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Attention Does Not Spread Automatically Along Objects: Evidence From the Pupillary Light Response

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Objects influence attention allocation; when a location within an object is cued, participants react faster to targets appearing in a different location within this object than on a different object. Despite consistent demonstrations of this object-based effect, there is no agreement regarding its underlying mechanisms. To test the most common hypothesis that attention spreads automatically along the cued object, we utilized a continuous, response-free measurement of attentional allocation that relies on the modulation of the pupillary light response. In Experiments 1 and 2, attentional spreading was not encouraged because the target appeared often (60%) at the cued location and considerably less often at other locations (20% within the same object and 20% on another object). In Experiment 3, spreading was encouraged because the target appeared equally often in one of the three possible locations within the cued object (cued end, middle, uncued end). In all experiments, we added gray-to-black and gray-to-white luminance gradients to the objects. By cueing the gray ends of the objects, we could track attention. If attention indeed spreads automatically along objects, then pupil size should be greater after the gray-to-dark object is cued because attention spreads toward darker areas of the object than when the gray-to-white object is cued, regardless of the target location probability. However, unequivocal evidence of attentional spreading was only found when spreading was encouraged. These findings do not support an automatic spreading of attention. Instead, they suggest that attentional spreading along the object is guided by cue–target contingencies.

Public Significance Statement
This study used the pupillary light response to challenge the common assumption that object-based attention spreads automatically along the object's contours. Instead, our findings suggest that attentional spreading is guided by current goals.

Keywords: attentional spreading, object-based attention, pupillometry, pupillary light response, response-free measure

Attention is a selective process that narrows down the immense amount of information to be processed at any given time. While the allocation of attention to spatial locations has been studied thoroughly (Carrasco, 2011; Posner, 1980), attention can also be guided by other factors. In particular, it has been consistently demonstrated that attention can select objects (for a review, see Chen, 2012). In one of the most common demonstrations of object-based attention (OBA), two rectangles are displayed to the participants (e.g., Egly et al., 1994). One end of one rectangle is cued followed by a target that can appear in the same location as the cue (valid), a different location within the same object (invalid-same), or a location on a different object at an equal distance from the cue (invalid-different). Typically, reaction times (RTs) are faster in the valid condition than in the invalid conditions (location-based advantage). Critically, RTs are also faster in the invalid-same than in the invalid-different condition. This object-based advantage serves as evidence of the attentional selection of objects.

Several mechanisms have been proposed for the emergence of object-based effects. The attentional spreading account is chief among them (e.g., Avrahami, 1999; Chen & Cave, 2006, 2008; Richard et al., 2008; Roelfsema & Houtkamp, 2011). This account posits that attention spreads automatically from the cued location to

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A portion of these data was presented at conferences (Vision Science Society, 2020 and 2022; European Conference on Visual Perception, 2021; and the European Conference on Eye Movements, 2022) and a previous version of this work appeared as a preprint on *PsyArXiv*.

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other locations within the object. Areas to which attention has spread are better processed, compared to areas at an equal distance but not within the object. Consequently, the invalid-same location is better represented than the invalid-different location leading to faster RTs to targets appearing in the former than in the latter. Other accounts have been proposed as alternatives to the spreading account. These include the "attentional shifting" account—which proposes that RTs to the invalid-different condition are slower because disengaging from the attended object is a time-consuming process (e.g., Brown & Denney, 2007; Lamy & Egeth, 2002; Luzardo et al., 2022; Yeshurun & Rashal, 2017)—and the "attentional prioritization" account—which proposes that areas within the attended object are prioritized when searching for a target (e.g., Drummond & Shomstein, 2010; Shomstein & Yantis, 2002, 2004). This account also incorporates a flexible component of attentional selection, allowing current goals and environmental contingencies to influence attentional deployment (e.g., Shomstein, 2012). Here, we utilized the attentional modulation of the pupillary light response (PLR) to reexamine the main account under debate—attentional spreading. That is, we tested whether or not attention spreads automatically along objects.

It has long been established that cognitive effort, arousal, and perceptual decisions can lead to pupillary dilation (reviewed in Einhäuser, 2017). Yet the PLR was largely regarded as a low-level reflex controlling pupil size to adapt to incident light levels, increasing pupil size in dark conditions and decreasing it in bright conditions (e.g., Loewenfeld, 1999). Recently, however, studies have shown that cognitive processes may also affect the PLR directly. For instance, the pupil constricts when an image is interpreted as very bright (e.g., a picture of the sun) compared to luminance-matched control images (e.g., Laeng & Endestad, 2012; Naber & Nakayama, 2013). Importantly, covert attention (i.e., the allocation of attention in the absence of eye movements) also modulates the PLR. Under identical levels of luminance, arousal, and cognitive load, covertly allocating endogenous or exogenous spatial attention to a brighter area leads to pupillary constriction, relative to shifting attention to a darker area, (e.g., Binda et al., 2013; Mathôt et al., 2013; Naber et al., 2013; Tkacz-Domb & Yeshurun, 2018).

Thus, the PLR can be used to infer which aspect of a visual scene is attended and how attentional allocation develops over the course of a trial. Indeed, this technique has recently been used to characterize different aspects of attention. These include the size of the attentional window (Tkacz-Domb & Yeshurun, 2018), and the focus of attention during spatial working memory tasks (Fabius et al., 2017). Notably, the attentional modulation of the PLR has recently provided evidence in favor of the shifting account of OBA (Luzardo et al., 2022). In that study, a single-object display was used. The task involved shifting attention from inside the object to an area outside of the object, in some trials, and a shift in the opposite direction in other trials. It was found that attentional modulations of the PLR occurred later in trials that required disengagement from the object than in trials that did not. This is in line with the predictions of the shifting account. Moreover, this finding cannot be explained by the spreading account because the spreading account was conceived to explain faster RTs in the invalid-same condition—a condition that was not present in that study.

It has been noted that the behavioral object-based advantage is typically small and unreliable when compared to the location-based advantage (e.g., Pilz et al., 2012). That is, the RT difference between the invalid-same and invalid-different conditions is usually small and sometimes not observed at all (e.g., Avrahami, 1999; Lamy & Egeth, 2002; for a review of successes and failures to replicate OBA effects, see Reppa et al., 2012). Hence, it is especially beneficial to adopt methods of measuring object-based effects that do not rely on behavior or RT. The attentional modulation of the PLR is one such method that does not rely on the behavioral response. It remains to be seen whether evidence for the spreading account can be found using this method with a paradigm that includes an invalid-same condition and therefore may involve the spreading of attention.

