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Coarse-to-fine eye movement strategy in visual search

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Abstract

Oculomotor behavior contributes importantly to visual search. Saccadic eye movements can direct the fovea to potentially interesting parts of the visual field. Ensuing stable fixations enables the visual system to analyze those parts. The visual system may use fixation duration and saccadic amplitude as optimizers for visual search performance. Here we investigate whether the time courses of fixation duration and saccade amplitude depend on the subject's knowledge of the search stimulus, in particular target conspicuity. We analyzed 65,000 saccades and fixations in a search experiment for (possibly camouflaged) military vehicles of unknown type and size. Mean saccade amplitude decreased and mean fixation duration increased gradually as a function of the ordinal saccade and fixation number. In addition we analyzed 162,000 saccades and fixations recorded during a search experiment in which the location of the target was the only unknown. Whether target conspicuity was constant or varied appeared to have minor influence on the time courses of fixation duration and saccade amplitude. We hypothesize an intrinsic coarse-to-fine strategy for visual search that is even used when such a strategy is not optimal.

Keywords: Visual search; Coarse-to-fine; Eye movements; Fixation; Saccade; Conspicuity

1. Introduction

During visual search, eye movement parameters depend on a large number of stimulus properties and idiosyncratic factors. Jacobs (1986) and Jacobs and O'Regan (1987) showed a relation between visual span (the area that is analyzed during one fixation) and saccade amplitude. Saccade amplitude increases when the target is more salient. How fixation duration is affected has been investigated too. Hooge and Erkelens (1996, 1998) showed that fixation duration increases if target and distracters are made more similar. They showed this in sparse stimuli with elements arranged in an imaginary hexagonal grid. In a recent experiment, Vlaskamp and colleagues (Vlaskamp, Over, & Hooge, 2005) showed that, with smaller target-distracter dissimilarity, not only fixation duration increases but also saccade amplitude decreases. This last finding corresponds to the result of Jacobs (1986). Therefore, a clear relation exists between target conspicuity and eye movement parameters: When the target is less conspicuous, saccade amplitude decreases and fixation duration increases. A conspicuous target can be detected at a larger distance from the point of fixation than an inconspicuous target. At equal eccentricities, a conspicuous target is detected faster than an inconspicuous target. We adopt the definition of "conspicuity" proposed by Engel (1971, page 563): "We consider visual conspicuity to be an object factor. More precisely, it is an object property in relation to its background", and further on: "We define visual conspicuity operationally as that combination of properties of a visible object in its background by which it attracts attention via the visual system, and is seen in consequence."

Eye movement parameters and search performance do not only depend on stimulus properties; they also depend

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on idiosyncratic factors. One of these factors is, for example, age. Mean fixation duration increases with age (Harris, Hainline, Abramov, Lemerise, & Camenzuli, 1988; Jernajczyk, Sobanska, Czerwosz, & Szatkowska, 2005). Other examples of idiosyncratic factors influencing eye movement parameters are acuity (Johnston, 1965) and the presence of disorders such as macular degeneration (Bullimore & Bailey, 1995).

Most of the factors mentioned above have been studied extensively, especially the influence of stimulus properties. However, a factor in saccadic search that is not as thoroughly investigated is the influence of the subject's knowledge of target conspicuity. The majority of eye movement literature on visual search involves search with known target conspicuity (for reviews see Davis & Palmer, 2004; Rayner, 1998; Viviani, 1990; Wolfe, 1998). Megaw and Richardson (1979) studied the effect of target uncertainty on search times in experiments where subjects were relatively free to choose their search strategies. When the target is one of several possible items, target conspicuity is at least partially unknown. Megaw and Richardson showed that mean search time did not increase with target uncertainty in their study, and neither did mean fixation duration. However, their analysis was not very sophisticated. Their results for mean fixation duration were based on fixations during the first full scan of the display only. Moreover, a fixation could actually consist of several fixations since they treated successive fixations on the same item as one fixation. They reported no other aspects of eye movements than mean fixation duration. Scinto, Pillalamarri, and Karsh (1986) also investigated aspects of target uncertainty during visual search. They used 'textons' (items consisting of identical spatial frequencies) arranged in a grid. The target textons were '10's among 'S's. The three conditions varied in the number of textons that formed the target. The target group consisted of 3, 6 or 9 '10's. The number of target textons in each trial was unknown. Their main questions were whether subjects use cognitive strategies, and if they did whether the experimenter could modify these strategies. They found (1) no evidence for cognitive strategies, (2) no evidence for external influence on search strategy, and (3) an increase in fixation duration and at the same time a decrease in saccade amplitude as search continued to be unsuccessful. This last finding does not "suggest any global or overall systematic search strategy, but rather only very general regulative adjustment of ocular behavior applicable to many visual information-processing tasks". They did seem to consider this finding to be the result of the fact that target conspicuity is at least partially unknown because the size of the target texton group was variable. We expect that knowledge of target conspicuity may be an important factor for choosing particular search strategies, and thereby also for the setting of eye movement parameters. In this chapter we therefore ask the question: How does eye movement strategy, as reflected in eye movement parameters such as fixation duration and saccade amplitude, depend on the subject's knowledge of target conspicuity?

To study the effect of knowledge about target conspicuity on human eye movement behavior we compared two search conditions: search with varying target conspicuity and search with constant target conspicuity. What is to be expected for the search strategies in these two conditions and how can we expect these strategies to be reflected in the eye movement parameters fixation duration and saccade amplitude? In the following, we assume the existence of an optimal strategy with respect to minimizing search time and maximizing accuracy. We further assume that subjects attempt to use this optimal strategy as good as they can.

1.1. Constant target conspicuity

When target conspicuity is equal in each trial, the optimal eye movement parameters are also equal in each trial. Subjects can determine the optimal settings and store them in memory. Once the conspicuity of the targets is stored in memory, the settings for saccade amplitude and fixation duration that lead to target detection can be used again in all next trials. Target conspicuity is constant in, for example, a blocked-design experiment with objects (one target among distracters) that do not change over trials. When these objects are arranged in a regular grid, object locations are identical in each trial. The only unknown parameter then is the target's location in the grid. In the first trials, appropriate settings for fixation duration and saccade amplitude can be determined, and these can be used in all following trials.

1.2. Varying target conspicuity

If target conspicuity is unknown in advance, and it is uncertain whether the target can be found easily, it makes sense to first take the chance that the target is conspicuous. If the target is conspicuous, search can be fast and may take only little effort, because the target can be found with only a few, short fixations and large saccades. If the target appears to be inconspicuous, short fixations and large saccades do not suffice and eye movement parameters should be changed so that it becomes possible to find a less conspicuous target. Finding an inconspicuous target can be accomplished by deploying smaller saccade amplitudes and fixations that last longer. Thus, more effort has to be put into the search. If we further assume that the transition from relatively effortless search to effortful search is not a step between two discrete states of search, but rather a gradual change, then the time course of search can be described as the result of a coarse-to-fine process (see below). If the visual system uses a coarse-to-fine process, then at first analysis of visual information is fast at a coarse spatial scale, and later analysis is slower at finer spatial scales. At the beginning of each search trial, fixation duration is short and saccade amplitude is large. When the target is not found, fixation duration will increase and saccade amplitude will decrease, adapting to the apparent difficulty of the stimulus at hand (see also Scinto et al., 1986). We