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Changes in the distribution of sustained attention alter the perceived structure of visual space

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ABSTRACT

Visual spatial attention is a critical process that allows for the selection and enhanced processing of relevant objects and locations. While studies have shown attentional modulations of perceived location and the representation of distance information across multiple objects, there remains disagreement regarding what influence spatial attention has on the underlying structure of visual space. The present study utilized a method of magnitude estimation in which participants must judge the location of briefly presented targets within the boundaries of their individual visual fields in the absence of any other objects or boundaries. Spatial uncertainty of target locations was used to assess perceived locations across distributed and focused attention conditions without the use of external stimuli, such as visual cues. Across two experiments we tested locations along the cardinal and 45° oblique axes. We demonstrate that focusing attention within a region of space can expand the perceived size of visual space; even in cases where doing so makes performance less accurate. Moreover, the results of the present studies show that when fixation is actively maintained, focusing attention along a visual axis leads to an asymmetrical stretching of visual space that is predominantly focused across the central half of the visual field, consistent with an expansive gradient along the focus of voluntary attention. These results demonstrate that focusing sustained attention peripherally during active fixation leads to an asymmetrical expansion of visual space within the central visual field.

1. Introduction

Vision is a fundamental sense with which humans assess their environments and plan actions to interact within these environments. Implicit in any theory of visual perception is the assumption of a spatial structure, whether it is a field within which both an observer and external object exists, or the internal spatial structure of a single object. The development of accurate spatial metrics regarding the direction and distance of an object is critical for allowing observers to effectively interact with their environment, whether reaching for a cup off of a kitchen counter or more complex actions such as navigating through crowded city streets.

At any given moment, however, our perception of the world is not simply a passive representation of the external environment. One factor that is known to modulate visual perception is the current attentional state of an observer. Changes in the focus of visuospatial attention alter not only the quality of object representations (Anton-Erxleben, Henrich, & Treue, 2007; Carrasco, 2011; Carrasco, Ling, & Read, 2004; Fortenbaugh, Prinzmetal, & Robertson, 2011; Kosovicheva, Fortenbaugh, & Robertson, 2010; Tsal & Shalev, 1996) but also the perceived location of those objects (Adam, Paas, Ekering, & Loon, 1995; Bocianski, Müsseler, & Erlhagen, 2010; Fortenbaugh & Robertson, 2011; Prinzmetal, 2005; Tsal & Bareket, 2005; Tsal & Shalev, 1996; Uddin, Kawabe, & Nakamizo, 2005; Yamada, Kawabe, & Miura, 2008).

While changes in attentional distribution have been shown to alter perceived object size and location, there are conflicting theories regarding what these effects imply for the underlying structure of visual space. Some studies (Tsal & Bareket, 1999; Tsal & Bareket, 2005) using visual cues to direct attention toward or away from a given location have found that shifts in attention can alter perceived location by shifting the perceived locations away from fixation. Other studies have shown that directing attention toward the

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location of a target stimulus improves location precision, reducing its spatial spread. Still other studies (Adam, Davelaar, van der Gouw, & Willems, 2008; Newby & Rock, 2001; Prinzmetal, Amiri, Allen, & Edwards, 1998) have used dual-task paradigms to test how a secondary task performed at fixation alters perceived location in the parafoveal and nearer the periphery (i.e., <10° eccentricity). Interestingly, some of these dual-task studies (Adam et al., 2008) found evidence that being able to focus attention in a single-task relative to a dual-task condition reduces foveal biases, or underestimations of target eccentricity, while other studies (Newby & Rock, 2001; Prinzmetal, 2005; Prinzmetal et al., 1998) only found evidence for reductions in spatial spread of response locations. Given that the use of visual cues or dual-task paradigms introduce additional visual stimuli in a display, in addition to already known landmark effects that can alter localization performance (Diedrichsen, Werner, Schmidt, & Trommershäuser, 2004; Eggert, Ditterich, & Straube, 2001; Kerzel, 2002; Werner & Diedrichsen, 2002; Yamada et al., 2008), an additional paradigm that has been used to study the effects of voluntary attention on localization is to alter the distribution of sustained attention across blocks of trials by manipulating spatial uncertainty in the region where targets can appear (Fortenbaugh & Robertson, 2011). Manipulations of spatial uncertainty in these localization tasks provide a complementary approach to visual cueing paradigms by altering the spatial spread of voluntary attention, rather than shifting the focus of attention, in a manner similar to dual task paradigms but without introducing external objects into the display. Across these studies, several theories regarding the impact of attention on peripheral localization have been developed. Specifically, findings related to focusing voluntary attention have been interpreted as evidence for: (1) attention decreasing variability in perceived location without inducing spatial biases (Newby & Rock, 2001; Prinzmetal, 2005) and (2) attention expanding visual space at the focus of attention and increasing perceived target distances or the size of attended objects (Anton-Erxleben et al., 2007; Fortenbaugh & Robertson, 2011; Fortenbaugh et al., 2011).