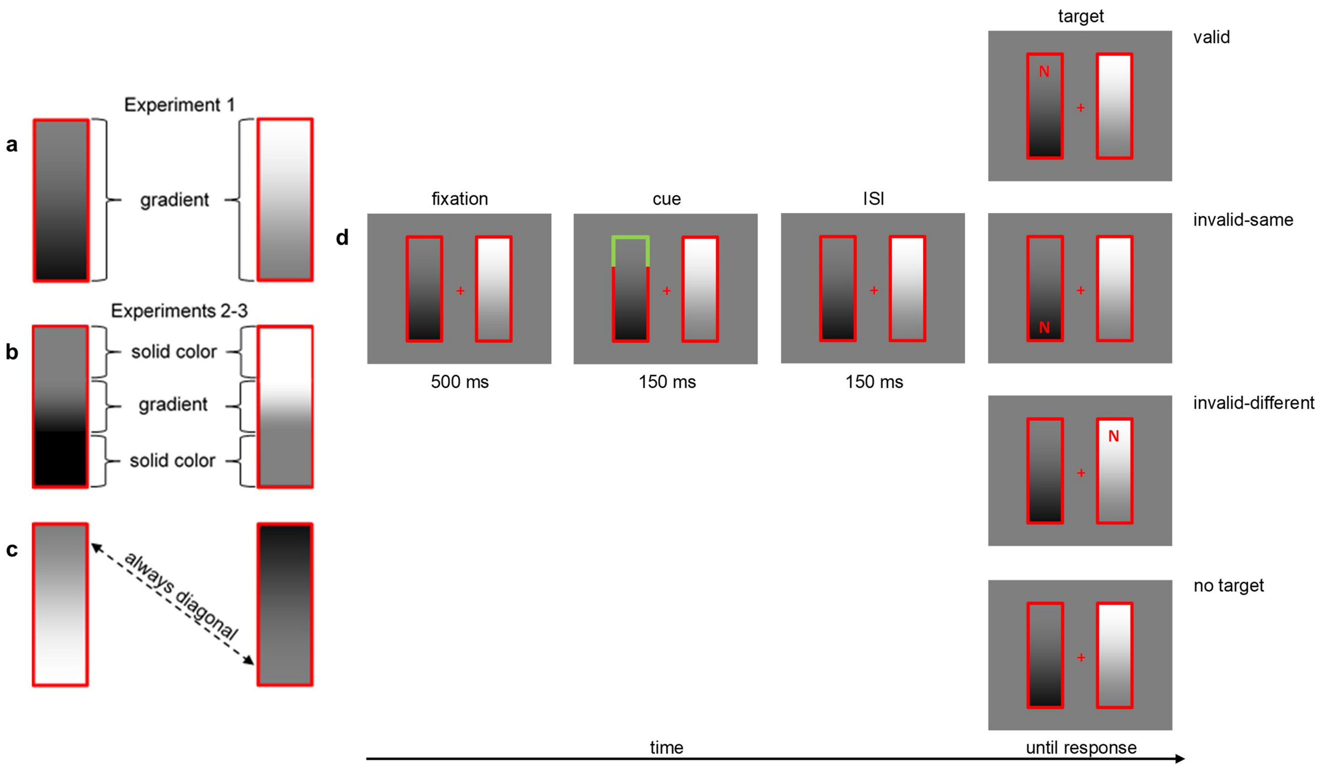
To that end, in the present study, we modified the two-rectangle paradigm by adding a gray-to-black luminance gradient to one rectangle and a gray-to-white gradient to the other rectangle in three experiments (Figure 1). In Experiments 1 and 2, the gray end of one of the rectangles was cued and then the target followed at one of the three possible locations (valid—60%, invalid-same—20%, or invalid-different—20%). In these experiments, attentional spreading was not encouraged because the target appeared most often at the cued location. In Experiment 3, attentional spreading was encouraged because the target always appeared within the cued object in one of the three equally probable locations (cued end, middle of object, opposite end). Additionally, all experiments contained some no-target trials. This was important because the hypothesis we tested postulates that after the initial shift of attention to the cued location, attention automatically spreads along the object *before* target onset. By the time the target appears in the uncued end of the object (in the invalid-same condition), attention is already there. However, following the convention for OBA (Reppa et al., 2012), the cue–target stimulus-onset asynchrony (SOA) in our experiments was 300 ms. The pupil takes longer than that on average to react to events (Ellis, 1981). Thus, attentional modulations of PLR that are measured in trials with a target reflect a mixture of attention allocation in response to the cue and attention allocation in response to the target. The no-target trials were needed to reveal the effect of the attentional precue *by itself* on the PLR. If attention indeed spreads along the object, pupil size should be significantly larger in the no-target trials when the gray end of the dark rectangle is cued than when the gray end of the light rectangle is cued. This is because attention is expected to spread toward a darker area in the first case and toward a lighter area in the second case. Furthermore, if such spreading occurs automatically, this pattern of results should be observed regardless of the likelihood of the different target locations. In other words, according to the spreading account, the same pattern of results for no-target trials must emerge in all experiments: greater pupil size when the gray end of the dark rectangle is cued compared to cueing the gray end of the light rectangle. Finally, in Experiments 2 and 3, the luminance gradient started outside the cued area to ensure changes in PLR patterns reflect the spreading of attention rather than merely attending the cued area.

