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Spatial deployment of attention influences both saccadic and pursuit tracking[☆]

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Abstract

We examined the effects of changing spatial aspects of attention during oculomotor tracking. Human subjects were instructed to make a discrimination on either the small (0.8°) central or the large (8°) peripheral part of a compound stimulus (two counter-rotating concentric rings) while the stimulus either translated across the screen or was stationary. During this period, a transient perturbation with either step or ramp movement profile occurred. For perturbations leading to a change in position larger than the small ring, saccades occurred more frequently and had much shorter latencies (by 135 ms) when attention was directed to the small ring than when attention was directed to the large ring. These latency differences were sufficiently great that from a single saccade one can identify the attentional instruction with 94% accuracy. However, with target steps as small as the small ring, saccade latencies differed less. For pursuit, ramp perturbations caused larger changes in eye velocity with little change in latency when attention was directed to the small ring. Finally, when only the motion of the non-attended ring was perturbed, most subjects showed stronger saccadic responses to perturbations of the small than the large ring, and stronger pursuit responses to perturbations of the large than the small ring. By fitting the saccade latency distributions with the Reddi and Carpenter LATER model, we found that our subjects apparently employed at least two distinct strategies for changing latency when attending large vs. small. We propose that the timing of the saccade decision process depends on both the size of the attended object and the magnitude of the perturbation.

Keywords: Eye movements; Attention; Saccade; Pursuit; Latency; Motor control; Human

1. Introduction

Saccades and pursuit are the voluntary eye movements used to acquire and stabilize the retinal image of a target on the fovea, the high-acuity region of the retina. Attention is important, perhaps even necessary, for the execution of both saccades and pursuit by allowing for the selection of relevant stimuli.

In the case of saccades, generating the movement appears to require a prior shift of attention to the target location. First, studies using single-unit recording, fMRI, and microstimulation suggest that the same brain areas are involved in both saccades and shifts of attention (frontal eye fields: Corbetta et al., 1998; Moore & Fallah, 2004; Schall, 2004; superior colliculus: Carello & Krauzlis, 2004; Cavanaugh & Wurtz, 2004; Ignashchenkova, Dicke, Haarmeier, & Thier, 2004; Kustov & Robinson, 1996). Second, subjects are poor at making visual discriminations just before a saccade except at the target location (Deubel & Schneider, 1996; Kowler,

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Anderson, Dosher, & Blaser, 1995; Posner, Snyder, & Davidson, 1980; Shepherd, Findlay, & Hockey, 1986), and the same is true for auditory discriminations (Rorden & Driver, 1999). Third, saccades are triggered sooner if attention is first drawn to the target location and are delayed if attention is directed elsewhere (Crawford & Muller, 1992; Hoffman & Subramaniam, 1995; Kowler et al., 1995; Shepherd et al., 1986). Taken together, these results argue that a shift of the location of attention necessarily precedes saccadic eye movements.

In the case of smooth pursuit, the ability to selectively attend to the moving target while ignoring stationary stimuli is required to produce pursuit eye movements; without attention, the self-induced visual motion of the background would cancel pursuit (Kowler, van der Steen, Tamminga, & Collewijn, 1984; Lindner, Schwarz, & Ilg, 2001; Schwarz & Ilg, 1999; Suehiro et al., 1999). Because of the continuous nature of the pursuit response, it has been postulated that attention moves smoothly with the eyes during tracking (Kowler, 1990). As with saccades, discrimination performance is better at (Khurana & Kowler, 1987) or near (van Donkelaar & Drew, 2002) the location of the pursuit target than at other locations, suggesting that pursuit and perception share the same attentional mechanism. The amount of attention allocated to pursuit is not constant: adding attentional load impairs the quality of pursuit more at the start of pursuit than later (Chen, Holzman, & Nakayama, 2002), and other evidence also suggests that pursuit uses more attentional resources at the start and end of pursuit than during pursuit maintenance (van Donkelaar, 1999; van Donkelaar & Drew, 2002).

In everyday life, visual targets are usually complex and offer a variety of spatial scales at which they can be attended. That is, attention has a spatial extent as well as a spatial location, and these two aspects are somewhat independent in that one can attend either to a whole visual stimulus or to a single part of it, both at the same spatial location. This spatial feature of attention is not shared by saccadic or pursuit eye movements in any obvious way, in that the eye movements can be adequately described as a change in eye position; spatial extent is not relevant. In this paper, we investigate the effects of a spatial aspect of attention on both pursuit and saccadic eye movements by recording the response to position and velocity errors (i.e., the mismatches between the motion of the eye and the target) while a subject tracks a compound stimulus, consisting of two concentric, segmented rings rotating in opposite directions, with instructions to attend to and make a discrimination on one of the rings.

2. Methods

Four human subjects (26–38 years of age, one female and three males) participated in the experiment. Two of the subjects (R and L) were authors of the study; the other two (J and C) were naïve as to the experimental conditions and hypotheses. Subjects gave their written informed consent.

The probe and mask stimuli each consisted of two concentric rings (0.8° and 8° in diameter, 42% contrast) made up of several segments (Fig. 1A). The thickness of each ring and the size of the gaps between the segments were scaled according to the cortical magnification factor (Rovamo & Virsu, 1979). The two rings spun in opposite directions at different velocities. In each condition, the number of trials in which each ring spun clockwise and counterclockwise were equal. In all three experiments, the mask stimulus (nine segments in each ring) was briefly (166 ms) replaced by a probe stimulus and then reverted to a mask stimulus for 600 ms. In the probe stimulus, the small ring contained either four or five segments and the large ring either five or seven segments. At the beginning of each trial, subjects were instructed by a high or low frequency auditory tone to attend either to the small ring ("attend small" condition) or the large ring ("attend large" condition) and were asked to report the number of segments in the corresponding ring of the probe stimulus in a two-alternative forced-choice design. After each trial, subjects indicated the number of segments by a key-press; auditory feedback indicated whether the report was correct. In practice, to perform the task in the experiments in which the ring was moving across the screen, it was necessary to track the translational movement of the stimulus, but no specific instruction was given to track the stimulus. Thus, although the emphasis was on the discrimination, not the tracking, subjects generally kept the stimulus well centered on their foveas.

The size of the gaps between the segments was kept constant between mask and probe stimuli, so that the discrimination task could not be performed by analysis of just a segment of the ring, but instead required attention to the entire ring. Prior to the experimental sessions, we obtained psychometric functions for each subject to determine the spinning speed of each ring that yielded approximately 85% correct reports. The spinning speeds were 40–80 rpm, and were adjusted during the experiments to maintain this level of discrimination. The success of these procedures is demonstrated by the similar levels of performance when attending to the large and small rings; overall the percent correct was 79% for the attend small condition and 82% for the attend large condition (Table 1).

2.1. Assessment of attentional task

To confirm that the task required subjects to deploy their attention differently in the attend small and attend large conditions, we performed a control experiment to evaluate the effect of the instructions. This experiment