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Efficient saccade planning requires time and clear choices

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ABSTRACT

We use eye movements constantly to gather information. Saccades are efficient when they maximize the information required for the task, however there is controversy regarding the efficiency of eye movement planning. For example, saccades are efficient when searching for a single target (Nature, 434 (2005) 387–391), but are inefficient when searching for an unknown number of targets in noise, particularly under time pressure (Vision Research 74 (2012), 61–71). In this study, we used a multiple-target search paradigm and explored whether altering the noise level or increasing saccadic latency improved efficiency. Experiments used stimuli with two levels of discriminability such that saccades to the less discriminable stimuli provided more information. When these two noise levels corresponded to low and moderate visibility, most observers did not preferentially select informative locations, but looked at uncertain and probable target locations equally often. We then examined whether eye movements could be made more efficient by increasing the discriminability of the two stimulus levels and by delaying the first saccade so that there was more time for decision processes to influence the saccade choices. Some observers did indeed increase the proportion of their saccades to informative locations under these conditions. Others, however, made as many saccades as they could during the limited time and were unselective about the saccade goal. A clear trend that emerges across all experiments is that conditions with a greater proportion of efficient saccades are associated with a longer latency to initiate saccades, suggesting that the choice of informative locations requires deliberate planning.

1. Introduction

Our eyes are moving constantly at the rate of approximately three times per second to gather information from our dynamic surroundings. We know from Yarbus (1967) that we move our eyes to different parts of the image depending on the task. Recently there has been an interest in determining if these eye movements gather information efficiently for the task at hand, i.e., whether each saccade maximizes task-relevant information. Studies to date provide mixed results, depending on the task. Some studies indicate that saccadic targeting is efficient. For instance, eye movements executed during search for a single target appear to be efficient (Najemnik & Geisler, 2005, 2008) and appear to incorporate knowledge about where the target is most likely to occur (Chukoskie et al., 2013; but see Araujo, Kowler, & Pavel, 2001). On the other hand, other studies show that saccades are not always directed to maximize expected gain in a reward/penalty paradigm (Ackermann & Landy, 2013; Schutz, Trommershäuser, & Gegenfertner, 2012; Stizke, Trommershauser, & Gegenfertner, 2009), nor do they fully incorporate the decrease in visibility with target eccentricity (Zhang, Morvan, & Maloney, 2010). Furthermore, saccades are grossly inefficient in tasks requiring a sequence of eye movements to gather information about multiple targets (Verghese, 2012). Here we investigate conditions that may lead to improvements in the efficiency of active visual search for an unknown number of targets.

The current study is based on the Verghese (2012) study that used 6 potential target locations and a limited time for active visual search. Here, the observer's task is to find an unknown number of targets embedded in noise. As trial duration is limited and there is not sufficient time to examine all potential target locations, an efficient strategy within a Bayesian information-maximization framework is to saccade to a location that maximizes the information gained across all target locations (Najemnik & Geisler, 2005; Renninger, Verghese, & Coughlan, 2007). For instance, a saccade directed midway between 2 uncertain locations increases the information at both locations, compared to a saccade that goes directly toward one of the target locations. However, our studies (Verghese, 2012) show that human saccades are not directed at locations that maximize global information, but are directed at potential target locations. But even this local strategy is not

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efficient; observers make saccades to locations where the posterior probability is high (probable locations), rather than to informative locations where the uncertainty (entropy) is high. Thus saccade strategy does not appear to be efficient at either a global or a local level. But why are observers not able to implement a local strategy that selects informative locations over probable target locations, where there is little information to be gained?

Does this occur because the noise level was so high, that it is hard to distinguish the more probable target locations from uncertain locations? Here, we investigate whether making the probable target locations clearly visible minimizes the need to examine them and therefore helps the observer direct saccades to more uncertain locations.

In this study, the targets and distractors were horizontal and vertical Gabor patches respectively, embedded in noise. Because of the large orientation difference, the stimuli were clearly discriminable at high signal-to-noise ratios (SNR). We used two levels of SNR in our experiment: low, and moderate or high. The low level was set so that observers were uncertain about the orientation of the patch and needed to make a saccade to the patch to determine the orientation. The "moderate" level was set so that observers were reasonably confident about target identity (>80%) without having to make a saccade. The first experiment indicated that most observers did not look preferentially at uncertain locations.

We wondered whether increasing the discriminability between the two SNR levels (as in Hooge & Erkelens, 1998) would make it easier to ignore the more discriminable stimuli and select the more uncertain stimuli. Accordingly, in subsequent experiments we set the "high" SNR to near infinity by removing all the noise. This manipulation increased the number of saccades to the uncertain targets. However some observers still tended to make short-latency saccades to the clearly visible horizontal targets. To determine whether delaying saccades would give observers the time necessary to determine the most uncertain locations we asked observers to hold fixation briefly after display onset. Delaying saccades helped some observers make more efficient saccades. Others, however, still attempted to make saccades to as many locations as possible without selecting uncertain locations.