Method

Participants

Sixteen students participated in each experiment. This sample size was predetermined a priori based on previous demonstrations of attentional modulation of the PLR (e.g., Mathôt et al., 2013). A power analysis using the R pwr package (Champely, 2020) with the previously reported effect size (Cohen's $d = 1$; Mathôt et al., 2013) and $\alpha = 0.05$ showed that this sample size affords a power of 0.96. Three participants were removed from Experiment 1 and

Figure 1
Task Design in Experiments 1–2



Note. (a) In Experiment 1, the luminance gradients extended along the whole object. (b) In Experiments 2–3, the luminance gradient occupied the mid-section of the object, while the ends consisted of a patch of uniform luminance. (c)The gray ends of the objects were always diagonal; the lighter rectangle appeared equally often on the left or right side of the display and its lighter end was equally often in the upper or lower part of the display. The attentional cue always appeared on the gray end of an object. (d) The sequence of events in a single trial in Experiments 1 and 2. Objects were displayed on their own for 500 ms, followed by a cue for 150 ms. After a 150 ms ISI, the target could appear either in the valid, invalid-same, or invalid-different locations. Targets were red letters in Experiment 1 (as depicted here), and green letters in Experiments 2 and 3. Figure not to scale. See the online article for the color version of this figure.

one participant was removed from Experiment 3 due to a large proportion (over 20%) of eye movements that were larger than 1.5° from the fixation mark. Because of this a priori defined exclusion criterion, the final sample size was 13 in Experiment 1, 16 in Experiment 2, and 15 in Experiment 3. Additional power analyses were carried out to estimate statistical power given the final sample sizes. These power analyses indicated that the sample sizes afford a power of 0.91 in Experiment 1, 0.96 in Experiment 2, and 0.95 in Experiment 3 ($\alpha = 0.05$ in all analyses). Two of the students participated in Experiments 1 and 2, two participated in Experiments 2 and 3, and two participated in Experiments 1 and 3. All participants were students from the University of Haifa with normal or corrected to normal vision who signed a consent form. This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the ethics committee of the University of Haifa (approval number 265/17). Informed consent was obtained from all individuals who participated in the study.

Stimuli and Apparatus

Stimuli were generated and presented using Psychopy (Peirce et al., 2019) on a 19-in. CRT monitor of an IBM-compatible PC (1,280 × 1,024 resolution at a refresh rate of 85 Hz). Eye movements were recorded from the right eye with an EyeLink 1,000 eye-tracker (temporal resolution of 1,000 Hz; SR Research, Ottawa, ON, Canada) to ensure the participants fixated the center of the screen at all times.

Experiment 1

Two vertical rectangles (4° × 12° of visual angle) with a red outline were presented on a gray background (14 cd/m^2; Figure 1). One rectangle contained a gray-to-black luminance gradient (14–0 cd/m^2; Figure 1a) and the other rectangle contained a gray-to-white gradient (14–80 cd/m^2). The luminance gradient started at one end of the rectangle and ended on the other end (Figure 1a). The rectangles were displayed at an eccentricity of 5° from a fixation cross (a red plus sign spanning 1° × 1°); eccentricity was measured from the center of the rectangle to the center of the screen. The gray ends of the rectangles were always diagonal (Figure 1c). The attentional cue consisted of the outline (4° × 4°; Figure 1d) on one end of the rectangles briefly changing to green (14 cd/m^2). The target was a red letter (“*Z*” or “*N*”; height = 1°) presented at one of the ends of the rectangles. All red stimuli were isoluminant to the gray background (14 cd/m^2).

Experiments 2 and 3

Stimuli and apparatus were identical to those of Experiment 1 except for the following changes. The ends of the rectangles consisted of 4° × 4° squares filled with a solid color (gray, black, or white; Figure 1b). The gradual change from gray to black and from gray to white spanned the mid-section (4° × 4°) of the rectangles. Additionally, the target letters were green (14 cd/m^2) instead of red, and when the target was presented on one of the gray sections, its luminance was increased to 38 cd/m^2. This value was chosen based on a short pilot experiment, which demonstrated that with this luminance modification target identification on the gray background is comparable to that on the white or black background and was further validated by the results of a previous study (Luzardo et al., 2022).

Procedure

A 5-point eye-tracker calibration preceded a practice session, and additional calibrations were performed as needed. The participants were instructed to fixate the center of the screen throughout all trials. A trial started only after observers fixated the center of the screen; if needed, the eye-tracker was recalibrated.

Experiments 1 and 2

Each trial began with the fixation cross and rectangles (Figure 1d). Each rectangle (gray-to-white, gray-to-black) appeared equally often to the left or right of fixation, and the gray end of each rectangle was equally often up or down. After 500 ms, the cue appeared for 150 ms. Following a 150 ms interstimulus interval (ISI) the target was displayed until response, except in no-target trials, in which no target was displayed. Only the gray end of a rectangle could be cued, and the cue accurately predicted the location of the target in 60% of trials that contained a target (valid trials). In the remaining trials that contained a target, it appeared on the invalid-same location in 20% of trials, and in the invalid-different location in the other 20% of trials. No target was displayed in 16.6% of the total trials. The participants were asked to indicate, as fast and accurately as possible, if the target was a "*Z*" or an "*N*." If no response was given for 2 s the next trial started. In the no-target trials, no response was required, and participants were instructed to wait until the next trial began 2 s later. Auditory feedback followed the participants' response. If the eye-tracker detected an eye position that was more than 1.5° away from the center of the display during a trial, the trial was immediately canceled, and auditory feedback was given to indicate that eye movements were detected. Participants completed 30 practice trials in both experiments, 720 experimental trials in Experiment 1 (∼1 hr), and 600 experimental trials in Experiment 2 (∼50 min). Trial types (i.e., objects' locations, gradient direction, and cue location and validity) were mixed randomly while keeping the same number of trials in each condition for every participant.

Experiment 3

The procedure was identical to that of Experiments 1 and 2 except for the following changes. The target always appeared within the cued object (Figure 2), either at the cued end of the object (valid), the center of the object (invalid-middle), or the uncued end of the object (invalid-end). These three conditions had an equal probability of occurring. In 25% of total trials, no target was presented. Participants completed 30 practice trials and 400 experimental trials (∼35 min).

Data Preprocessing and Statistical Analysis

Pupil Size Data

Trials that were canceled because of eye movements were removed from all analyses (see Procedure; 11% of total trials in Experiment 1, 10% in Experiment 2, and 9% in Experiment 3). Preprocessing of pupil size data was done in R using the gazeR package (Geller et al., 2020). Blink events were linearly interpolated (e.g., Bradley et al., 2008; Luzardo et al., 2022; Tkacz-Domb & Yeshurun, 2018). Then, the median absolute deviation was used to detect rapid pupil size disturbances in the data (Kret & Sjak-Shie, 2019). Such data points were removed (0.17% of total data points in Experiment 1, 0.20% in Experiment 2, and 0.28% in Experiment 3). The data were then smoothed using a 5-point moving average (e.g., Schmidtke, 2018; Zekveld & Kramer, 2014). The baseline was the median pupil size of the 100 ms period preceding the onset of the cue. For each trial, the pupil size at each time point was divided by the baseline value.