The present study was designed to address the latter hypothesis, that distributing voluntary attention across smaller and smaller regions of space can systematically alter where objects are seen in the visual periphery. In particular, the results of the study by Fortenbaugh and Robertson (2011) showed systematic changes in judged location across three attention conditions that manipulated the distribution of attention by varying the number of attended visual axes from fixation (i.e., spatial uncertainty). Targets could appear along 1, 2 or 4 horizontal or vertical axes. The task was to judge target location relative to fixation and a 30° aperture boundary that was mounted on a computer monitor. Results showed that when participants distributed attention across all four visual axes they significantly underestimated the eccentricity of the targets (i.e. foveal bias). For example, reporting 25% when the target was at 30% eccentricity from fixation. As spatial uncertainty and thus the number of attended axes was reduced, the degree of foveal bias was also reduced, consistent with an expansion of visual space.

However, the observed reduction in foveal bias could be due to two potential effects of attention on perceived location: namely, an increase in location accuracy along the attended axes (the Accuracy hypothesis) or an expansion of perceived space along these axes (the Expansion hypothesis). In order to tease apart these two competing hypotheses, in the present study we utilized methods from another study looking at peripheral localization judgments with the same response method but within a Goldmann perimeter. This perimeter type is traditionally used to map visual fields in optometry exams and is a half-dome that allows peripheral localization judgments relative to perceived visual field extent without visible external object contours (Fortenbaugh, Sanghvi, Silver, & Robertson, 2012). Importantly, this study showed that when attention was distributed across the four cardinal visual axes participants showed a peripheral localization bias, overestimating the target eccentricities for similar briefly flashed, static targets (e.g., reporting 35% when the target was at 30%). This stimulus design thus provides an opportunity to disentangle the two hypotheses regarding the impact of focusing attention on perceived location (see Fig. 1). Specifically, given that in the experimental context of the Goldman, participants already show a peripheral bias when attention is spread across the visual field, the accuracy hypothesis predicts that focusing attention on a subset of axes will reduce peripheral biases relative to this baseline (attending to all axes), thus reducing the absolute magnitude of errors during localization. In contrast, the expansion hypothesis predicts that focusing attention will increase the perceived distance between fixation and the target location, increasing peripheral biases and leading to less accurate performance on the task.

2. Experiment 1

2.1. Method

2.1.1. Participants

Fifteen naïve participants completed the experiment (8 female; 20.3 ± 2.7 years). All participants reported 20/20 visual acuity, either without any optical correction or with contact lenses. Participants were excluded if they wore eyeglasses, as these can artificially restrict visual field extent (Steel, Mackie, & Walsh, 1996). One participant did not complete all blocks. The remaining fourteen participants were included in the following analyses. All procedures were approved by the Committee for the Protection of Human Subjects at the University of California, Berkeley, and followed the tenets of the Declaration of Helsinki. All participants provided signed informed consent before the study began.

2.1.2. Materials and procedure

The methods followed those developed in our previous study (Fortenbaugh et al., 2012). Briefly, participants were seated in a Goldmann kinematic perimeter, a self-illuminated half-dome with a uniform white background that allows targets dots to be presented at any location within the visual field (see Fig. 2). Visual field extent was first measured using standard clinical procedure. The experimenter was seated on the opposite side and viewed the participant's right eye through a telescope and monitored participant fixation. The telescope is affixed to the center of the dome where a 1° radius hole with a glass plate (1 cm diameter) is located. Within the hole, a metal pin provides a fixation point in the exact center of the dome for participants (Fig. 1, right panel). For each participant, binocular visual field extent along the four cardinal axes (left and right horizontal; upper and lower vertical) was measured using the III4e test target (0.44° target dot; viewing distance = 30 cm; 318 cd/m^2 on a background luminance of 10 cd/m^2; Weber contrast ratio = 30.8). While the participant fixated on a point in the center of the perimeter, the experimenter first presented the target at a location outside of the visual field. The experimenter then slowly moved the target foveally along a visual meridian. When the participant first detected the target dot entering their visual field they pressed a button that made a tone and the experimenter marked the location on a chart.

The behavioral task used the same experimental set-up as for the visual field measurements. However, here, while participants maintained fixation at the center of the perimeter, the experimenter briefly flashed the target dot. Presentation of target dots is manually controlled in the Goldmann perimeter, with average target durations of 176.8 ms ± 25.5 ms (Fortenbaugh et al., 2012). Across trials, potential target locations were eccentricities from