2. Methods

2.1. Participants

Five (4 female, 1 male) individuals, ranging in age from 27 to 50 voluntarily took part in our experiments. Two observers were authors (O1 and O2); the other three were naïve as to the purpose of the experiment. Observer O3 had participated previously in psychophysical experiments, observers (O4 and O5) were practiced at psychophysical and eye movement experiments. All observers had normal vision or vision corrected to normal, and provided informed consent, in writing, to participate in the experiments. The Smith-Kettlewell Institutional Review Board approved the experimental protocol. All experiments were carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Stimuli

The basic design of the experiment was similar to Verghese (2012). Stimuli were presented on 21" ViewSonic G225f monitor that was gamma-corrected. Observers viewed the display binocularly at a distance of 1 m, such that a pixel subtended 0.02°. In this study the stimuli were made up of six Gabor patches equally spaced on an invisible circle centered at fixation with a radius of 3° (see Fig. 1). To avoid placement of targets along cardinal axes, stimuli were placed at 60° angular intervals starting at 15° counter clockwise from right horizontal (i.e., at 15°, 75°, 135°, 195°, 255° and 315° around the circle). Targets were horizontal Gabor patches, and distractors were vertical Gabor patches. The spatial frequency of the sine wave in the Gabor was 5 c/deg and the standard deviation of the Gabor envelope was set to spatial period/$\sqrt{2}$, or 0.14°. This resulted in about 1.5 cycles of the grating being visible. Random noise of contrast 0.38 was added to the patches at each location. Each patch was 1° in diameter. The Gabors were displayed in cosine (even) phase and the contrast of the sinusoid was randomly set to one of two values—0.19 and 0.38 in Experiment 1, corresponding to low and moderate SNR values of 0.5 and 1, respectively. In Experiments 2 and 3 the noise was removed from the higher-contrast patch, taking the signal-to-noise ratio towards infinity. Each of the six locations had equal probability of being assigned a lower or higher SNR signal, regardless of whether it was a target or distractor.

2.3. Design

Each location had an independent probability of having a horizontal target. This probability was held fixed within a block of 100 trials and was set to one of three values: 0.17, 0.5, or 0.83. Participants were informed about the value of the prior before each block. Viewing was binocular. Monocular (left) eye movements were monitored with an Eyelink 1000. A block of experiments began with an eye-tracker calibration using a 5-point grid. At the start of each trial, the observer was required to fixate a central fixation dot and press the space bar to initiate the trial. The trial was initiated only if eye position was within 1° of the fixation dot. Observers were free to move their eyes once the trial started. Display duration was limited to 900 ms. The central fixation dot remained visible throughout the trial except in Experiment 3, where it disappeared 200 ms into the trial. At the end of the trial observers were presented with a report screen with gray discs marking the location of the six stimuli and had to indicate all target locations by clicking on them. A trial was scored correct only if all targets and no distractors were selected. The observer had the option to click a "Forgot" button if he/she could not remember the location of the targets. These trials were rare (<5%) and were not analyzed further. Auditory feedback was provided.

Before the main search experiments, we determined the ability of observers to discriminate horizontal from vertical Gabor patches. Observers were asked to identify the orientation (horizontal/vertical) of a single Gabor patch presented at one of 5 SNR values. The patch was presented for 100 ms followed by a mask, in a known location at an eccentricity of 0°, 1°, 2° or 3° to the right of fixation, along the horizontal meridian. This measurement also provided a visibility map for the target as a function of eccentricity. Of the 5 SNR values, we chose SNR values of 0.5 and 1 for Experiment 1 because they satisfied our criterion for a pair of SNR values for which visibility at an eccentricity of 3° was poor at the lower SNR, and was good at the higher SNR. Fig. S2 in Supplementary materials shows the visibility plots for these two SNR values: visibility declines considerably at 3° for an SNR of 0.5, but is high and declines only slightly with eccentricity for an SNR of 1. Because we measured visibility only along the horizontal meridian, it could be argued that our measurements do not take into account horizontal–vertical asymmetries or enhanced visibility in the lower visual field (Carrasco, Talgar, & Cameron, 2001). However, Carrasco, Talgar, and Cameron (2001) showed that these anisotropies are not significant at the small eccentricity (3°) and low spatial frequency (5 c/deg) used in our study.

Experiments 1 and 2 consisted of two parts. The first part determined the visibility of the peripheral patches in the absence of eye movements, while the observer fixated the central spot for 900 ms.