes in the central or the peripheral visual field affects the distribution of attention. For this purpose, participants had to detect central or peripheral targets while viewing scenes under experimental gaze-contingent degradation. Previous research suggests that the useful field of view shrinks with increasing processing demands in the central or the peripheral visual field (Crundall et al., 1999; Holmes et al., 1977; Ikeda & Takeuchi, 1975; Loschky & McConkie, 2002; Williams, 1985, 1989, 1995); consequently, performance in a peripheral detection task would be expected to decrease when either part of the scene is degraded. However, saccades are typically

longer with central filtering and shorter with peripheral filtering (Foulsham et al., 2011; Laubrock et al., 2013; Loschky & McConkie, 2002; Loschky et al., 2005; Nuthmann, 2013, 2014; Nuthmann & Malcolm, 2016; Reingold & Loschky, 2002; Shiori & Ikeda, 1989; van Diepen, 2001; van Diepen & Wampers, 1998). This saccade amplitude pattern might reflect a modified distribution of attention: a narrower attentional focus with peripheral filtering and a stronger attentional bias toward the periphery with central filtering.

To explicitly test this hypothesis, we filtered high or low spatial frequencies in the central or the peripheral visual field during scene viewing and measured the detection of peripheral (Experiment 1) or central (Experiment 2) targets that were present in the scenes during randomly chosen fixations. Assuming that saccade amplitudes reflect attentional selection, peripheral target detection was expected to decrease with peripheral but not with central filtering whereas central target detection was expected to decrease with central but not with peripheral filtering.

Main experimental findings

Both experiments show that peripheral spatial frequency filtering shortens saccade amplitudes and that central filtering lengthens saccade amplitudes, which is in line with previous findings (Foulsham et al., 2011; Laubrock et al., 2013; Loschky & McConkie, 2002; Loschky et al., 2005; Nuthmann, 2013, 2014; Nuthmann & Malcolm, 2016; Reingold & Loschky, 2002; Shiori & Ikeda, 1989; van Diepen, 2001; van Diepen & Wampers, 1998). These effects were stronger when spatial frequencies that are most important for foveal analysis and peripheral target selection were missing, that is, with central low-pass and peripheral high-pass filtering. The latter finding differs from our previous finding in Laubrock et al. (2013), in which peripheral low-pass filtering shortened saccade amplitudes slightly more than peripheral high-pass filtering did. The present experiments, however, corroborate the notion that saccade amplitudes are increasingly adjusted as the potential usefulness of information decreases.

A new result reported here is a strong and specific effect of central and peripheral scene degradation on target detection in these regions. We observed that target detection probability changed according to the different filter conditions, indicating that central and peripheral scene degradation entail a modulation of attention. Peripheral filtering decreased detection probability and increased response times for peripheral targets, particularly with high-pass filtering. With central filtering, detection probability and response times for peripheral targets were similar to the

unfiltered control condition with both filter types. For central targets, effects were reversed. Central filtering decreased detection probability and increased response times for central targets, particularly with high-pass filtering. With peripheral filtering, target detection was unaffected with both filter types, and response times slightly increased with high-pass filtering but not with low-pass filtering.

Effects of peripheral filtering: Tunnel vision

Our findings support the hypothesis that peripheral degradation of natural scenes provokes tunnel vision (Mackworth, 1965; Williams, 1988) with a reduced attentional focus that leads to a decreased perceptibility of peripheral stimuli. Thus, shorter saccade amplitudes reflect a reduced spatial extent of attention. Filtering spatial frequencies in the peripheral visual field impairs the processing of peripheral scene information and saccade target selection. With peripheral low-pass filtering, viewers took more time to process the blurred peripheral information, indicated by increased fixation durations and increased response times to peripheral targets. Furthermore, decreased saccade amplitudes together with a decreased probability to detect the peripheral target indicate a reduced attentional span with the attentional focus on the unfiltered central region. This focus became even stronger with peripheral high-pass filtering. High-pass filtering attenuates low spatial frequencies that are essential for the processing of peripheral information so that little useful information is left in the periphery. As a consequence, mean saccade amplitude shortened to about 5°, and mean fixation duration numerically decreased below the baseline, which is reasonable because the amount of potentially useful information needing to be processed was reduced. Furthermore, peripheral detection performance was markedly worse, and target response times were strongly inflated compared with low-pass filtering and the unfiltered control. Thus, shorter saccades reflected a smaller attentional span that often caused peripheral information to be ignored (hence the decrease in fixation durations with reduced time for peripheral processing) and saccade targets to be chosen from the unfiltered central visual field.

