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Eccentricity effects in vision and attention

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ABSTRACT

Stimulus eccentricity affects visual processing in multiple ways. Performance on a visual task is often better when target stimuli are presented near or at the fovea compared to the retinal periphery. For instance, reaction times and error rates are often reported to increase with increasing eccentricity. Such findings have been interpreted as purely visual, reflecting neurophysiological differences in central and peripheral vision, as well as attentional, reflecting a central bias in the allocation of attentional resources. Other findings indicate that in some cases, information from the periphery is preferentially processed. Specifically, it has been suggested that visual processing speed increases with increasing stimulus eccentricity, and that this positive correlation is reduced, but not eliminated, when the amount of cortex activated by a stimulus is kept constant by magnifying peripheral stimuli (Carrasco et al., 2003). In this study, we investigated effects of eccentricity on visual attentional capacity with and without magnification, using computational modeling based on Bundesen's (1990) theory of visual attention. Our results suggest a general decrease in attentional capacity with increasing stimulus eccentricity, irrespective of magnification. We discuss these results in relation to the physiology of the visual system, the use of different paradigms for investigating visual perception across the visual field, and the use of different stimulus materials (e.g. Gabor patches vs. letters).

1. Introduction

When attention is unguided (i.e., when stimulus location is uncued), many studies indicate that the same stimulus is processed both faster and with higher accuracy when presented at the fovea compared with the visual periphery. For instance, increasing the eccentricity of a visual target has been reported to increase reaction times and error rates (Carrasco et al., 1995; Wolfe et al., 1998), deteriorate performance in object recognition tasks (Juttner and Rentschler, 2000), attenuate the ability to quickly process emotional facial expressions (Bayle et al., 2011), and even to make it more difficult to discriminate attractive and unattractive faces (Guo et al., 2011). However, other findings indicate that some aspects of visual processing are enhanced in the peripheral visual field. In a seminal study, using a forced-choice orientation discrimination task, Carrasco and colleagues found that processing speed increases with increasing eccentricity (Carrasco et al., 2003).

While the existence of eccentricity effects is well-established, their nature is debated. Some argue that the effects are purely visual, suggesting that they can be explained by the structural layout of the human visual system (Anstis, 1998; Carrasco and Frieder, 1997). Others argue that attentional mechanisms are involved as well, holding that an anatomical explanation alone cannot adequately account for the effects observed (Wolfe et al., 1998).

Eccentricity effects have often been linked to the *cortical magnification factor* (Daniel and Whitteridge, 1961; Rovamo and Virsu, 1979; Virsu and Rovamo, 1979); a concept that accounts for the relationship between visual acuity and distance from the fovea. It expresses the surface area of cortex in V1 that corresponds to one degree of visual angle at different eccentricities (However, see Harvey and Dumoulin (2011), for a discussion of magnification in other areas). Since a larger cortical area is devoted to processing visual information at the fovea, rather than more eccentric locations, the fovea is said to have the largest magnification factor. By scaling stimuli according to the cortical magnification factor (*M*-scaling), it has been demonstrated that performance on various detection and discrimination tasks in the periphery becomes similar to the performance near or at the fovea (Carrasco and Frieder, 1997; Motter, 2009; Rovamo and Raninen, 1990). Such findings support the notion of invariance in visual processing, i.e. that stimuli are processed the same way across all locations of the visual field, predicting equal performance at all eccentricities when stimuli are scaled to achieve similar cortical representations (Yu et al., 2014). However, though scaling has accounted for eccentricity-dependent performance differences in some visual tasks, it has failed to do so in a number of other tasks (Bao et al., 2013;

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Valsecchi et al., 2013; Wolfe et al., 1998). Based on such findings, Wolfe (1998) argued for a model in which eccentricity effects are linked to an attentional bias for stimuli presented centrally. Such an attentional bias would enhance perception in everyday life, as we are inclined to foveate behaviorally relevant objects even though we might not be consciously aware of our limited perceptual abilities peripherally. Indeed, subjects tend to overestimate their peripheral performance (Solovey et al., 2015).

Some aspects of performance across the visual field may be given by the anatomy of the visual system or inherent central biases. However, an abundance of studies has attested to the potential for change by both environmental factors and practice. For instance, deaf individuals have been shown to allocate more attentional resources to the visual periphery, compared to hearing individuals, possibly reflecting a compensatory reorganization of spatial attention in the deaf (Dye et al., 2009b; Proksch and Bavelier, 2002). The notion of such alterations taking place is intuitively appealing, seeing that deaf individuals cannot depend on auditory cues to guide attention toward peripheral events. In the case of action video-gamers, the habitual or recent exposure to a demanding visual task have also been reported to improve visual processing speed and selective attention, especially in the far periphery (Hubert-Wallander et al., 2011). While it is suggested that a trade-off takes place between attentional resources available in central and peripheral vision in the deaf, no such trade-off has been reported for action ivideo gamers, suggesting that practice on a demanding visual task can lead to a general enhancement of visual ability across the visual field (Dye et al., 2009a; Green and Bavelier, 2007). Such evidence for the potential for change calls for a more precise characterization of eccentricity effects in order to clarify possible training prospects in the case of both healthy and clinical populations (e.g., patients with visual deficits). In addition, as previous experiments have often used simple stimuli (e.g., Gabor patches), knowledge of effects of eccentricity on the processing of more complex stimuli (e.g., letters) is needed.

