Attentional field model does not explain task-dependent spatial representation in human ventral temporal cortex

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Abstract:

One influential theory of attention is to regard it as a spotlight. Accordingly, previous studies have proposed the concept of an attentional field (AF), which describes the distribution of attentional resources over 2D visual space. In the present study, we tested the merits of the AF model in characterizing the effect of attention on spatial representation in human ventral temporal cortex (VTC). We mathematically implemented the AF as a 2D Gaussian that is multiplied with a bottom-up 2D Gaussian describing stimulus-driven responses. We evaluated whether this model accurately accounts for an existing dataset that includes cortical responses in VTC to position-varied face stimuli under different attentional tasks (Kay et al., 2015). Surprisingly, we found that the AF model does not satisfactorily account for the attentional effects in the data. Moreover, simpler, phenomenological models outperformed the AF model. These results suggest that although the AF is theoretically compelling, it does not accurately predict attentional effects in VTC, at least in its current mathematical form.

Keywords: attentional field, high-level visual cortex, population receptive field model

The theory of attentional field

Visual spatial attention is conventionally characterized as a spotlight, which presumably highlights the region where more attentional resources are deployed and information is preferentially processed. Mathematically, an attentional spotlight can be formulated as a 2D Gaussian, called an *attentional field* (AF), whose center and size can be flexibly adjusted depending on the stimulus and behavioral task (Posner et al., 1980). It has been shown that the AF model is capable of quantitatively explaining attentional effects on the neural representation of position using single-unit, fMRI, and psychophysical measurements (Klein et al., 2014; Reynolds & Heeger, 2009; Womelsdorf et al., 2006). Given the documented success of the AF model, we expect that, in general, the AF model should accurately account for attentional effects in different experimental paradigms.

In a previously published study, we presented face stimuli at 25 different locations across visual space and measured cortical responses in human VTC while participants performed distinct attentional tasks (Fig. 1A). Our pRF modeling (Kay et al., 2013) demonstrated that attending to face stimuli, compared to attending to fixation, shifted pRFs peripherally, expanded pRF size, and increased pRF gain (Kay et al., 2015). However, such modeling reveals only the consequences of attention on the apparent pRF, but does not provide a fully general model that can predict neural responses for an arbitrary combination of stimulus and attentional locus. Our goal in this paper is to test whether the AF model can predict the observed attentional transformations in our dataset.

Implementing the attentional field model

We first fit the pRF model (Eqs. 1–2) to each individual voxel's responses in the fixation task to obtain their bottom-up stimulus-driven pRFs.

$$pRF = e^{-\frac{(x-x_{prf})^2+(y-y_{prf})^2}{2*\sigma_{prf}^2}} / (2\pi * \sigma_{prf}^2) \quad (1)$$

$$resp_{fix} = g_{fix} * (\sum_{x,y} stim(x,y) * pRF)^{0.2} \quad (2)$$

where pRF center (x_{prf}, y_{prf}), size (σ_{prf}) and gain (g_{fix}) are free parameters. We then formulated the AF as another 2D Gaussian function:

$$AF = e^{-\frac{(x-x_{af})^2+(y-y_{af})^2}{2*\sigma_{af}^2}} \quad (3)$$

where (x_{af}, y_{af}) is the center of the AF corresponding to the stimulus location on each trial (since participants performed the attention task on the presented stimulus). σ_{af} is the AF size. It is assumed that attention influences a voxel's responses via multiplying the AF and the bottom-up stimulus-driven pRF; hence the predicted responses in the attention task can be written as:

$$resp_{attend} = g_{attend} * g_{fix} * (\sum_{x,y} stim(x,y) * (pRF * AF))^{0.2} \quad (4)$$

where the size of the AF (σ_{af}) and a new overall gain factor (g_{attend}) are free parameters. We also construct two phenomenological models that incorporate either a simple scaling or additive factor on the stimulus-driven responses observed under the fixation task, and two benchmark models that either assume no response change from the fixation task to the attention task (nochange model) or fit the standard pRF model to responses in the attention task (apparent pRF model). The two benchmark models contain the smallest and largest number of free parameters respectively; thus they can be considered as the lower and

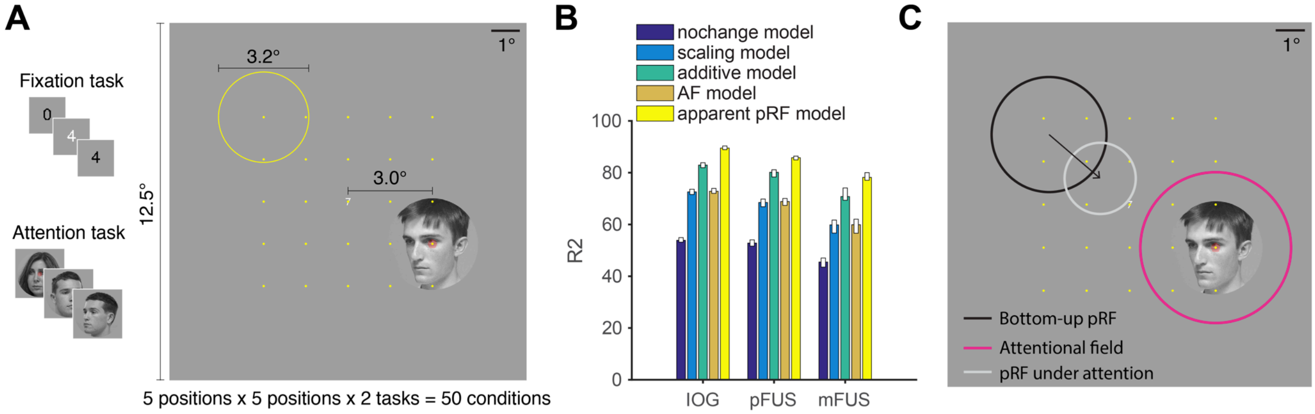

Figure 1. A) Experiment. Face stimuli are presented at one of 5x5 grid locations. Participants perform either a fixation task (one-back digit task), during which they hold attention at fixation or an attention task (one-back face identity task), during which they covertly attend to the face stimuli. B) Evaluation of five computational models on cortical responses in the attention task for three face-selective regions in human VTC (*x*-axis). The AF model (orange) is worse than the apparent pRF model (yellow) and even worse than the additive model (green). C) Illustration of the AF computation. When a face stimulus is shown, participants attend to the stimulus and form an attentional field centered on the stimulus (magenta). It can be shown analytically that multiplication of a bottom-up pRF (black) with the AF produces a new pRF (gray) that is smaller than both the bottom-up pRF as well as the AF.

upper limit on the goodness-of-fit that a candidate model can achieve.

Results show that the AF model is considerably worse than the apparent pRF model and even worse than the additive model (Fig. 1B). These results suggest that the AF model misses some key aspects of the attentional effects in the data. This is surprising since the AF has been routinely suggested as a good approximation of attentional operation. We suspect that the inadequacy of the AF model might stem from its current mathematical form: multiplying two Gaussian functions (pRF and AF) inevitably shrinks the size of the product pRF (Fig. 1C), which deviates from our previous finding that attention actually expands apparent pRFs. Our results invite a reconsideration of the adequacy of the AF model for explaining cortical responses. To better account for the data, further studies might either change the mathematical form of the AF model or explore a different model of top-down influences on cortical responses, such as the IPS-scaling model (Kay & Yeatman, 2017).

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