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Analysis of microsaccades and pupil dilation reveals a common decisional origin during visual search

Claudio M. Privitera [a,*], Thom Carney [a], Stanley Klein [a], Mario Aguilar [b]

[a] School of Optometry, University of California, Berkeley, CA, United States
[b] Intelligent Systems and Planning, Teledyne Scientific Company, Durham, NC, United States

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ABSTRACT

During free viewing visual search, observers often refixate the same locations several times before and after target detection is reported with a button press. We analyzed the rate of microsaccades in the sequence of refixations made during visual search and found two important components. One related to the visual content of the region being fixated; fixations on targets generate more microsaccades and more microsaccades are generated for those targets that are more difficult to disambiguate. The other empathizes non-visual decisional processes; fixations containing the button press generate more microsaccades than those made on the same target but without the button press. Pupil dilation during the same refixations reveals a similar modulation. We inferred that generic sympathetic arousal mechanisms are part of the articulated complex of perceptual processes governing fixational eye movements.

1. Introduction

It is well known that eye fixations are characterized by a rich continuum of small motions of the eye. In particular, microsaccades, tiny jumps of the eye position that occur during fixation have been attracting a lot of attention because of their correlation with many aspects of visual perception (see for example Engbert, 2006; Rolfs, 2009). Microsaccades share with their macro (saccade) counterparts several physiological, dynamic and perceptual mechanisms. For example, their peak velocity linearly increases as the movement amplitude increases, following a relationship well known in the eye movement community as main sequence. Moreover, the microsaccadic sampling rate, one discrete event every 200–500 ms, is similar to what is observed for normal sized saccades (Benedetto, Pedrotti, & Bridgeman, 2011; Otero-Millan et al., 2008; Rolf et al., 2008; Zuber, Stark, & Cook, 1965). Microsaccades are believed to produce cortical transients that facilitate spatial and temporal integration in the visual system allowing synchronization among different cortical structures and thus enhancing and allowing perception (Leopold & Logothetis, 1998; MacEvoy, Hanks, & Paradiso, 2008; Martinez-Conde, Macknik, & Hubel, 2000, 2002; Melloni et al., 2009; Rolfs, 2009). They are closely interconnected with attention; this is evidenced for example by a widely documented pattern, first an inhibition of microsaccades (and then an augmentation) in anticipation of (and then in response to) a perceptual event (Betta & Turatto, 2006; Engbert & Kliegl, 2003; Gowen et al., 2007; Laubrock, Engbert, & Kliegl, 2005; Rolfs, 2009). In addition, cuing experiments have been employed to demonstrate a link between microsaccades and attentional shifts during eye fixation (Engbert, 2006; Engbert & Kliegl, 2003; Rolfs, Laubrock, & Kliegl, 2006) even though the agreement of the microsaccade direction with the attentional cue is a source of debate and it might ultimately depend on experimental settings concerning the type, position and timing of the cue used in the experiment (Gowen et al., 2007; Horowitz et al., 2007; Laubrock et al., 2010; Martinez-Conde, Otero-Millan, & Macknik, 2013; Tse et al., 2004). In free viewing, the rate of microsaccades and the duration of the fixations seems to be correlated with the visual content of the image and the visual task (Otero-Millan et al., 2008); it follows that microsaccades could be triggered by small attentional shifts serving to scan and visually resolve the small regions being fixated (Donner & Hemilä, 2007; Otero-Millan et al., 2008; Rolfs, 2009).

At the saccadic scale, eyes position is intently and ballistically moved over different regions of interest in the scene to allow foveation. The sequence of movements appear spontaneously without specific instructions to subjects and has been shown to be repetitive (Bahill & Stark, 1979; Noton & Stark, 1971a). This implies that viewers tend to refixate one or more times the same location in the field of view during the visual search or viewing session (Smith & Henderson, 2011a, 2011b). The phenomenon has several interpretations: either, (i) a memory limitation that requires revisits of previously attended locations (Gilchrist & Harvey, 2000; Peterson et al., 2001; Wienrich, Heße, & Müller-Plath, 2009) or, (ii) the

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* Corresponding author. Address: 416 Minor Hall, School of Optometry, University of California, 94720 Berkeley, CA, United States.

E-mail address: claudiop@berkeley.edu (C.M. Privitera).

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presence of a time limited allocation of attention for each fixation causing the next saccade to be generated even when the processing of the current location might not be completed (and needs to be completed with future refixations, Henderson, 1992) or, (iii) a particular saliency of a region that is contingent on the visual task (i.e. a visual target requiring further confirmation, Droll, Gigone, & Hayhoe, 2007; Henderson, Malcolm, & Schandl, 2009).

Our results confirm that locations in the image containing a target are refixated more frequently. The rate of microsaccades and the duration of the fixations during a visual search were both correlated with the spatial information in the fixation or the visibility or contrast of the target fixated. In cases where the target location is refixated, we also found a modulation of microsaccades that depends on which fixation the target was recognized and reported. This defines an association with non-visual cortical prerogatives that mediate the decision-making and motor response.

