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Limited flexibility in the filter underlying saccadic targeting

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Abstract

The choice of where to look in a visual scene depends on visual processing of information from potential target locations. We examined to what extent the sampling window, or filter, underlying saccadic eye movements is under flexible control and adjusted to the behavioural task demands. Observers performed a contrast discrimination task with systematic variations in the spatial scale and location of the visual signals: small ($\sigma = 0.175°$) or large ($\sigma = 0.8°$) Gaussian signals were presented 4.5°, 6°, or 9° away from central fixation. In experiment 1, we measured the accuracy of the first saccade as a function of target contrast. The efficiency of saccadic targeting decreased with increases in both scale and eccentricity. In experiment 2, the filter underlying saccadic targeting was estimated with the classification image method. We found that the filter (1) had a center-surround organisation, even though the signal was Gaussian; (2) was much too small for the large scale items; (3) remained constant up to the largest measured eccentricity of 9°. The filter underlying the decision of where to look is not fixed, and can be adjusted to the task demands. However, there are clear limits to this flexibility. These limits reflect the coding of visual information by early mechanisms, and the extent to which the neural circuitry involved in programming saccadic eye movements is able to appropriately weigh and combine the outputs from these mechanisms.
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1. Introduction

The highest resolution vision is only possible in the central one or two degrees of the visual field. Therefore, in order to explore or interact with the visual environment humans shift their gaze at regular intervals, typically 3 or 4 times every second (Findlay & Gilchrist, 2003). Saccadic eye movements are a critical element of almost any behavioural activity that involves the use of visual information. When an observer decides to look at some part of the visual scene, it is likely that this decision was, at least partly, driven by the visual signals sampled from that region. An important question is “how much” visual information is taken into account. In other words, how does the observer weigh visual signals over space in order to decide where to look?

Such a weighting function is often referred to as a template or filter. Simple perceptual decisions, like detecting whether a signal is present in noise, can be modelled as a process of template-matching (Burgess, Wagner, Jennings, & Barlow, 1981; Lu & Dosher, 1999; Pelli, 1985). A useful tool to estimate the filter used by human observers to perform such a visual task is the so-called ‘classification image’. This image is essentially a description of what parts of a visual stimulus the human observer takes into account to make a perceptual decision (Abbey & Eckstein, 2002; Ahumada, 2002; Murray, Bennett, & Sekuler, 2002). The general approach to calculate this description is to present signals in visual noise, and then on each trial relate the observer’s decision to the properties of the noise. Work of this type has shown that human observers have

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considerable flexibility in their ability to adapt the filter to the demands of the visual task, ranging from simple contrast detection (Abbey & Eckstein, 2002) to completion of illusory contours (Gold, Murray, Bennett, & Sekuler, 2000). For successful interaction with the visual environment, such flexibility clearly is desirable.

Saccadic eye movements can be regarded as a unique class of perceptual decisions. Saccades are, by definition, directed to visual targets outside the fovea, where sensitivity to fine detail is drastically reduced (Anstis, 1974; Pointer & Hess, 1989; Robson & Graham, 1981). In addition, these movements are generally made in quick succession, and appear to be based on a rather brief temporal integration period (Caspi, Beutter, & Eckstein, 2004; Ludwig, Gilchrist, McSorley, & Baddeley, 2005). These constraints may impose limits on the interaction between the oculomotor and visual systems, which in turn may limit the kinds of weighting that can be achieved. As an extreme example, it may be that the region from which visual signals are sampled is fixed, or perhaps directly dependent on eccentricity in the visual field (Garcia-Perez & SierraVazquez, 1996; Virsu & Rovamo, 1979). In this study we assess (1) the shape of the filter underlying saccadic eye movement decisions in a contrast discrimination task; (2) whether the filter is adjusted according to the task demands (integrate either over small or large regions); and (3) whether the filter depends on eccentricity in the visual field.

2. Methods

2.1. Study outline

Observers were presented with four Gaussian signals embedded in spatially uncorrelated, Gaussian white noise. The contrast of one of the four patterns (the target) was slightly higher than that of the other three (distractors), and observers signalled the location of the target with a manual response. We varied the size of the display items (spatial standard deviation of the pattern, σ, was either 0.175° or 0.8°), and the eccentricity at which they appeared (4°, 6.5°, and 9° of visual angle) in separate blocks. Observers were free to move their eyes and we recorded the landing position of their first saccade after display onset. The first saccade can considered the observers' best guess (decision), at that point in time, of the target location. Because the task is to find the highest contrast pattern, both the stimulus-driven contrast response and the task instructions induce participants to directly aim their first saccade to the target (Ludwig & Gilchrist, 2006). We analysed and modelled the accuracy of these first eye movement decisions.

