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Spatial frequency processing in the central and peripheral visual field during scene viewing

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ABSTRACT

Visuospatial attention and gaze control depend on the interaction of foveal and peripheral processing. The foveal and peripheral regions of the visual field are differentially sensitive to parts of the spatial-frequency spectrum. In two experiments, we investigated how the selective attenuation of spatial frequencies in the central or the peripheral visual field affects eye-movement behavior during real-world scene viewing. Gaze-contingent low-pass or high-pass filters with varying filter levels (i.e., cutoff frequencies; Experiment 1) or filter sizes (Experiment 2) were applied. Compared to unfiltered control conditions, mean fixation durations increased most with central high-pass and peripheral low-pass filtering. Increasing filter size prolonged fixation durations with peripheral filtering, but not with central filtering. Increasing filter level prolonged fixation durations with low-pass filtering, but not with high-pass filtering. These effects indicate that fixation durations are not always longer under conditions of increased processing difficulty. Saccade amplitudes largely adapted to processing difficulty: amplitudes increased with central filtering and decreased with peripheral filtering; the effects strengthened with increasing filter size and filter level. In addition, we observed a trade-off between saccade timing and saccadic selection, since saccade amplitudes were modulated when fixation durations were unaffected by the experimental manipulations. We conclude that interactions of perception and gaze control are highly sensitive to experimental manipulations of input images as long as the residual information can still be accessed for gaze control.

1. Introduction

Why do we move our eyes? Due to sensory and cognitive limitations, high-acuity vision is restricted to the central 2° of the visual field, the fovea, whereas the visual periphery is rather blurry (Strasburger, Rentschler, & Jüttner, 2011; Wertheim, 1894). As a consequence, high-velocity saccades shift the gaze about three times each second to bring regions of interest from the low-resolution periphery into the fovea for closer inspection. Two tasks are accomplished during the following fixation: fine-grained foveal information is analyzed to identify objects and details, and coarse-grained peripheral information is analyzed to select the next saccade target among competing regions of interest. Thus, visual information in the central and the peripheral visual field serve different tasks (Gilchrist, 2011).

The present study investigates how the two tasks of foveal analysis and peripheral selection are accomplished during real-world scene viewing when fine-grained or coarse-grained information is selectively attenuated in the central or the peripheral visual field. Inherently this also sheds light on the question to what degree central and peripheral vision contribute to spatial and temporal aspects of eye-movement behavior. The issue can be tackled by attenuating high or low spatial frequencies in the central or the peripheral visual field. High spatial frequencies provide the fine-grained information of an image and low spatial frequencies provide the coarse-grained information of an image. High-pass filters preserve high spatial frequencies and attenuate low spatial frequencies; with low-pass filters, it is vice versa. Information can be selectively altered in either the central or the peripheral part of the visual field by applying a gaze-contingent window of arbitrary size that moves with the current gaze position of the viewer in real-time during scene inspection (McConkie & Rayner, 1975; Rayner & Bertera, 1979). Spatial frequencies are filtered either inside or outside the gaze-contingent window with central or peripheral filtering respectively, while the other region of the scene remains unchanged.

Previous research on this topic is rather scant and has mostly been focused on the effects of peripheral low-pass filtering. Corresponding studies indicate that spatial-frequency filtering impairs

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scene processing, as viewers' performances in several tasks decrease with filtering. For example, when searching for objects in scenes, search accuracy decreases and search times increase with peripheral as well as with central low-pass filtering; these effects get stronger as filter level and filter size increase (Loschky & McConkie, 2002; Nuthmann, 2014). Furthermore, the probability to detect target stimuli in low-pass or high-pass filtered scene regions decreases and response times for detected targets increase (Cajar, Schneeweiß, Engbert, & Laubrock, 2016). Central low-pass filtering has also been shown to decrease response accuracy to memory questions about scenes (Cajar et al., 2016). These findings suggest that the processing difficulty of a scene increases with spatial-frequency filtering, and increases more the larger or stronger the filter gets.

In agreement with the decrease in task performance, eye-movement behavior has been reported to deviate progressively from viewing behavior in unfiltered scenes as spatial-frequency filtering increases processing difficulty. Studies consistently show that viewers prefer unfiltered scene regions as saccade targets. Peripheral filtering shortens mean saccade amplitudes, since viewers tend to keep their gaze inside the unfiltered central region and avoid longer saccades to the filtered periphery (Cajar et al., 2016; Foulsham, Teszka, & Kingstone, 2011; Laubrock, Cajar, & Engbert, 2013; Loschky & McConkie, 2002; Loschky, McConkie, Yang, & Miller, 2005; Nuthmann, 2013; Nuthmann, 2014; Shioiri & Ikeda, 1989). Central filtering, on the other hand, lengthens mean saccade amplitudes, since viewers tend to place fewer saccades inside the filtered center and make more long saccades to the periphery (Cajar et al., 2016; Laubrock et al., 2013; Nuthmann, 2014). With both central and peripheral low-pass filtering, the effects get larger with increasing filter size (Loschky & McConkie, 2002; Nuthmann, 2013; Nuthmann, 2014) and filter level (Loschky & McConkie, 2002). Thus, saccadic selection is modulated more and more as processing difficulty increases. It has been shown recently that these changes in saccade amplitudes go along with corresponding changes in visuospatial attention (Cajar et al., 2016).