The mental effort involved with the process of decision-making, especially in times of hesitation or uncertainty, can be monitored by looking at other expressions of the human body. For example, the human pupil is known to be associated with perceptual mental activities related to decision-making and target detection (Einhäuser, Koch, & Carter, 2010; Einhäuser et al., 2008; Privitera et al., 2010). The pupil responds with dilation to visual detection and the amount of dilation depends on the presence of a button press reporting the detection. We analyzed pupil dilation during eye fixations and we found the same modulation observed for microsaccades. We propose that generic sympathetic arousal mechanisms could be part of the articulated complex of perceptual processes governing micro eye movements.

2. Methods

2.1. Visual stimuli and image presentation

Visual stimuli were synthesized with the amplitude spectra of natural images; that is approximately equal to reciprocal of the spatial frequency (the 1/f rule, Burton & Moorehead, 1987). Using artificial images allowed full control of the positioning, number, contrast and size of the targets in the image. The procedure for generating realistic 1/f images was as follows:

1. A satellite photo of mountain terrain was used as a template or seed for the generation.
2. Fourier transform was taken of the image and phases were randomized keeping conjugate symmetry.
3. The image was reconstituted using the original spectra and the scrambled distribution of phases.
4. Finally, a non-linear gamma transformation of the pixel values aimed to skew the histogram towards higher luminance was applied to the resulting images. The gamma pixel level distribution is skewed towards brighter intensity because the luminance and contrast of natural images have very low correlation (as suggested by Frazor & Geisler, 2006).

The procedure is automatic and can generate an unlimited number of images (each with its own randomization as specified above in point 2) out of the same unique template. The resulting images looked noisy (Fig. 1, left) but they preserve the natural spatial and orientation structure of the template. Image size was 620×620 pixels and subtended a visual angle of approximately 10°. The targets were Gabor patches at different orientations; the frequency of the patches was set equal to 0.075 cycles/pixel (4.65 cy/deg) and the sigma of the Gaussian was 8 pixels (7.25 arcmin of visual angle). The patches were zero-mean normalized, their gray level ranged between -1 (black) to 1 (white) and then multiplied by a scalar gain controlling the contrast or visibility of the patch; a scalar gain of 1 means maximum (or 100%) contrast. Two different gains were used, 0.15 (15% of full contrast, i.e. less visible) and 0.25 (25% of full contrast, i.e. more visible).

Gabor targets were added to the original image with their locations randomly selected for each presentation. The number of targets (0–3) was randomly chosen at each image presentation. If two or more targets were selected, each of them was randomly assigned to a quadrant in the image and the position within a quadrant was randomly assigned. A quadrant could only contain one target. The arrow (Fig. 1, left panel) identifies a target rotated 45°.

Stimuli were presented sequentially to the subjects in blocks of 10 unique images, four seconds per image, using the WinVis stimulus delivery software that provided synchronization pulses to align eye, pupil and button press data with stimulus presentation (Carney, Ales, & Klein, 2006). The WinVis linearization routine was also used to linearize the luminance of the monitor.

Fifteen subjects (ten males, 24–60 years old) participated in the experiment. They were seated in a booth that isolated them from the surrounding environment. The booth contained the EyeLink 1000 head supported eye-tracker system (http://www.sr-research.com/EL_1000.html, temporal resolution of 1000 Hz) for recording monocularly, eye position and pupil diameter. The monitor was the only source of illumination. The experiment was approved by the Committee for the Protection of Human Subjects at the University of California, Berkeley.

Subjects were instructed to search for a Gabor and a few examples were showed to each subject prior the experiment; they were asked to press a key on the keyboard anytime they found a target. They were also informed that each image could have zero or at most three targets. A rest of few seconds was provided between consecutive images during which subjects were asked to fixate a point in the center of a salt-and-pepper noise image having the average luminosity of the images used for the experiment. Each subject completed at least ten blocks of images (one hundred measurements).

2.2. Definition of microsaccades

The definition of microsaccades in a free viewing paradigm is problematic; analysis of the velocity waveform and amplitude is the only possible criterion (Martinez-Conde, 2006; Martinez-Conde & Macknik, 2008) but, as discussed above, both types of saccades share similar if not identical dynamics and neuro-physiological characteristics (Engbert, 2006; Otero-Millan et al., 2008; Zuber, Stark, & Cook, 1965). Operationally, microsaccades are involuntary saccades produced during an attempted stable fixation; their characteristics have been investigated by many authors, resulting in a wide and often contradictory range of physical parameters. Amplitude of microsaccades for example, ranges from small flickers (1′–20′ arc) as reported by Ditchburn and Ginsborg (1953), West and Boyce (1968), Winterson and Collewijn (1976), Malinov et al. (2000), up to larger movements (1′–120′ arc) as more recently documented (see for example, Bair & O'Keefe, 1998; Engbert, 2006; Engbert & Kliegl, 2003; Hafed & Clark, 2002; Otero-Millan et al., 2008; Snodderly, Kagan, & Gur, 2001). Speed or acceleration definitions of microsaccades also varies across studies (for a review, see Table 3 in Martinez-Conde, Macknik, & Hubel, 2004).

In our analysis, the threshold for the peak velocity of a saccade was set to 50 deg/s; all movements slower than this threshold were defined as part of the fixation. A second pass was applied after the thresholding, and saccades smaller than 1.2° were considered as microsaccades and the two fixations before and after these microsaccades merged into one fixation.

Within a fixation, detection of microsaccades was performed using an algorithm similar to the one proposed by Engbert and