Vision Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The influence of endogenous attention on contrast perception, contrast discrimination, and saccadic reaction time

Madhumitha S. Mahadevan*, Harold E. Bedell, Scott B. Stevenson

University of Houston, College of Optometry, USA

ARTICLE INFO

Number of Reviews = 2

Keywords:
Attention
Contrast
Saccadic eye movement
Latency

ABSTRACT

Visual spatial attention has been shown to influence both contrast detection and suprathreshold contrast perception, as well as manual and saccadic reaction times (SRTs). Because SRTs are influenced also by stimulus contrast, we investigated if the enhancement of perceived contrast that accompanies attention could account for the shorter SRTs observed for attended targets locations. We conducted two dual-task experiments to assess psychophysical and oculomotor responses to non-foveal targets of various contrast for different spatial-attention-cueing conditions. Cues were either: valid, an arrow at fixation pointing in the direction of the upcoming target; invalid, an arrow pointing in a different direction from the target; or neutral, a small circle instead of an arrow. In both experiments, subjects were instructed to make a saccade to the location of a subsequent, briefly flashed target. In the first experiment, the psychophysical judgment was a two-alternative-forced-choice (2AFC) contrast-detection task, in which subjects reported whether the flashed target was at a near (3°) or far (6°) eccentricity. In the second experiment, the judgment was a contrast matching task, in which subjects reported whether the target's contrast was higher or lower than a remembered standard contrast. The results exhibit a robust, ~40–50 ms reduction of SRTs with a valid compared to an invalid cue. Cueing effects on contrast detection and matching were small and inconsistent across subjects. Hence, the observed decrease in SRTs could not be accounted for fully by an enhancement in the target's effective contrast due to attention, as attended and unattended targets that were equally detectable or were perceived to have the same suprathreshold contrast showed substantial differences in SRT.

1. Introduction

Visuo-spatial attention refers to a covert process that leads to an enhancement of sensitivity or awareness favoring one region of visual space over another. Studies of this phenomenon generally rely on a cueing paradigm to direct attention to a location (Bashinski & Bacharach, 1980; Lu & Dosher, 1998, 2000; Posner, 1980) where the stimulus is most likely to occur. Studies have used different stimulus features like spatial frequency (Abrams, Barbot, & Carrasco, 2010; Carrasco, Loula, & Ho, 2006; Carrasco, Williams, & Yeshurun, 2002), contrast (Ling & Carrasco, 2006; Cameron, Tai, & Carrasco, 2002; Carrasco, Fuller, & Ling, 2008; Pestilli & Carrasco, 2005), or orientation (Lu & Dosher, 1998) to determine where attention is allocated. The comparison of sensitivity for attended and unattended targets requires occasional presentations that are not at the cued location (invalid-cue trials), with the assumption that attention is deployed instead to the higher-likelihood cued location.

When visuo-spatial attention is deployed to the target's location (valid cue), the time taken to respond to a change or the sudden appearance of a stimulus, either with a saccadic eye movement or a manual response, is much faster than when the target appears at an unattended location (Katnani & Gandhi, 2013; Kowler, Anderson, Dosher, & Blaser, 1995; Posner, 1980). Visual attention and eye movements are deeply interconnected with each other because, together, they serve as tools to scan the visual scene and facilitate the processing of relevant visual information (Kowler, 2011). Hence, attention is thought to be associated with an oculo-motor plan to shift gaze to the attended location. When a stimulus is presented in an unattended location there is an attentional cost (an increase in manual reaction time, MRT) that presumably involves first the cancelation and then a reprogramming of the manual movement response (Rizzolatti, Fogassi, & Gallese, 2001; Rizzolatti, Riggio, Dascola, & Umilta, 1987).

1.1. Attention and stimulus-feature enhancement

Orienting cues such as an arrow or the sudden flash of an eccentric stimulus have been used to direct and deploy observers' attention to a particular location in space (Posner, 1980). Feature-based cues

* Corresponding author at: College of Optometry, University of Houston, Houston, TX 77204-2020, USA.
E-mail address: msmahade@Central.uh.edu (M.S. Mahadevan).

https://doi.org/10.1016/j.visres.2017.11.005
Received 12 July 2016; Received in revised form 15 November 2017; Accepted 16 November 2017

(orientation, color, spatial frequency, motion processing, and direction of motion) have been used extensively in visual search (singleton and conjunction) paradigms to indicate the relevance of one or a combination of specific stimulus features (Eriksen & Schultz, 1979; McElree & Carrasco, 1999; Muller, Heller, & Ziegler 1995; Treue & Maunsell, 1996). Two types of attentional shifts have been identified, depending on the factors that modulate the deployment of attention: (1) for **exogenous** attentional mechanisms, the salience of the visual stimulus itself captures attention; and (2) for **endogenous** mechanisms, attention is directed either by an instruction or a symbolic cue. Exogenous attention is thought to be involuntary and transient; it gets deployed at the cued location close to 50 ms post cue presentation and its effect decays quickly (100–120 ms). Endogenous attention is thought to be voluntary or goal driven, involving the observer's expectations and prior stimulus probabilities. It has a slower time course, taking about 300 ms to deploy to a location (Nakayama & Mackeben, 1989) and does not decay quickly. Attention to a spatial location is found to enhance perception at that location relative to other unattended locations, but the mechanism by which attention enhances the features of a stimulus is still debated (Carrasco, 2011; Lu & Dosher, 1998, 2000). Suggested mechanisms include signal enhancement (Ling & Carrasco, 2006; Lu & Dosher, 2000), exclusion of extraneous information (Lu & Dosher, 1998), and a change in the response criterion (Prinzmetal, McCool, & Park, 2005; Schneider, 2011; Schneider & Komlos, 2008).