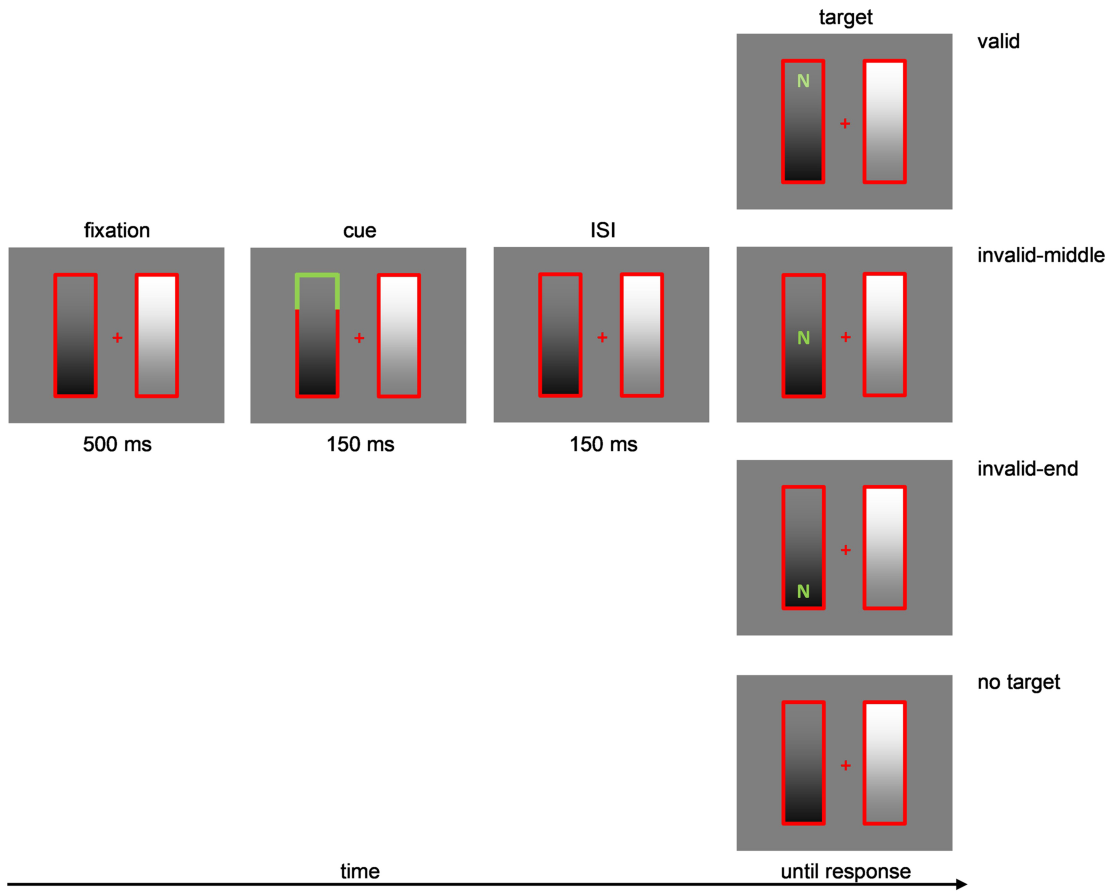
Linear mixed-effects (LME) analyses were performed for each time point in R using the lme4 package (Bates et al., 2014). Pupil size was entered as the dependent variable and subject ID as a random effect. To evaluate the time course of the effect of "cued object" (dark vs. light) separately for the different cue validity conditions, we ran separate LMEs for each cue validity condition and no-target condition with the cued object as a fixed effect. Note that degrees of freedom are not well defined in LMEs (Baayen et al., 2008); therefore, t values are used here instead of p values. A threshold of $t > 2$ is comparable to $p < .05$. Similar to previous studies, the significance criterion was defined as $t > 2$ for at least 200 consecutive ms (Luzardo et al., 2022; Mathôt et al., 2013; Tkacz-Domb & Yeshurun, 2018).

Additionally, Bayesian t tests between the different cue location conditions were calculated for the critical "no-target" trials for each time point in all three experiments. This complimentary analysis offers several advantages. For instance, it allows examining the evidence in favor of the null hypothesis. It also does not rely on p values or on the significance level, so multiple comparisons do not cause α inflation (Hershman et al., 2022). A default Cauchy prior width of $r = .707$ was used for effect size on the alternative hypothesis (Rouder et al., 2012).

Behavioral Analysis

Accuracy in trials involving a target was near ceiling (95%) in all three experiments and will not be discussed further. In no-target trials, there were virtually no false alarms (<0.6% in all experiments). Trials with incorrect responses were removed from the RT data prior to analysis. Responses faster or slower than 2 *SD*s from the mean of each participant were similarly removed from RT data (4% of all trials). No-target trials were not included in the RT analysis. RT was analyzed in a repeated-measures analysis of variance (ANOVA) with cue validity (valid, invalid-same, and invalid-different in Experiments 1 and 2; valid, invalid-middle, and invalid-end in Experiment 3) as the independent variable. Two-tailed t tests were performed to compare the different levels of cue validity.

Figure 2
Task Design in Experiment 3



Note. The sequence of events in a single trial in Experiment 3. The target could only appear within the cued object, either at the cued location (valid condition), the center of the cued object (invalid-middle condition), or the uncued end of the cued object (invalid-end condition). Figure not to scale. See the online article for the color version of this figure.

Experiment 1

The goal of Experiment 1 was to test whether differences in pupil size would emerge when participants' attention was covertly directed toward the gray end of a dark rectangle compared to the gray end of a light rectangle. According to the spreading account, greater pupil size should be observed when the dark rectangle is cued even in the absence of a target.