Fixation duration also varies with visual-cognitive processing and usually increases as the acquisition of information from the scene becomes more difficult (Henderson, 2003; Nuthmann, Smith, Engbert, & Henderson, 2010). Thus, studies show that fixation durations increase with spatial-frequency filtering of the entire scene (Glaholt, Rayner, & Reingold, 2013; Henderson, Olejarczyk, Luke, & Schmidt, 2014; Mannan, Ruddock, & Wooding, 1995) as well as with central low-pass filtering (Cajar et al., 2016; Nuthmann, 2014) and with peripheral low-pass filtering (Cajar et al., 2016; Laubrock et al., 2013; Loschky & McConkie, 2002; Loschky et al., 2005; Nuthmann, 2013; Nuthmann, 2014; Parkhurst, Culurciello, & Niebur, 2000; van Diepen & Wampers, 1998). Fixations also increasingly prolong with increasing low-pass filter size (Nuthmann, 2013; Nuthmann, 2014; Parkhurst et al., 2000). However, Loschky and colleagues found that increasing filter level with detectable peripheral low-pass filtering hardly affected fixation durations (Loschky & McConkie, 2002; Loschky et al., 2005). In summary, previous research suggests that eye-movement behavior is increasingly modulated as visual-cognitive processing difficulty increases due to spatial-frequency filtering.

In contrast, we recently found evidence in two studies (Cajar et al., 2016; Laubrock et al., 2013) that fixation durations are not always longer under conditions of increased processing difficulty. In both studies, high-pass filters or low-pass filters were applied to either the central or the peripheral part of the visual field during the viewing of color (Laubrock et al., 2013) or grayscale (Cajar et al., 2016) real-world scenes. We assumed that scene processing would be most difficult with central low-pass and peripheral high-pass filtering, as these conditions strongly attenuate the critical spatial frequencies for foveal analysis (high spatial frequencies) and peripheral target selection (low spatial frequencies) respectively. In both studies, however, mean fixation durations increased most with central high-pass and peripheral low-pass filtering, which were expected to be less disruptive for processing. Central low-pass and peripheral high-pass filtering involved shorter mean fixation durations, often similar to the mean fixation duration in the unfiltered control condition. The results suggest that viewers invested more processing time when the information left after filtering was useful enough to accomplish the task at hand (foveal analysis, peripheral selection) in a reasonable amount of time; when visual-cognitive processing became too difficult to make an investment of more processing time worthwhile default timing, that is, stimulus-independent random timing of saccades was adapted. To account for these effects, we developed a computational model in which fixation durations are controlled by the dynamical interaction of foveal and peripheral processing (Laubrock et al., 2013). The model assumes that foveal and peripheral information processing evolve in parallel and independently from one another during fixation, a notion that was recently corroborated by an experimental study (Ludwig, Davies, & Eckstein, 2014).

1.1. The present study

Most studies on the effects of gaze-contingent spatial-frequency filtering on eye movements during scene viewing applied peripheral low-pass filters. There is only little research on the effects of central filtering (Nuthmann, 2014) and high-pass filtering (van Diepen & Wampers, 1998) on eye-movement behavior. Our own studies (Cajar et al., 2016; Laubrock et al., 2013) were the first to investigate the effects of central and peripheral high-pass and low-pass filtering within the same experiment. Moreover, to our knowledge, there is no study on the effects of varying filter level and filter size with high-pass filtering. The investigation of the latter is interesting on its own. In addition, the aforementioned effects on fixation durations in our previous studies with varying filter type (low-pass/high-pass) in the central or peripheral visual field are striking—they raise the question how fixation durations adapt to processing difficulty due to spatial-frequency filters of varying filter level and filter size. The present study investigated this question in two experiments.

In both experiments, participants inspected real-world scenes in preparation for a memory task while high or low spatial frequencies were filtered either in the central or the peripheral visual field. Gaze-contingent filtering was compared with control conditions that presented scenes either unfiltered or entirely low-pass or high-pass filtered. In Experiment 1, the level of filtering (i.e., the cutoff frequency) varied between trials using weak, moderate, or strong high-pass or low-pass filters. Processing difficulty was assumed to increase from weak to strong filters. In Experiment 2, filter level was constant, but the size of the filter (i.e., the size of the gaze-contingent window) varied—the filter either subtended a small, medium, or large region of the central or the peripheral visual field. Processing difficulty was assumed to increase from small to large filters. The experiments tested for the effects of filtering on task performance, fixation durations, and saccade amplitudes.

For both experiments, we expected saccade amplitudes to increasingly deviate from normal viewing behavior with increasing processing difficulty. Compared with unfiltered scene viewing, amplitudes were expected to increase with central filtering and decrease with peripheral filtering, particularly when critical spatial frequencies were attenuated (i.e, with central low-pass filtering and peripheral high-pass filtering). These effects were expected to grow with increasing filter level (Experiment 1) or filter size (Experiment 2). For fixation durations, we expected an increase