Temporal dynamics of the allocation of spatial attention

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When gaze is directed towards a relevant object during natural vision, the "attentional window" must be adjusted around this object to filter out surrounding irrelevant visual input. This adjustment must be made dynamically, because the retinal size of a visual target is not necessarily predictable, depending on the object's size, its viewing distance, and occlusion. This concept of the adjustment of an attentional window within which sensory information is facilitated bears much resemblance to the spotlight view of attention (e.g., Eriksen & St. James, 1986). However, understanding the nature and time course of the expansion and contraction of attention around the point of fixation has received relatively little study, even though it is one of the most common uses of attention in natural vision. The present study used event-related potentials (ERPs) to assess the attentional modulation of sensory processing of stimuli inside versus outside of the window and the time course over which the window is adjusted.

Preceding the adjustment of the attentional window, an initial parallel stage of feature-based detection can provide guidance about the spatial location of a potentially relevant target (Folk, Leber, & Egeth, 2002; Leonard & Egeth, 2008; Serences & Boynton, 2007). For example, the memory that a lost friend was wearing orange could help guide spatial attention to a location at which this feature is detected, allowing for further examination of a potentially relevant person in the crowd. To improve the ability to discriminate friend from stranger, the attentional window must be adjusted around the currently examined object. Our task is much like this, requiring participants to initially attend to a spatially broad region, detect a region containing relevant information, and then adjust the spatial window of attention accordingly to facilitate target discrimination.

We used the occipital P1 ERP component (onset at 70–80 ms) to measure sensory processing. Previous studies show that P1 amplitude is increased for both target and nontarget stimuli when they appear in attended locations compared to when they appear in unattended locations, indicating a modulation of sensory processing (Heinze, Luck, Mangun, &

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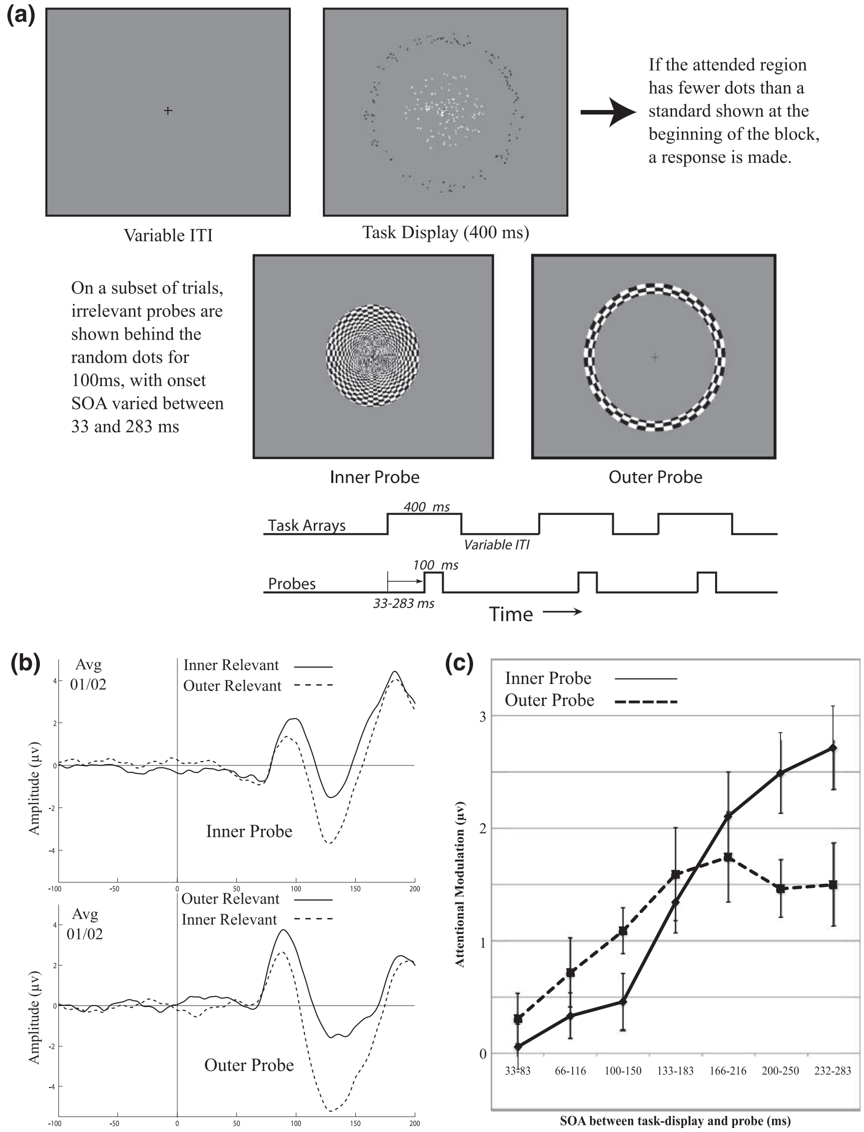

Figure 1. (a) Example of trial, probes, and timeline; in actual displays, random dots were red and blue on middle grey background. (b) ERPs to the inner and outer probes, when they occur in the task-relevant and task-irrelevant region. (c) The time course of attention effects to the inner and outer probes.