Results

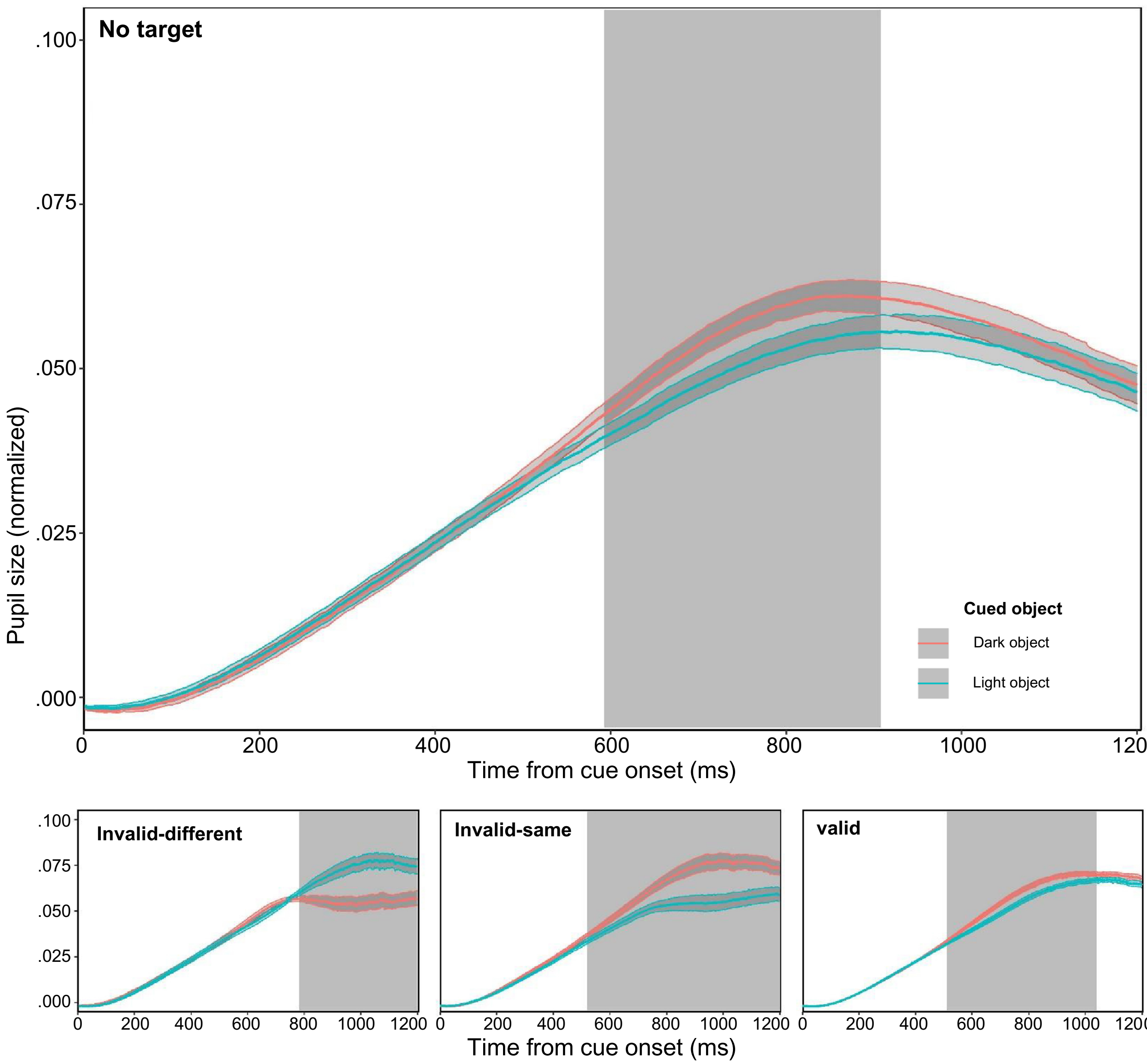
Pupil Size Analysis

In all conditions, an overall pupillary dilation was observed that started following cue presentation and continued as the trial advanced (Figure 3). This general pattern likely reflects task-evoked dilation which is not related to light levels (Beatty, 1982). The LME analysis revealed significant pupil size differences between the two "cued object" conditions (dark object vs. light object) under all cue validity conditions. Critically, there was a significant difference between the cued object conditions for the no-target trials, which reveals the dynamics of attention before a target is presented. Thus, attention allocation to the cue itself led to a larger pupil size when the cue appeared on the gray end of the dark rectangle compared to the gray end of the light rectangle, consistent with attentional spreading.

Although all the conditions containing a target reflect a combined response to the cue and the target, we applied the same analysis as for the no-target trials to these conditions. As expected, pupil size was larger when the cue appeared on the gray end of the dark object than on the gray end of the light object under the valid and invalid-same conditions. Under the invalid-different condition, the target appeared on the white background when the dark object was cued and on the black background when the light object was cued, thus resulting in larger pupil size in the second case, consistent with attention shifting to the target.

The significant differences in the no-target trials are in line with the spreading account and could be the result of attention spreading from the cued location along the object. However, the gradual change from gray to black and from gray to white started from the ends of the objects, and the initially cued gray areas themselves had slightly different luminance levels. This fact, on its own, might have led to differences in pupil size, even without attention

Figure 3
Pupil Size as a Function of Time from Cue Onset in Experiment 1



Note. Each panel depicts pupil size as a function of time from cue onset in each cue validity condition and the no-target condition. The area around the curves indicates 1 *SEM*. Shaded gray areas indicate a significant difference in an LME analysis between trials in which the gray end of the dark object was cued (red line) and trials in which the gray end of the light object was cued (light blue line). See the online article for the color version of this figure.

spreading along the object. To rule out this alternative explanation, in Experiments 2 and 3, the luminance gradient was restricted to the middle section of the objects (see Method; Figure 1b) so that the cued regions of the two rectangles were identical.

Behavioral Analysis

The main effect of cue validity on RT was not significant, $F(2, 24) = 1.159$, $p = .331$, $\eta_p^2 = .09$ (Table 1). This can be explained by the fact that the target's contrast was the lowest in the valid condition in which the target appeared in the cued location because the gray end of the objects and the target were isoluminant. The lower contrast in the valid condition likely increased RT in comparison with the invalid conditions, effectively counteracting the RT advantage that spatial attention affords the valid condition over the invalid conditions. More critical for OBA, a *t* test between the invalid-same and invalid-different conditions revealed that the participants responded significantly faster in the invalid-same condition than in the invalid-different condition, $t(12) = 2.802$, $p = .016$. This suggests that an object-based effect was present regardless of the low

Table 1
Mean Reaction Times (RTs) for Each Cue Validity Condition in Experiment 1 (N = 13)

Cue validity	RT (ms)	95% CI
Invalid-different	498	[493, 502]
Invalid-same	492	[488, 497]
Valid	495	[493, 498]

contrast in the valid condition. Notably, the main interest of this study was pupil size differences following the attentional cue, therefore the contrast of the target is of little consequence to the pupil size results. This is especially true for the no-target condition which was the critical condition for the goals of this study. Nevertheless, in Experiments 2 and 3, the target contrast on the gray background was increased to ensure comparable RTs for the different target backgrounds (see Method).

