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Fixational saccades during grating detection and discrimination

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ABSTRACT

We investigated the patterns of fixational saccades in human observers performing two classical perceptual tasks: grating detection and discrimination. First, participants were asked to detect a vertical or tilted grating with one of three spatial frequencies and one of four luminance contrast levels. In the second experiment, participants had to discriminate the spatial frequency of two supra-threshold gratings. The gratings were always embedded in additive, high- or low-contrast pink noise. We observed that the patterns of fixational saccades were highly idiosyncratic among participants. Moreover, during the grating detection task, the amplitude and the number of saccades were inversely correlated with stimulus visibility. We did not find a systematic relationship between saccade parameters and grating frequency, apart from a slight decrease of saccade amplitude during grating discrimination with higher spatial frequencies. No consistent changes in the number and amplitude of fixational saccades with performance accuracy were reported. Surprisingly, during grating detection, saccade number and amplitude were similar in grating-with-noise and noise-only displays. Grating orientation did not affect substantially saccade direction in either task. The results challenge the idea that, when analyzing low-level spatial properties of visual stimuli, fixational saccades can be adapted in order to extract task-relevant information optimally. Rather, saccadic patterns seem to be overall modulated by task context, stimulus visibility and individual variability.

1. Introduction

During fixation, the eyes are continuously moving over short distances. These miniature eye movements have been classified into three different types (see Collewijn & Kowler, 2008 for a review), known as tremor, drift and fixational saccades, the latter being often referred to as microsaccades under stringent amplitude criteria. While it is now well established that slow drift may have a significant impact on low-level visual processing (Ahissar & Arieli, 2012; Kuang et al., 2012; Poletti & Rucci, 2010; Rucci et al., 2007), the debate is still open about the functional roles of fixational saccades (see Martinez-Conde, Macknik, & Hubel, 2004; Martinez-Conde, Otero-Millan, & Macknik, 2013; Rolfs, 2009 for reviews). Several studies have proposed that these small saccades may contribute to visual inspection of images, in a similar way to what larger, regular saccades do (e.g., Steinman et al., 1973). In this perspective, fixational saccades would redirect the gaze toward task-relevant details falling within the foveal region. For instance, Ko, Poletti, and Rucci (2010) required observers to perform a virtual threading of a needle and found that fixational saccades improved the judgment of the relative alignment of the two objects by dynamically shifting the gaze between the two critical locations, the tip of the thread and the eye of the needle. Coherently, Poletti, Listorti, and Rucci (2013) demonstrated that they might counterbalance the small differences in visual acuity across the foveal region by redirecting the preferred fixation locus on the critical portion of the stimulus. In both studies fixational saccades significantly improved perceptual performance.

Whether, and how, these saccades also modulate low-level visual perception is less clear. Their impact was originally suggested by the seminal observation that retinal stabilization impairs visual detection and discrimination of fine spatial patterns (Rucci & Desbordes, 2003; Rucci et al., 2007; Steinman et al., 1973). However, these studies do not rule out the possibility that the enhancement of fine spatial details and of discrimination performance might be primarily due to the temporal modulations introduced by drift and tremor. Another cue for a role of fixational saccades in vision comes from investigating how they may be influenced by the statistics of the fixated patterns. Indeed, several studies have shown that the saccadic properties may depend on both global and local patterns of luminance information. During simple fixation tasks, the distribution of saccade amplitude and

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direction may be related to the size and the shape of the foveated input (e.g., Cherici et al., 2012; Steinman, 1965). During free-viewing of oriented Gabors embedded in noise, Wismeijer and Gegenfurtner (2012) found that small saccades (amplitude <1 deg), but not larger ones, tended to be preferentially oriented orthogonally to the Gabor orientation. Work from our team has however indicated that, in humans and monkeys, the amplitude and direction patterns of both small and regular saccades may be similarly biased by the statistical content of the fixated textures (Simoncini et al., 2012). If the properties of fixational saccades are influenced by the spatial characteristics of the image to be freely fixated, one may wonder whether their pattern further depends on whether observers are actively engaged in a perceptual task. Requiring discrimination of the orientation of large ellipses embedded in visual noise, Hicheur et al. (2013) reported that, during the time interval preceding a correct behavioral choice, the distribution of saccadic direction was biased along the ellipse's principal axis. This result consolidates early observations of stimulus-specific modulations of the saccade amplitude and of the fixation pattern when participants scanned or detected a periodically luminance-modulated stimulus (Arend & Skavenski, 1979; Deubel & Elsner, 1986). In the most meticulous study to date, Deubel and Elsner (1986) reported that observers produced saccades of amplitude close to half the grating's period during trials in which they showed the highest sensitivity for grating detection. In a subsequent modeling study, they suggested that such behavior would maximize information related to changes in the retinal input between successive periods of stability across saccades (Elsner & Deubel, 1986). They modeled this effect as a classical linear filter for the early visual stages that samples the luminance profile at the beginning and the end of saccades. Thus, the filter's response is maximized for a saccade that shifts the grating on the retina by a semi-period (i.e., from the peak to the trough of the grating). This work has led to the hypothesis that a saccade amplitude corresponding to about half of the spatial period of the grating (for saccades directed orthogonally to the luminance pattern) would optimally enhance the retinal input for contrast detection and, thus, be particularly beneficial in conditions of low visibility. Whilst these studies have claimed for a direct link between the adaptive nature of fixational saccades and the optimal information sampling for perceptual performance, a closer look at the experimental results questions this conclusion. First, pattern-specific modulations of saccade amplitude were reported for only some participants (Deubel & Elsner, 1986). Second, the predictions regarding saccade amplitude and direction have not been tested across a wide range of grating spatial frequencies, contrasts and orientations, or across different low-level perceptual tasks. Third, a recent study (Mostofi, Boi, & Rucci, 2014) has shown that fixational saccades were rarely produced during contrast-based discrimination of grating's orientation and led to only a slight enhancement of contrast sensitivity, limited to low-frequency gratings.

