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Current Opinion in Psychology

The spatial distribution of attention

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Understanding how spatial attention is distributed over space (i.e. the attentional window) is highly important for theoretical, methodological, as well as applied reasons. One fundamental challenge to the study of the attentional window is that most of our current knowledge is based on measuring distractors interference, or relying in some other way on properties of the participants' responses (e.g. response time). However, other factors such as distractor visibility may mediate distractor interference, and in general participants' response can be influenced by many other factors including higher-level strategies, experience, response history, response biases, and so on. Recent paradigms, which do not rely on participants' response, such as measuring attentional modulations of the pupillary light response, may help us face this challenge.

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Current Opinion in Psychology 2019, **29**:76–81

This review comes from a themed issue on **Attention and perception**

Edited by **Sarah Shomstein**, **Andrew Leber** and **Joy Geng**

https://doi.org/10.1016/j.copsyc.2018.12.008

Introduction

Spatial attention refers to selection processes that grant priority to information gathered from a specific location. From the beginning of the rigorous study of spatial attention questions were asked regarding the topographic nature of the restricted area to which attention is allocated (henceforth, the attentional window): Does the attentional window have a fixed size [1] or is it flexible [2,3]? Does the effect of attention decrease with distance in a monotonic fashion [3,4], or is the central enhancement accompanied by suppression at the surrounds [5,6]? What is the window's minimal size [7,8••], and what is its maximal size [9]? Which factors affect the extent of the attentional window [10,11••,12]? These questions bear important implications for many conceptual and computational models of visual attention [2,5,13–15]. For instance, the size of the attentional window plays an important role in both the attentional-attraction-field model [13] and the normalization model [14]. Knowledge of this value is essential for their ability to simulate performance. Yet there is little agreement regarding the answers to these questions. One reason for this lack of agreement may lie with differences between different manipulations of the window's size (e.g. varying the size of an attentional cue to encourage variations in window size [16,17], or manipulating the degree of uncertainty regarding the target location [18,19] under the assumption that the window gets larger as uncertainty increases). Although different methods have the same goal, their outcomes are not always the same [20]. The controversy regarding the nature of the attentional window may also be rooted in the way it is measured. In the following sections, I describe the canonical method for measuring the spread of attention and its limitations, and then I review several alternative methods that may help solving some of the controversies in the field.

Methods relying on the participant's response

The most prevalent way to study the size of the attentional window relies on distractor interference [3,6,7,21–26]. The task-relevant target is presented together with distractors (irrelevant items) that may interfere with responding. The target-distractor distance is manipulated, and the degree to which the distractors hinder performance is measured as a function of this distance. Distances at which the distractors influence performance are considered within the window. This method generated several assertions about the attentional window. For instance, Eriksen and Hoffman [7] presented a target flanked by distractor, and measured response time (RT) to identify the target with different target-distractor distances. They found significantly slower RT with a 0.53° distance, but no RT difference with larger distances. They concluded that only the distractors at the 0.53° distance fell within the window, suggesting that the window can be narrowed down to a diameter of ~1° (i.e. 0.5° center-to-edge). Another example is a flanker-task designed to examine how load affects the spread of attention [21,22]. The participants had to identify a target while ignoring a distractor that was either compatible or incompatible with the target. Distractor interference was defined as RT difference between these two conditions. Target-distractor distances and the levels of perceptual and/or working-memory load were manipulated. A complex pattern of results emerged: the window was narrower with high perceptual load, but only when working-memory load was low. Similarly, the window was narrower with low working-memory load, but only when perceptual load was high. Additionally, the window was narrower for participants with high working-memory capacity. These findings suggest that the participants could reduce the size of the attentional window to meet perceptual demands but this required cognitive resources.

Notwithstanding the contribution of this paradigm to our understanding of the spatial distribution of attention, measuring the attentional window via distractibility relies on two core assumptions. First, it is assumed that only items within the attentional window are sufficiently processed to generate interference. However, a large body of evidence suggests that unattended items are processed and may affect performance [23,27,28]. Second, it is assumed that items within the window will generate interference. However, other factors than the spatial extent of attention may limit items' ability to generate interference. One such a factor is visual acuity limitations arising when distractors at larger distances appear at more peripheral regions [24,25].