Experiment 2

The goal of this experiment was to ensure that differences in pupil size observed between the "cued object" conditions in Experiment 1 could not be attributed to differences in luminance of the initially cued areas. To that end, the luminance gradients inside the objects were changed slightly so that the initially attended areas in both rectangles had the same luminance level. The spreading account of OBA generates the same prediction for no-target trials in this experiment as in Experiment 1: greater pupil size when the gray end of the dark rectangle is cued compared to cueing the gray end of the light rectangle.

Results

Pupil Size Analysis

Condition-independent task-evoked pupil dilation was observed following cue onset in all conditions (Figure 4). LME analyses revealed no significant difference between the two cued object conditions under the no-target condition, which provides the critical test of the spreading account of OBA (all t values <1.76). This result does not follow the predictions of the spreading account, as a difference between the cued object conditions would be expected if attention spread along the objects.

As for the invalid-same and invalid-different validity conditions, a significant difference was found between the cued object conditions. However, the relatively late difference observed in these conditions likely reflects the fact that the targets themselves appeared in areas of different luminance levels (i.e., this effect is likely due to attention allocation to the target *after* its onset rather than spreading). In the valid condition, both the cue and target appeared on the gray area of the objects, and the lack of difference in this condition may also be consistent with a lack of spreading, or it may reflect a mixture of spreading and a shift back to the gray area following target onset.

The lack of a difference in the no-target trials could be interpreted in a few ways. It could reflect a lack of spreading of attention, or it could indicate that attention automatically spreads in all directions regardless of object contours. It could also reflect a lack of sufficient sensitivity in the measure. To test whether the current methods are sensitive enough to reveal spreading of attention along an object, we conducted Experiment 3 in which we encouraged spreading as a strategy.

Behavioral Analysis

There was a significant main effect of cue validity, $F(2, 30) = 17.061$, $p < .001$, $\eta_p^2 = .53$. Participants responded faster in the valid condition than in the invalid conditions, invalid-same: $t(15) = 4.119$, $p < .001$; invalid-different: $t(15) = 4.835$, $p < .001$ (Table 2), reflecting a space-based advantage. RTs were also faster in the invalid-same than in the invalid-different condition, $t(15) = 2.709$, $p = .016$, reflecting an object-based advantage.

Experiment 3

The goal of this study was to test whether evidence of attentional spreading could be obtained with the PLR when such spreading was encouraged. To that end, when a target was present, it appeared in one of the three equally likely locations within the cued object, ensuring that spreading attention along the cued object was the most beneficial strategy to adopt. The spreading account still generates the same prediction for the no-target trials in this experiment: greater pupil size when the gray end of the dark rectangle is cued. However, because of the cue–target contingencies in this experiment, this would not argue for an *automatic* spreading, rather it would indicate that our design in principle allows us to find attentional spreading.