We conclude that peripheral filtering shrinks the attentional focus and thus lowers the sensitivity to peripheral stimuli in the scene. This effect strengthens as the amount of potentially useful information decreases. The detectability of target stimuli in the central visual field, however, was similar to the control condition with peripheral filtering for both filter types. Thus, peripheral filtering did not impair central target detection. However, it did not elevate detection probability above the baseline either, which is what one

might expect when attention is mainly focused on the central visual field and withdrawn from the periphery. The lack of improvement in target detection is compatible with results from experiments that orthogonally varied the size of the attended area and found that, given a situation with a small stimulus and a large attention field, valid cues do not cause cueing benefits whereas invalid cues lead to costs (Herrmann et al., 2010). Furthermore, the visibility of the target was set to 75% detection probability for each background and participant in advance, and it might not be possible for participants to exceed this threshold even with more attentional resources available for processing in the central region.

Effects of central filtering: Attentional bias toward the periphery

When information in the central visual field was degraded, detection probability for central targets decreased markedly and response times increased whereas detection probability for peripheral targets was unaffected. This indicates that longer saccade amplitudes with central filtering reflect a withdrawal of attention from the central visual field toward the periphery, thus decreasing the perceptibility of central stimuli. With low-pass filtering, only blurred information is left in the central visual field, impairing the identification of objects and the analysis of details. Consequently, central information is not processed exhaustively, but attention is shifted more frequently toward the unfiltered peripheral region as indicated by a reduced proportion of short saccades, an increased amount of long saccades, and a decrease in detection probability for central targets.

Surprisingly, performance in the central detection task was substantially weaker with central high-pass than with low-pass filtering. As the central visual field is very sensitive to medium and high spatial frequencies (Hilz & Cavonius, 1974; Robson & Graham, 1981), which are critical for foveal analysis, we expected processing to be easier with central high-pass filtering than with central low-pass filtering. Therefore, target detection probability was expected to be higher for high-pass filtering as attention should not be withdrawn that much from the central visual field. We suggest two post hoc explanations for the strong decrease of detection probability. First, we did not directly test for the usefulness of high or low spatial frequencies in either part of the visual field. Thus, we cannot rule out that high-pass filtering actually hampered processing more than low-pass filtering (e.g., due to the loss of contrast, luminance, and color), leading to a stronger withdrawal of attention from the central region and thus to a lower perceptibility to

central targets. However, effects of central high-pass filtering on saccade amplitudes—if reflecting attentional selection—are not compatible with this interpretation as mean amplitudes were smaller than with low-pass filtering, and the amplitude distribution was similar to the one for the unfiltered control condition. We therefore suggest the following explanation. High-pass filtered information was more critical for processing than low-pass filtered information, making it more worthwhile to analyze the filtered central region. However, the processing of experimentally degraded information requires more resources than the processing of undegraded information; hence, the attentional focus during the processing of high-pass filtered central information might have been smaller than usual, concentrating strongly on foveal information processing.