Another method for studying the attentional window presents a pre-cue at various distances from the upcoming target. The pre-cue, typically, attracts attention to its location. Performance decrement as a function of cue-target distance is taken to reflect the spatial distribution of attention [5,12]. Employing this method, Cutzu and Tsotsos [5] demonstrated that the accuracy decrement, observed with increasing cue-target distance, follows a U-shape. This suggested that the facilitatory area of the attentional window has an inhibitory surround. The advantage of this method over measuring distractibility is that there is no need to assume that only items within the window are sufficiently processed. However, because the measurement of the attentional window depends on absolute RT or accuracy, it could be contaminated by other factors than attention (e.g. with small cue-target distances masking effects may interact with attentional effects). A possible remedy is to include a neutral condition that is similar to the cued condition but does not trigger attention. This could be established by employing a 'multi-cue' neutral condition: cues are presented simultaneously at all possible locations ensuring that no unique location is indicated, but also that the physical information at the cued location is identical in both conditions [29,30]. Then, one can measure how the cued-neutral difference changes as a function of distance, thereby cancelling out factors that are not attention-related. Indeed, Shioiri *et al.* [31] employed a variant of this method. They first demonstrated that attention reduces the flash-lag effect (FLE), and then measured the FLE as a function of the distance from the cue. Critically, the attentional window was evaluated based on differences in FLE between cueing a single location and cueing all possible locations. This revealed that the size of the window varies as a function of spatial-uncertainty, and corroborated the assertion that the enhancement at the window's central regions is accompanied by suppression at its surrounds. Still, all methods that rely on participants' response suffer from similar limitations brought about by the fact that this response could be modulated by factors that are not directly related to the spatial spread of attention, such as higher-level strategies [32–34], response history [35], experience [36], learning [37], response biases [24,38,39], personality [40], and so on. This is especially so with RT, which may also reflect factors related to motor preparation [38].