Results

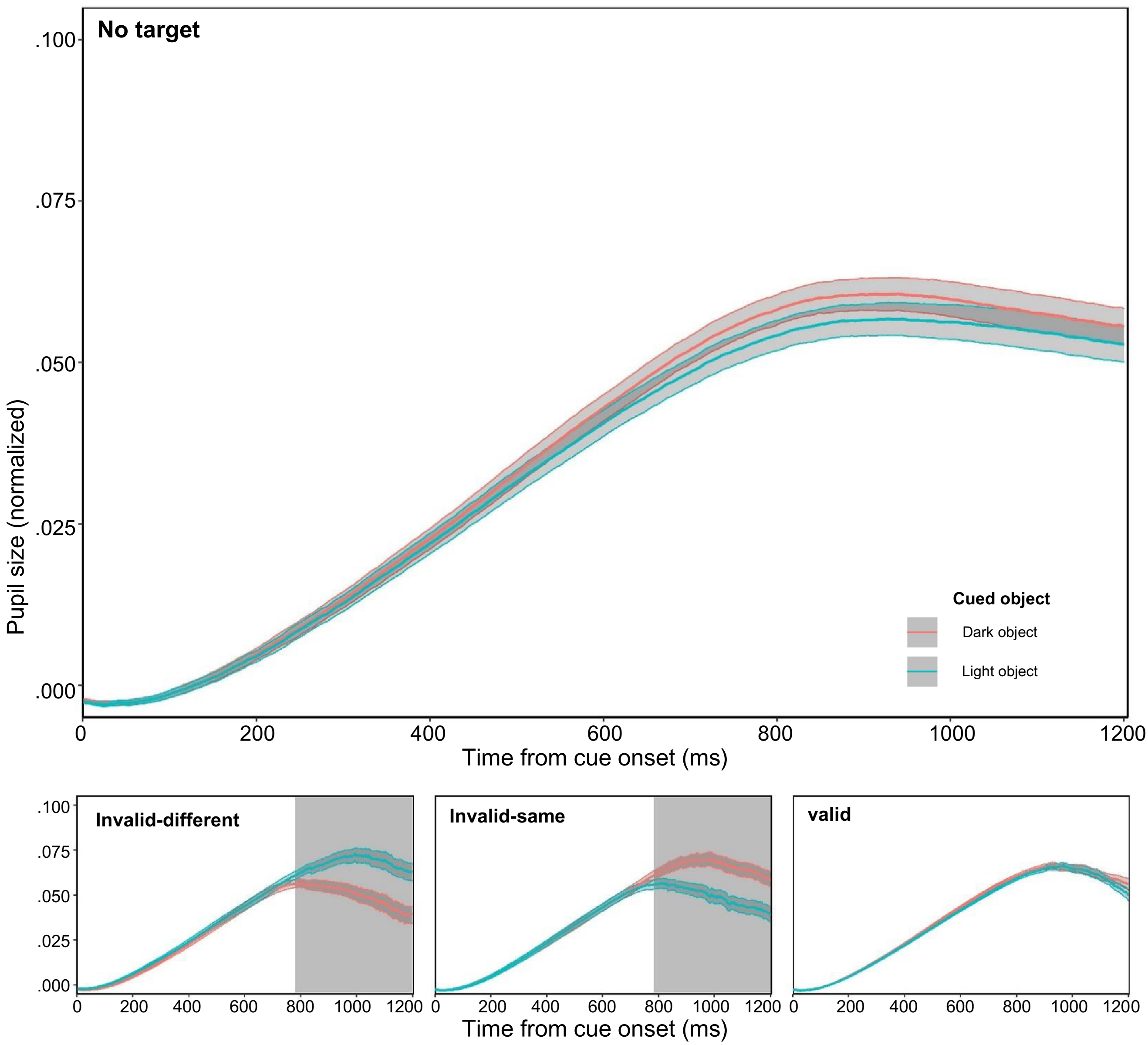
Behavioral Analysis

The main effect of validity on RT was significant, $F(2, 28) = 9.593$, $p < .001$, $\eta_p^2 = .41$. Participants responded significantly slower when the target appeared at the uncued end of the object than in the other two locations, invalid-middle: $t(14) = 5.490$, $p < .001$; valid: $t(14) = 3.395$, $p = .004$ (Table 3). There was no significant difference in RT between the valid and invalid-middle conditions, $t(14) = .874$, $p = .397$.

Pupil Size Analysis

The same general pattern of dilation following cue onset obtained in the previous experiments was also observed in this experiment (Figure 5). LME analyses revealed that the pupil size was significantly greater when the gray end of the dark object was cued than when the gray end of the light object was cued for all cue validity conditions. Critically, this was true for the no-target condition in which only the cue was presented and, as such, reveals the dynamics of attention in response to the cue. Because the cued areas of the two objects had identical levels of luminance (solid gray patch), the difference in pupil size between trials in which the dark object was cued and trials in which the light object was cued suggests that attention spread from the cued (gray) region along the object toward darker/lighter areas following cue presentation in the no-target trials. Hence, when spreading is encouraged, evidence of attentional spreading emerges. Note that the fact that evidence for attentional spreading was observed here with the PLR measurements demonstrates that this method is sensitive

Figure 4
Pupil Size as a Function of Time from Cue Onset in Experiment 2



Note. Each panel depicts pupil size as a function of time from cue onset in each cue validity condition and the no-target condition. The area around the curves indicates 1 *SEM*. Shaded gray areas indicate a significant difference in an LME analysis between trials in which the gray end of the dark object was cued (red line) and trials in which the gray end of the light object was cued (light blue line). See the online article for the color version of this figure.

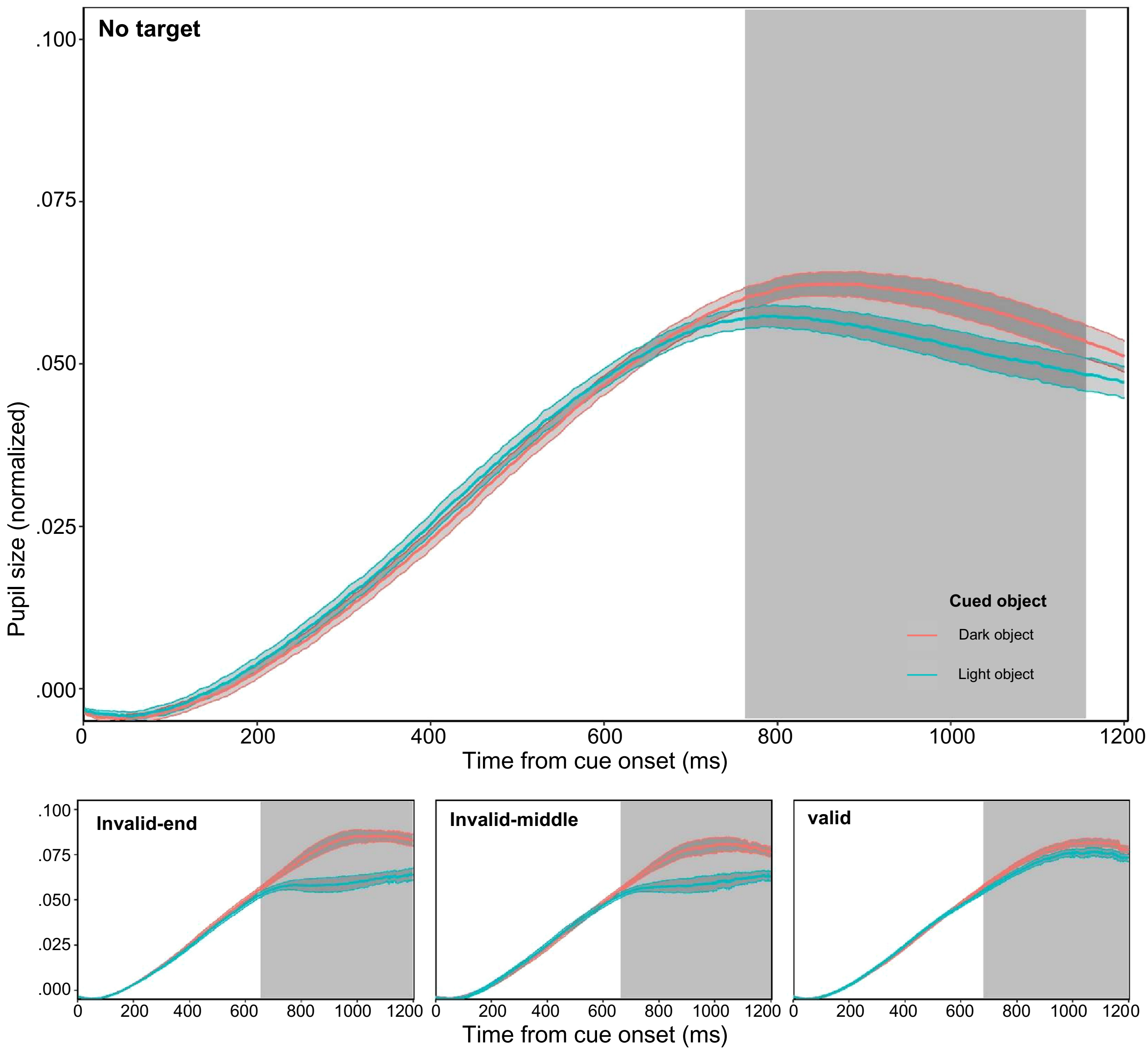
Table 2
Mean Reaction Times (RTs) for Each Cue Validity Condition in Experiment 2 (N = *16)*

