Dynamic recovery of the size of the attentional field in visual cortex

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Abstract:

It has long been known that spatial attention can improve behavioral performance in attended locations at the expense of performance at unattended locations, leading to a conceptualization of spatial attention as akin to a 'spotlight.' While the neural correlates of the location of this attentional spotlight have been comparatively well studied, less is known about its size: whether and how the spotlight can be broadened or narrowed in response to attentional demands. Here, we developed a paradigm and model to directly investigate the size of the attentional field using fMRI in humans. As attentional cue width increased, the attentional enhancement of BOLD activity in visual cortex also broadened. This broadening was accompanied by a diminishing amplitude of the attentional enhancement.

Keywords: spatial attention; visual cortex; fMRI

Introduction

We must adaptively deploy our attention based on our anticipation of relevant future events and stimuli. This encompasses both moving as well as broadening or narrowing our attentional focus.

Covert spatial attention has been shown to improve behavioral performance at attended locations in a range of tasks, but this is associated with diminished performance at unattended locations (Castiello & Umiltà, 1990; Eriksen & St James, 1986; Posner, 1980; Shaw & Shaw, 1977).This common finding has led to the portrayal of attention as a 'zoom lens' or 'spotlight,' associated with both a location and size, which selectively enhances processing at the attended location and suppresses processing elsewhere. This view has been bolstered by a surfeit of data showing increases in visual responses in attended locations in both animal and human studies (Brefczynski & Deyoe, 1999; Datta & DeYoe, 2009; Kastner et al., 1999; McAdams & Maunsell, 1999; McMains & Somers, 2004; Puckett & Deyoe, 2015).

Though these neural signatures of the *location* of the attentional field have been relatively well studied, comparatively less is known about the *spread* of attention (Yeshurun, 2019). Though spreading and splitting the attentional window is associated with decreased behavioral performance (Castiello & Umiltà, 1990; Eriksen & St James, 1986), only a few studies have investigated the associated neural correlates directly (Herrmann et al., 2010; Itthipuripat et al., 2014). This lack of data is all the more surprising as the size of the attentional field is a key aspect of a formative model of attention (Reynolds & Heeger, 2009). From the few studies that have manipulated attention window size, the attentional field appears to expand, and this might be accompanied by a decrease in the amplitude of the overall population response (Feldmann-Wüstefeld & Awh, 2019; Herrmann et al., 2010; Müller et al., 2003).

Here, we investigate the size of the attentional field directly, developing a model to dynamically recover the extent of the covert attentional field using fMRI in humans. We confirmed that covert attention was associated with an enhancement of activity in corresponding retinotopic areas in visual cortex. This showed a clear broadening of extent of attention with wider attentional cues, and was accompanied by a diminished amplitude of enhancement.

Method

All procedures were approved by the Boston University Institutional Review Board, and informed consent was obtained for all participants (N=8, 4 male, 4 female, mean age = 30).

Procedure

While undergoing fMRI, participants were required to maintain central fixation while a dynamic white noise annulus was presented. The annulus was divided into 20 equally-sized bins (18° polar angle), and a number or letter was superimposed onto each bin (Figure 1).

Participants were cued to attend to a subset of bins (18°, 54°, 90°, or 162° polar angle) and report whether more numbers or letters were present within the cued region via keypress. Cues could be centered on any bin, and were stable for five-trial blocks (3.1s/trial). Each participant completed between 8 and 12 runs of the task, containing 100 trials each with a period of 15.5s of white noise beginning and ending the run.

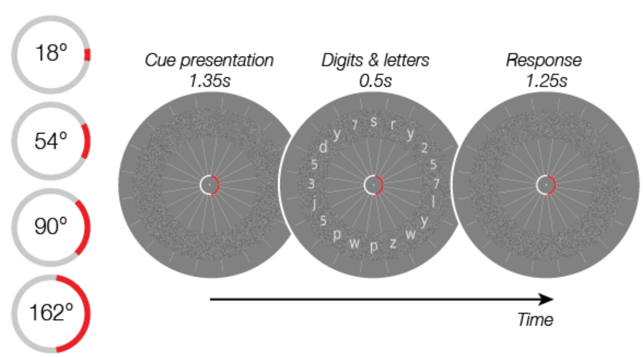

Figure 1: Task schematic.

Model

We reconstructed the BOLD attentional enhancement by selecting voxels with population receptive fields overlapping the annulus and arranged them according to polar angle preference. These response profiles were averaged for each five-trial block (10 TRs/15.5s).