An interesting new finding of the present study is that central filtering did not affect the sensitivity to peripheral targets. Thus, although foveal load presumably increased due to higher processing demands with central filtering, the size of the attentional focus was not reduced. Previous research, however, suggests that performance on peripheral detection is reduced by increased foveal load (Crundall et al., 1999; Holmes et al., 1977; Ikeda & Takeuchi, 1975; Ringer, Throneburg, Johnson, Kramer, & Loschky, 2016; Williams, 1985, 1989, 1995) because more attentional resources are needed in the central region, which shrinks the functional field of view. The present study provides no evidence for such shrinkage with increased central processing demands. However, we induced increased foveal load in terms of a very low-level visual feature, namely the spatial frequency content of the images, which is known to be processed by cells in V1 (Shapley & Lennie, 1985; Tootell, Silverman, & De Valois, 1981). An attentional filter may thus be applied at a fairly low level of processing. Conversely, the aforementioned studies on foveal load appear to involve attentional resources at a higher, often executive, level of processing (e.g., foveal letter discrimination). Thus, the opposing results between our study and previous studies might be explained by the different levels of processing that the respective foveal tasks involved. Note, however, that the increase in fixation durations we found with central filtering suggests that the filtering effects were propagated to the cognitive level.

Our results, although suggesting that attentional resources are withdrawn from the degraded central region toward the peripheral visual field, provide no evidence for an improvement of peripheral target detection. We assume that three factors contribute to the lack of improvement in the peripheral detection task with central filtering. First, viewers were confronted with two tasks that they had to trade off against each other (scene memorization and target

detection). As central filtering hampered the encoding of the central stimulus, scene memorization was more difficult, which might have interfered with peripheral target detection. Second, the peripheral visual field comprises the largest part of the scene, so any given area has only a small chance to be covered by a narrow attentional spotlight, and conversely, a very diffuse spotlight of attention (i.e., a zoomed-out zoom lens of attention) would only barely raise the level across the whole field (Eriksen & James, 1986; Eriksen & Yeh, 1985; Müller, Bartelt, Donner, Villringer, & Brandt, 2003). Therefore, it is unlikely a priori that peripheral target sensitivity was elevated to a level markedly above the baseline. Third, as explained above, it is unlikely that the threshold of 75% detection probability that was determined for each background and participant in advance could be exceeded.

Post hoc analyses: Partial independence of saccade amplitudes and direction

As viewers were engaged in a dynamic task that allowed them to freely move their eyes around, we also investigated the coupling of attention and eye-movement planning and execution. We analyzed how the probability of covertly detecting the central or peripheral target varied as a function of size and direction of the subsequent saccade. Results for both central and peripheral targets showed a marked enhancement of target detection probability for saccade amplitudes corresponding to the target's distance from the fovea, surprisingly, with the enhancement being rather independent of saccade direction. This is compatible with a ring-shaped allocation of covert attention induced by the present task demands and might indicate that attention scans several parafoveal or peripheral locations in parallel for detecting the target, of which only one is chosen as the next saccade target. Although we obtained these results in a post hoc analysis and thus cannot disentangle cause and consequence, our findings appear to corroborate the idea that covert attentional scanning is faster than overt attention and that it can be allocated in a ring-shaped fashion (Egly & Homa, 1984; Juola et al., 1991). Alternatively, the results might suggest that saccade amplitude and saccade direction are computed in partial independence.

Conclusions

In summary, we observed reduced saccade lengths induced by peripheral scene degradation and increased saccade lengths induced by central scene degradation. Our results lend support to the interpretation that these effects in scene-exploration behavior are created by modulations of covert attention. We have shown that increased peripheral processing demands lead to tunnel vision with a withdrawal of attention from the peripheral visual field. This effect is considerably reduced when low-frequency information is preserved in the periphery, which constitutes further evidence for the selective importance of different spatial frequency bands for saccade planning and peripheral scene analysis. Furthermore, the present findings indicate that increased central processing demands during scene viewing can lead to a withdrawal of attention from (at least part of) the central visual field and an attentional bias toward the periphery. Thus, the attentional focus does not necessarily become smaller with increasing central processing demands. Finally, we have shown in a post hoc analysis that, although saccade planning and target detection tend to go along, attention can also select locations that are not related to saccades. These results are highly relevant to theories on the coupling of attention and eye movements.

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Footnotes

[1] More precisely, the target was set on and off at the next possible display refresh, usually 6.7 ms after detection of the event.

[2] Note that this effect was consistently found for all five filter conditions separately (not shown).

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