Neurophysiological measurements

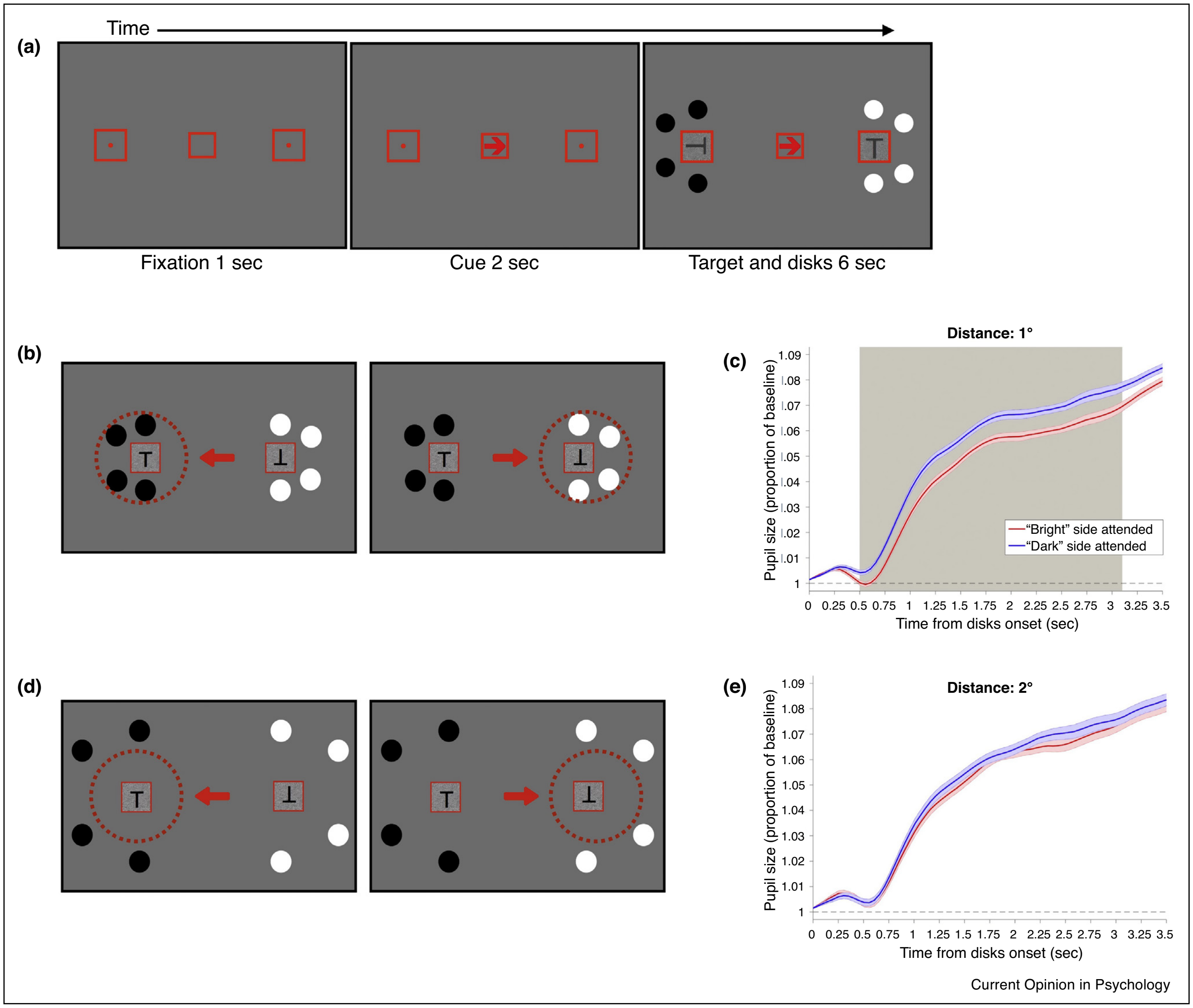
One way to avoid the shortcomings involved in relying on participants' response is to measure the spatial extent of attention as it is reflected in brain activity [41••,42••,43,44]. One such a recent study [41••], estimated the attentional window by measuring both steady state visual evoked potential (SSVEP) and event related potential (ERP). SSVEPs are oscillatory brain responses that match the frequency of a continuously flickering stimulus, whereas ERPs are recorded in response to an isolated event. The display included eight disks, of which one (or two) was cued as task-relevant. Letters appeared on all disks, but only those on the cued disk required response. The disks flickered at different frequencies, allowing a separate activity measurement for each disk as a function of its distance from the cued disk. Additionally, the authors measured how target-distractor distance modulated the difference between target-locked and distractors-locked ERPs, focusing on the P3 component. The SSVEP analysis suggested that attention was spread broadly, whereas the ERP analysis suggested that attention was narrowly focused. Because the neuronal origins of SSVEPs are presumably earlier than those of the P3 component, the authors proposed that attention is initially broadly spread, but later on it is focused more narrowly.

Another recent study [42••] estimated the spread of attention from single-voxel fMRI time course modeling. The rational was to estimate the population receptive field (pRF) of a given voxel with/without covert attention, and then compute the spatial spread of attention based on how attention modulated the pRF, as the stimulus traversed it. Repeating this procedure for two different eccentricities with different brain areas revealed that the size of the attentional window increases with eccentricity and varies across the hierarchy of brain areas.

Oculomotor capture

Another way to preclude the undesired involvement of factors related to participants' response is eye-movements measurements [33,34,45,46]. Accordingly, van Beilen *et al.* evaluated the attentional window via measurements of eye-movements [11••]. Their rational was based on Belopolsky and Theeuwes [47] who demonstrated that an irrelevant color-singleton is more likely to hinder performance when a large attentional window is encouraged,

Figure 1



The experimental procedure, rational and results of Tkacz-Domb and Yeshurun [8••]. **(a)** A trial started with a central square that had to be fixated throughout the trial, and two peripheral squares. A central arrow followed, marking the side to which covert attention should be allocated. Finally, two rotating Ts were presented, each surround by four task-irrelevant disks that were either bright or dark. The task was to count the number of times the attended T assumed an upright orientation. The attended side, and disks' brightness at the attended side varied between trials in a random order. T-disks distance was blocked. Display luminance levels were identical in all trials. **(b)** When the T-disks distance is small enough so that the disks fall within the attentional window (marked here by a doted red line for demonstration purpose) pupil size should be larger when the participants are attending the side with the dark disks (left panel) than when they attend the side with the bright disks (right panel). **(c)** Such results were observed for a T-disks distance (center-to-edge) of 1° suggesting that the minimal diameter of the attentional window is at least 2°. **(d)** When the T-disks distance is larger than the radius of the attentional window (i.e. the disks fall outside the attentional window) pupil size should be similar regardless of whether the participants are attending the side with the dark (left panel) or bright (right panel) disks. **(e)** Such results were observed for a T-disks distance (center-to-edge) of 2° suggesting that the minimal diameter of the attentional window is smaller than 4°.
Image (a) is taken from Figure 1 in Tkacz-Domb and Yeshurun [8••], and images (c) and (e) were taken from Figure 3 in Tkacz-Domb and Yeshurun [8••].