The aim of the present study was to re-evaluate this issue by assessing whether and how the patterns of fixational saccades vary during the execution of two low-level perceptual tasks. Using state-of-the-art video-based eye tracking, we required human observers to maintain the gaze on the center of the screen across all image presentations and we recorded their fixational saccades (see Procedure) during either the detection of a luminance grating embedded in pink noise (Experiment 1) or a spatial frequency discrimination between two gratings (Experiment 2). In particular, we compared grating detection and discrimination tasks in order to probe the adaptive, task-dependent nature of fixational saccades. We varied the grating's spatial frequency to test Elsner and Deubel's (1986) prediction regarding the relationship between saccade amplitude and grating spatial period in order to optimize detection. Manipulating the grating's orientation we were able to probe its impact upon saccade direction. Moreover, we changed the difficulty of the task by varying the contrast (or the spatial frequency difference in the discrimination task) of the grating and the contrast of the background noise: in this way, we were able to compare fixation patterns around and above detection or discrimination thresholds, and to estimate any potential correlation between fixational saccade parameters and perceptual performance.

2. Experiment 1: grating detection task

2.1. Material and methods

2.1.1. Participants

Four participants (two authors and two naïve colleagues, who gave informed consent) were tested in accordance with CNRS ethical regulations for behavioral research and with The Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. Apparatus

The experiment and the stimuli were generated in Matlab 7.12.0 using the Psychophysics Toolbox (Brainard, 1997) and the Eyelink Toolbox (Cornelissen, Peters, & Palmer, 2002). The experiment was conducted on a Apple MacPro4 computer running OS X 10.6.8. Stimuli were displayed on a 19-inch ViewSonic CRT monitor (resolution: 1024×768 pixels, refresh rate: 100 Hz). Eye movements were recorded using a tower-mounted EyeLink 1000 (SR Research Ltd., Ottawa, Canada), sampling at a rate of 1000 Hz. Viewing was binocular, but only the right eye was tracked. A chin and forehead rest stabilized the head and the eyes 57 cm away from the screen. Manual responses were made on a standard DELL keyboard.

2.1.3. Materials

The experimental materials consisted of either sinusoidal gratings (radius of 15 deg) embedded in pink ($1/f$) noise or pink noise-only images. Gratings were smoothed with a circular Gaussian mask with a standard deviation of 3 deg. The noise was smoothed by a circular Gaussian mask with a standard deviation of 5 deg, and was presented at high (0.60) or low (0.03) root mean square pixel contrast. When overlapped with high-contrast noise, the gratings were drawn with one of three different spatial frequencies (0.5, 1 or 2.5 c/deg), one of four luminance contrast levels (0.015, 0.03, 0.06 or 0.12, defined as Michelson contrast) and with one of two different orientations (vertical or oblique with a clockwise 45-deg rotation around the vertical). When presented with low-contrast noise, only two grating spatial frequencies (0.5 or 2.5 c/deg), three levels of contrasts (0.03, 0.06 or 0.12) and one orientation (vertical) were used. Gratings and pure noise images were displayed on a medium-gray background (luminance: 32 cd/m^2).

2.1.4. Procedure

We used a two-interval forced choice paradigm, presenting the two types of test-images (grating-with-noise or noise-only) in the first and the second interval of each trial. The experiment had a blocked design for all factors, except for grating contrast. The order of stimuli presentation was counterbalanced and random within each block, for each participant. In the high-noise condition, three participants were presented with two blocks (80 and 64 trials) with a vertical grating and one block (80 trials) with a titled grating, for each of the three spatial frequencies. In the low-noise condition, the same participants ran one block (90 trials) with a vertical grating for each of the two spatial frequencies. The last