In this study, we investigated the effects of stimulus eccentricity on discrete components of visual attention using the Theory of Visual Attention (TVA; Bundesen, 1990). In TVA, attention is said to comprise several distinct parameters that can be independently estimated from the same set of behavioral data. This is advantageous when seeking to understand potential differential effects of stimulus eccentricity on different components of visual attention. In one experiment, we investigated the effects of eccentricity on visual short-term memory (VSTM) capacity (K), the visual perceptual threshold (t_0), and visual processing speed (C). In a subsequent experiment, we tested the effect of M-scaling on estimates of these parameters. Additionally, we manipulated expectancy of spatial location by introducing a blocked trial design in one half of the experiment, where each block contained only trials with the same stimulus eccentricity, and an intermixed design in the other. If eccentricity effects arise from magnification alone, we expect potential effects of eccentricity in Experiment 1 to be abolished by the M-scaling in Experiment 2. If attentional mechanisms are involved, we expect eccentricity effects to be diminished in the blocked part of Experiment 2, where participants know where to direct attention, compared to the intermixed part.

1.1. Theory of visual attention (TVA)

TVA (Bundesen, 1990) is a computational theory of visual attention, in which attention is described as a mechanism for selecting the currently most relevant information and encoding it into VSTM. According to TVA, objects in the visual field compete for access to VSTM in a parallel processing race. Since storage capacity is limited, only K objects can be encoded, assuming a slot-based model of VSTM (Luck and Vogel, 1997; but see Wilken and Ma, 2004; Bays and Husain, 2008). The probability of an object being encoded into VSTM depends on its attentional weights, reflecting the strength of the object's sensory evidence and its relevance (subjective attentional bias). In the processing race, each object in the visual field is assigned an attentional weight that determines the proportion of the total processing capacity allocated to it, and accordingly, how fast it is processed. The more processing resources an object is allotted, the higher the probability is that the object will gain access to VSTM. The total processing capacity, C, is assumed to be a constant and independent of the number of objects in the visual field. Thus, the visual system is assumed to have a limited fixed processing capacity. In mathematical terms, the processing speed of an object x in the visual field can be expressed as:

$$v_x = C\frac{w_x}{\sum_{z \in S} w_z}$$

where C is the total processing capacity, w_x is the attentional weight assigned to object x and the denominator is the sum of attentional weights across all objects in the visual field, S (see

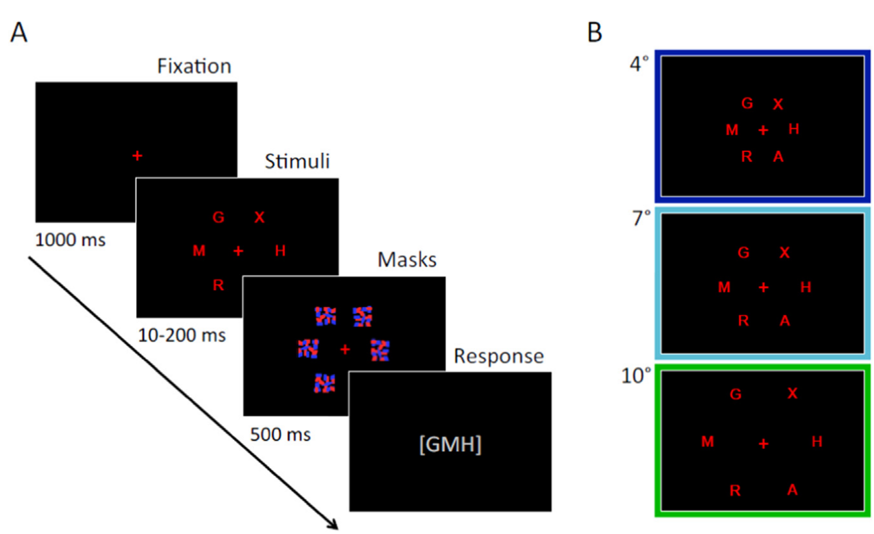

Fig. 1. Trial outline (A) and eccentricity conditions (B) for Experiment 1. First, participants were presented with a central cross on which they were instructed to fixate throughout the trial. Then, six randomly chosen target letters were shown at an eccentricity of either 4°, 7°, or 10° of visual angle from the central fixation point. Target letters were terminated with pattern masks. Lastly, a blank screen probed participants to report the letters they had seen.