and concluded that only irrelevant items within the window can capture attention. Hence, van Beilen *et al.* estimated the size of the window by measuring the region in which an abrupt onset evoked an eye-movement towards its location. They varied the predictive value of the abrupt onset and its eccentricity, and found that peripheral abrupt onsets were more likely to evoke an eye-movement when they were more predictable. This led them to conclude that the participants could voluntarily control the size of their window. This study did not rely on participants' response and therefore avoided the above-mentioned limitations. However, its paradigm requires the assumption that items outside the window cannot capture attention, even when they involve abrupt onsets.

Pupillometry

To refrain from making arguable assumptions about the degree to which items outside the attentional window are processed or capture attention, and avoid the confounds involved in relying on participants' response, we [8••] recently suggested to examine the attentional spread by measuring the pupillary light response (PLR) — pupil's constriction when luminance is high and dilation when it is low. The PLR was considered a low-level reflex. However, recent studies showed PLR modulations by awareness [48•], and most importantly by spatial covert attention. Under identical overall luminance levels, covertly attending a brighter area produced pupillary constriction relative to covertly attending a darker area [49•,50,51•,52,53]. We used these attentional modulations of the PLR to estimate the spatial extent of attention without having to rely on performance. We were particularly interested in the window's minimal size and therefore we employed a task requiring a narrowly focused attention (Figure 1a). The display included two rotating Ts surrounded by irrelevant disks. The disks were dark on one side and light on the other. An arrow indicated which T to attend. Critically, overall luminance level was always the same, but the T-disks distance varied. Hence, when the disks appear within the window, attention should modulate the PLR (Figure 1b); but when the T-disks distance is larger than the window, attention should not affect pupil size (Figure 1d). We found that attention modulated pupil size with the 1° T-disks distance (Figure 1c) but not with larger distances (Figure 1e), suggesting that the minimal diameter of the attentional window is at least 2° — twice the size measured based on participants' response [see 'Methods relying on the participant's response' section, Ref. 7]. Note, that here the disks were neither compatible nor incompatible with the required response, and we did not assume that they were not processed without attention. In fact, we assumed their luminance level always affected the PLR, but we tested PLR modulations beyond those of overall luminance level; we tested effects that are specific to covert attention [49•,50,51•,52,53]. Moreover, because pupil size is not under direct volitional control [54], it is less affected by higher-level cognitive processes. Thus, this study underscores the merit of utilizing the PLR for direct examination of visual attention and its spatial extent.

Conclusions

Understanding how attention is spread across space is essential for any attempt to develop a comprehensive model of visual attention. Thus far, a large part of our knowledge about the attentional window was established based on participants' response. However, responses can be influenced by many other factors, such as personality traits, experience with the task, learning on various time scales, processing history, biases, speed accuracy trade-offs, and more [24,32–40]. Additionally, the most common paradigm for measuring the attentional window relies on assumptions regarding the fate of unattended information that may not always hold. Fortunately, several recent studies were set out to measure the attentional window with novel and exciting methodologies. We find particularly exciting the finding that covertly attending areas of different local luminance affects the PLR, even with constant overall luminance. Measuring such attentional modulations of the PLR affords examining the spread of attention in complete independence of participants' response, and does not require any controversial assumptions. Using this method [8••] revealed that the minimal size of the window is twofold larger than that estimated using the traditional method [7]. Future research could use such techniques to test other hypotheses regarding the attentional window that were based on participants' response (e.g. that its size varies as a function of load, that it is controlled voluntary, etc.), evaluate the different size manipulations, and generate new hypotheses, including hypotheses aiming at integrating behavioral and neuronal models of attention.

Conflict of interest statement

Nothing declared.

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