We then modeled the BOLD profiles using a generalized Gaussian distribution (Figure 2a), characterized by a mean (μ) and standard deviation (σ), as well as a shape parameter (β), which allows the tails of the distribution to become heavier than a typical Gaussian (β < 2) or lighter (β > 2). We also used amplitude (a) and baseline offset (b) parameters to scale and shift the distribution, fitting all parameters by minimizing the squared error between the model prediction and the BOLD response profile.

$$G = a \cdot exp\left\{-\left|\frac{x-\mu}{\sigma}\right|^{\beta}\right\} + b$$

We quantified model accuracy using the percentage of variance explained (R^2). To account for the influence of both σ and β on attentional field width, we report the full-width at half maximum (FWHM) as our measurement of attentional field breadth (Figure 2b).

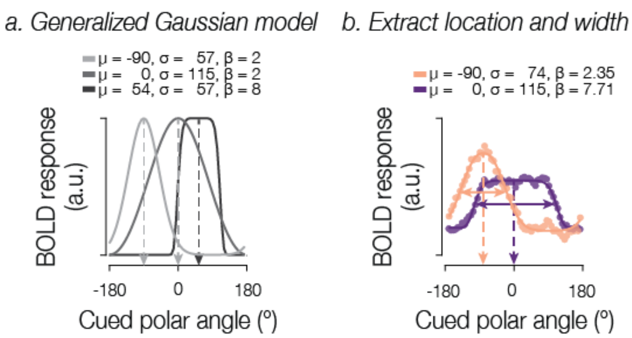

Figure 2: Model of attentional field. a. Generalized Gaussian model. **b.** Two example model fits. Dots show BOLD response for two cued locations and widths; solid lines show best fitting model; arrows represent the mean and FWHM.

Results

Participants were successfully able to report whether more numbers or letters were present within the cued region across all cue widths (all conditions above chance, t-test, all $p < 0.001$).

We next assessed the size of the attentional window by visualizing how the BOLD response changed based on the size and location of the cue. Separately for V1, V2, and V3, we rotated all BOLD response profiles for each five-trial block to align cues to 0° polar angle (rightward). We then visualized the overall averages for each cue width (Figure 3a). These average spatial response profiles reveal a clear attentional enhancement centered on 0°, which both broadened and decreased in amplitude with cue width.

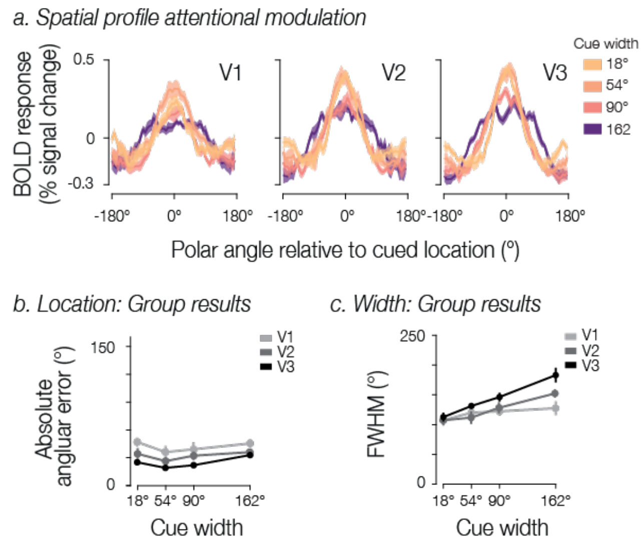

Figure 3: Location and width of attentional field. a. Spatial profiles of attention, separated by cue width and brain region. **b.** Mean error magnitude in estimated mean, separated by brain region. **c.** Mean FWHM, separated by brain region.

We next fit the generalized Gaussian model to the BOLD profile for each five-trial block. First, we evaluated the estimated *location* of the attentional window by calculating the magnitude of the error between the estimated mean of the best-fitting model and the actual cue center (Figure 3b). The model reliably captured the locus of attention, independent of cue width (linear regression, all $p >= 0.494$).

Finally, we evaluated the width of the attentional field for each five-trial block using the FWHM of the best-fitting model. The FWHM reliably broadened with cue width in both V2 and V3 (linear regression, both $p < 0.001$), though V1 did not reach significance ($p = 0.093$).

Conclusions

Using our model, we were able to dynamically recover the locus of the attentional field from BOLD visuocortical activity. Our results reveal a broadening window with a decreasing amplitude associated with cue width. This suggests that the attentional 'spotlight' can indeed broaden and narrow with attentional demands, providing additional support for theoretical models of attention.

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