A first step was to provide a detailed characterisation of saccadic targeting with variations in size and eccentricity of the display items. Here it is important to not just examine accuracy in terms of proportion correctly directed saccades, but to relate this proportion to the amount of information that is available for the task. Thus, in experiment 1 we quantified accuracy of the first saccade relative to an ideal observer in the form of an efficiency measure (Burgess et al., 1981; Eckstein, Beutter, & Stone, 2001). In experiment 2, we assessed whether variations in efficiency could be attributed to changes in the filter. The filter was estimated using reverse correlation. This technique involves extracting the external noise from the location of the first saccade landing position for trials on which the first saccade was directed to one of the distractor items. The extracted noise images are then averaged to compute a classification image.

2.2. Observers

Three observers with normal or corrected-to-normal vision were tested in the two experiments. Author CL is the third observer. The data were collected in multiple sessions over a period of 6 weeks. Each observer completed ~23,000 trials (across the two experiments).

2.3. Stimuli

Stimuli were viewed binocularly on a linearised M17LMAX monchrome monitor (Image Systems, Minnetonka MN) The mean luminance of the display was 31 cd/m^2. Display items were 2-D Gaussians with a standard deviation of either 0.175° or 0.8° (blocked). Dark grey outline circles (radius of 3σ of the large patch) marked the locations where the 4 patterns were presented. They were arranged along the circumference of a circle (i.e. equidistant from the central fixation point). The 4 patterns appeared either in a square configuration or in a diamond configuration. The configuration varied randomly from trial to trial to prevent observers from anticipating the exact locations where items would appear.

The Gaussian patterns were embedded in 0-mean, spatially uncorrelated Gaussian noise with an RMS contrast of 25%. The peak contrast of the three distractors was 12% (pedestal contrast). In experiment 1, the target contrast was varied at 5 levels, resulting in signal-to-noise ratios (SNRs) that ranged from 0 to 5.6 for the small scale patterns, and from 0 to 25.77 for the large patterns. In experiment 2, the SNRs of the small and large items were kept fixed.

2.4. Trial sequence

At the start of a trial, a fixation display appeared. Observers fixated a small black cross in the centre of the screen, and initiated a trial by pressing the space bar. After a variable delay (667–1333 ms), the stimulus appeared, consisting of the circle outline markers, Gaussian patterns, fixation point, and external noise sample. It was presented for 800 ms, followed by a response display containing only the fixation point and the 4 marker circles. Observers moved the mouse cursor to the location where they thought the brightest pattern had appeared and responded by pressing the left button. The background of the fixation and response displays were uniform grey, with the same mean luminance as the noise background in the stimulus.

2.5. Eye movement recording and saccade classification

The position of the left eye was sampled at 250 Hz using an infrared video-based eye tracker (SMI EyeLink). A nine-point grid calibration was performed at the start of each block of 120 (experiment 1) or 96 (experiment 2) trials. Head movements were restricted through a chin rest. Observers viewed the display from a distance of 56 cm.

Eye movement data were analysed off-line. Saccades were detected using velocity and acceleration criteria of 35°/s and 9500°/s^2, respectively. Trials were excluded if the first saccade (i) starting position deviated from the display centre by more than 1°; (ii) latency was less than 80 ms; (iii) amplitude was less than half the distance of the display items. For observers 1–3, respectively, these criteria resulted in the rejection of 6%, 7%, and 5% of the trials. The landing position of the saccade was assigned to a display item if its angle fell within 90° of the direction of that item (i.e. within the correct quadrant). Landing positions were generally tightly clustered around display item locations: 95% of saccades had directional deviations smaller than 14°, 17°, and 26° for observers 1–3, respectively. Assigning the saccade landing position to the nearest item in the display is standard practice in this type of study (Beutter, Eckstein, & Stone, 2003; Ludwig & Gilchrist, 2006).

2.6. Analyses

2.6.1. Psychometric functions

First, the proportion of first saccades directed to the target was mapped onto the signal detection measure of d' according to (Green & Swets, 1966):

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