1.2. *Attention and eye movements*

Although one can focus attention in the periphery without shifting gaze, a phenomenon called covert attention, attending to an object and foveating that object usually are intimately linked (Kowler, 2011; Kowler et al., 1995). Numerous studies addressed the connection between attention and saccade planning. These studies suggest that covert attentional shifts are antecedent to saccades, so that attention is already at the saccade goal even before the saccade is executed (Deubel & Schneider, 1996; Deubel, 2008; Rolfs & Carrasco, 2012). SRTs are shorter for trials on which attention is deployed in advance to the saccadic goal (valid-cue trials) and are longer for trials on which the presumed locus of attention and the saccade goal do not match (Kowler et al., 1995). Better perceptual identification also is reported to occur at the saccadic goal compared to other locations (Hoffman & Subramaniam, 1995; Gersch, Kowler, & Dosher, 2004; Kowler, 2011; Kowler et al., 1995; Gersch, Kowler, Schnitzer & Dosher, 2009; Khan, Heinen, & McPeek, 2010). Various imaging and neurophysiological studies indicate that there is a good amount of overlap between the neural substrates that serve attention and eye movements (Basso & Wurtz, 1998; Corbetta, 1998; Corbetta et al., 1998; Goldberg, Bisley, Powell, & Gottlieb, 2006; Katnani & Gandhi, 2013; Katyal & Ress, 2014; Krauzlis, Lovejoy, & Zenon, 2013; Schall, Purcell, Heitz, Logan, & Palmeri, 2011).

1.3. *Saccades and contrast sensitivity*

While attention is known to influence saccadic reaction time, another significant factor is the visibility of the saccade target. For example, SRTs decrease with increasing target contrast, particularly within the range of low and medium contrasts (Felipe, Buades, & Artigas, 1993; Ludwig, Gilchrist, & McSorley, 2004). This effect is shown schematically in Fig. 1. The LATER model (linear approach to threshold with ergodic rate) is an empirical model used to explain the observed variability in reaction times (Carpenter & Williams, 1995; Schall et al., 2011). The model accounts for the latency of a saccade on any trial, based on how quickly the signal produced by the stimulus builds up from a baseline level to achieve a threshold, at which time a saccade is elicited. Low contrast stimuli produce relatively long latency saccades because these stimuli require a longer integration time to reach the threshold level (Reddi, Asrress, & Carpenter, 2003).

As both attention and contrast have been shown to influence SRT, we ask here if the effect of attention might be accounted for by an enhancement of effective contrast prior to the stage of saccade planning and execution. We used an endogenous cueing paradigm with dual motor and psychophysical tasks to measure both SRTs and perceived contrast simultaneously.

We started our investigation with the hypothesis that attention enhances effective contrast equally at all contrast levels and that the effect of attention on SRTs should be equivalent to a shift along the contrast axis. Fig. 1 (left) illustrates this prediction schematically. Alternatives are a pure latency shift, resulting in a uniform shift along the SRT axis (middle), or a combined effect of attention on the effective contrast and latency (right), which also are illustrated.

We conducted two experiments to test the hypothesis that attended and unattended targets with equal visibility will produce identical SRTs (i.e. attention-induced contrast enhancement, as measured psychophysically, accounts for the concurrent decrease in SRTs).

2. Experiment 1: Effect of attention on contrast threshold and SRTs

2.1 *Methods*

2.1.1. *Subjects*

Subjects included 3 authors and 4 other individuals who were naive to the specific research question addressed. All subjects had corrected-to-normal acuity and normal ocular motility. Subjects gave signed informed consent to participate and all procedures were approved by the University of Houston Committee for the Protection of Human Subjects. The research was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1.2. *Eye movement recording*

Eye position was recorded during the experiments using a binocular Generation V dual Purkinje image eye tracker (www.wardelex.com) with the stimulator attachment in place (Crane & Steele, 1978, 1985). Left- and right-eye horizontal and vertical eye positions were sampled in synchrony with the display frame rate of 120 Hz.

2.1.3. *Stimulus display*

Targets were displayed on an Image Systems monochrome multisync CRT display with fast phosphor (www.imagesystems.com). The display area subtended 36 × 28 degrees at the optical viewing distance of 57 cm, with a resolution of 25 pixels /deg and a frame refresh rate of 120 Hz. Stimuli were produced using a VSG2-3 video card from Cambridge Research Systems (www.crsltd.co.uk) with custom software written in Microsoft Visual Basic. This system provides 12 bits of gray scale resolution after linearization. Background luminance was 40 cd/m^2.

The display included a black central fixation circle of 0.2 degrees in diameter surrounded by an outer black concentric ring of 0.5 degrees. The target was a raised-cosine windowed, peak-centered concentric sinusoidal grating that looked like a 'bull's eye' (Fig. 2). This target was presented at either 3 or 6 deg eccentricity. The spatial frequency and the visual angle subtended by the target patches (including the cosine window) were 2.2 cpd and 3.63 deg, respectively, at 3 deg eccentricity, and 1.4 cpd and 5.84 deg at 6 deg eccentricity. These values were chosen to produce targets of similar effectiveness based on published values for the cortical magnification factor (Cowey & Rolls, 1974). The target could appear in any one of 16 locations, comprising 2 eccentricities and 8 directions from the fixation stimulus.

A central black arrow served as the endogenous cue to direct attention. The arrow indicated one of the eight target directions but did not indicate the target eccentricity. In the experiment, the direction cue was valid on 75% of the trials and equally often invalid or neutral on the remaining 25% of the trials.