Hillyard, 1990). For example, after attention has shifted to a target item in a visual search array, a small square can be flashed at either the target location or a nontarget location, and this flash will receive enhanced sensory processing (evoking a larger P1 response) if it appears at the target location rather than at a nontarget location (Luck, Fan, & Hillyard, 1993).

Whereas previous P1 studies have examined extrafoveal attention, the present study manipulated whether attention was directed to a narrow region at fixation or a broader annular region around fixation. The SOA between task display and probe was varied to examine the temporal evolution of attention. The sensory response to a probe will be modulated if, when it onsets, spatial attention is differentially allocated between task-relevant and task-irrelevant locations. At early SOAs, when the spatial window of attention has not yet been adjusted, the probe-evoked P1 should not differ depending on whether it appeared at the task-relevant or irrelevant region on that trial. The onset of spatial selection should be measurable as the earliest SOA at which modulation of the probe-elicited P1 is observed.

METHODS

ERPs were recorded from 12 participants while they performed a numerosity judgement task on an array of random dots (Figure 1a). Participants attended a single target colour (red or blue) for each 5-minute block, with the relevant colour equally likely to occur at the inner and outer region of the display. Thus, the observers did not know whether the inner or outer region would be task relevant until stimulus onset, and the spatial window of attention was presumably adjusted once the observer perceived which region contained the attended colour. On two-thirds of trials, a 100 ms probe (composed of black-and-white checks) was presented at either the inner or outer region of the task display, with SOA between the task array and the probe varying between 33 and 283 ms. The remaining trials contained no probe. The probe-absent waveform was subtracted from the probe-present waveform to isolate the probe-elicited ERP. Trials with EEG artifacts or eye movements were excluded.

RESULTS

Figure 1b shows the waveforms for inner and outer probe stimuli (after subtracting the response to the task display) when the task-relevant information occurred at the inner or outer location, averaged over SOAs. For both inner and outer probes, the P1 wave was larger when attention was directed to the region that was probed. This attention-related difference was measured for the inner probes and for the outer probes at each 50 ms SOA range, and the results are shown in Figure 1c. The attentional modulation of the P1 was near zero for the shortest SOA range (33–83 ms) and increased at longer delays. One-sample *t*-tests for each 50 ms SOA range revealed that the attention effect for the inner probe became significantly greater than 0 at the 133–183 ms SOA bin ($p < .001$) and remained significant for all subsequent bins. The attention effect for the outer probe emerged slightly earlier, reaching significance at the 66–116 ms SOA bin ($p < .001$), and also remained significant for all subsequent bins.

DISCUSSION

Overall, the results elucidate the temporal dynamics of how spatial attention adjusts to specifically select a task-relevant region of the visual field. This process occurs quickly, with attentional modulation of subsequent visual input occurring within about 100–150 ms of the onset of a relevant feature in the field. This attentional effect appeared earlier for irrelevant probes in the periphery compared to those presented foveally, although it was clearly visible for probes at both locations. These results demonstrate that adjusting the spatial extent of attention around the point of fixation leads to a change in sensory processing, just as attending to extrafoveal locations modulates sensory processing. They further demonstrate that the spatial window of attention can be adjusted rapidly on the basis of relevant features, a process critical for the coordination of goal-directed, stimulus-appropriate behaviour.

REFERENCES

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception and Psychophysics*, *40*, 225–240.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Perception and Psychophysics*, *64*, 741–753.

Heinze, H. J., Luck, S. J., Mangun, G. R., & Hillyard, S. A. (1990). Visual event-related potentials index focused attention within bilateral stimulus arrays. I. Evidence for early selection. *Electroencephalography and Clinical Neurophysiology*, *75*, 511–527.

Leonard, C. J., & Egeth, H. E. (2008). Attentional guidance in singleton search: An examination of top-down, bottom-up, and intertrial factors. *Visual Cognition*, *16*, 1078–1091.

Luck, S. J., Fan, S., & Hillyard, S. A. (1993). Attention-related modulation of sensory-evoked brain activity in a visual search task. *Journal of Cognitive Neuroscience*, *5*, 188–195.

Serences, J. T., & Boynton, G. M. (2007). Feature-based attentional modulations in the absence of direct visual stimulation. *Neuron*, *55*, 301–312.