Cue validity	RT (ms)	95% CI
Invalid-different	499	[494, 504]
Invalid-same	488	[483, 493]
Valid	475	[472, 478]

Table 3
Mean Reaction Times (RTs) for Each Cue Validity Condition in Experiment 3 (N = *15)*

Cue validity	RT (ms)	95% CI
Invalid-end	458	[454, 462]
Invalid-middle	446	[442, 451]
Valid	450	[446, 455]

Figure 5
Pupil Size as a Function of Time from Cue Onset in Experiment 3



Note. Each panel depicts pupil size as a function of time from cue onset in each cue validity condition and the no-target condition. The area around the curves indicates 1 *SEM*. Shaded gray areas indicate a significant difference in an LME analysis between trials in which the gray end of the dark object was cued (red line) and trials in which the gray end of the light object was cued (light blue line). See the online article for the color version of this figure.

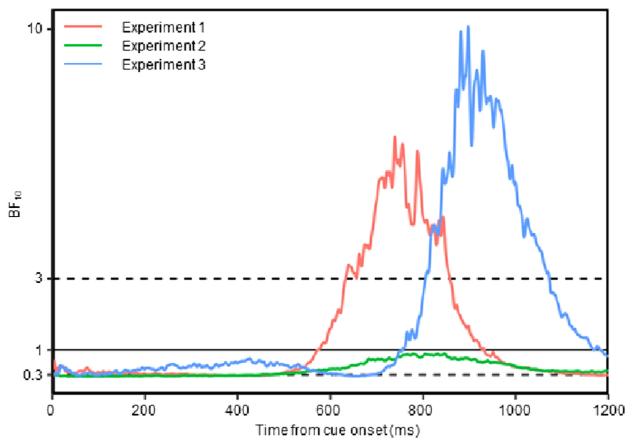
enough to reveal attentional spreading along the gradients when it occurs. This suggests that the lack of such evidence in Experiment 2 was because attentional spreading was not encouraged in that experiment.

Bayes Factors

Bayesian *t* tests were calculated between the "cued object" conditions for no-target trials in all experiments (Figure 6). The Bayes factors (BFs) threshold was 3, a value that represents moderate evidence (Jeffreys, 1961). This analysis indicates that there are significant differences between the cued object conditions in Experiments 1 and 3. These differences emerge numerically earlier in Experiment 1 than in Experiment 3, likely because of luminance differences in the initially attended area that were present in Experiment 1 and eliminated in later experiments. In Experiment 2, the BFs obtained for all time points are between 0.3 and 1 which indicates anecdotal evidence in favor of the null hypothesis that there is no difference in pupil size between the cueing conditions. Thus, analysis of the BFs leads to the same conclusions as the LME analyses.

Figure 6

Bayes Factors (BFs) as a Function of Time for the Comparison Between "cued object" Conditions for the No-Target Trials in all Three Experiments



Note. Each curve represents BF_{10} (evidence in favor of the alternative hypothesis) in a different experiment. Values between 1 and 3 represent anecdotal evidence for the alternate hypothesis, and values between 0.3 and 1 represent anecdotal evidence for the null hypothesis. Values above 3 (top dashed line) represent moderate evidence for the alternative hypothesis, and values below 0.3 (bottom dashed line) represent moderate evidence for the null hypothesis. See the online article for the color version of this figure.

Discussion

In three experiments, we investigated whether attention spreads automatically along cued objects using attentional modulation of the PLR. We employed a two-rectangle paradigm and added a gray-to-black gradient to one rectangle and a gray-to-white gradient to the other rectangle. If attention indeed spreads along cued objects, then pupil size should be greater when the gray end of the dark rectangle is cued, than when the gray end of the light rectangle is cued in the absence of a target. The cue–target contingencies (i.e., the likelihood of the target appearing at the cued location/object) were also manipulated to discourage/encourage attentional spreading.

Taken together, the findings of all three experiments provided evidence for the proposition that attentional spreading is guided by cue–target contingencies. A pattern of results that was consistent with attentional spreading emerged in Experiment 1. However, said pattern of results was no longer present in Experiment 2, in which the gradual luminance change was constrained to the middle section of the objects (with a solid gray/black/white patch on the ends of the objects). The fact that the expected pattern of results was not present once we controlled for luminance differences at the cued location suggests that the pattern of PLR modulations obtained in Experiment 1 was mostly due to these luminance differences at the cued location rather than attentional spreading. Surprisingly, these findings seem to indicate that the small luminance difference between the gray-cued areas in Experiment 1 was sufficient to contribute to pupil size differences triggered by attention. Although previous demonstrations of attentional modulation of the PLR employed stimuli with large luminance differences (e.g., Mathôt et al., 2013; Naber et al., 2013; Tkacz-Domb & Yeshurun, 2018), our findings suggest that even very small luminance differences are enough to observe it, further demonstrating the robustness of attentional modulation of the PLR.

In any case, given that the cue–target contingencies in Experiment 2 did not encourage attentional spreading, the outcomes of this experiment do not support automatic attentional spreading because in the most critical condition of this experiment—the no-target condition—the PLR was similar when the cue appeared on the dark and light objects. The possibility that attention spreads along the object only when such spreading is encouraged is further supported by the fact that when the cue–target contingencies did encourage spreading, PLR evidence in favor of spreading emerged. Specifically, in Experiment 3, the luminance gradients and time constraints were identical to those of Experiment 2, but the cue–target relationship was changed to strongly encourage attentional spreading. The target always appeared somewhere along the cued object with equal probability, making spreading attention along the object the most beneficial strategy to adopt. Under these conditions, the pupil size was larger when the dark object was cued than when the light object was cued, consistent with attention spreading from the gray area to the darker/lighter areas of the objects. This demonstrates that it is possible to obtain evidence of attentional spreading using the PLR, but that such evidence of spreading is observed only if the participants are sufficiently motivated to do so. However, note that the attentional spreading evidenced by Experiment 3 is not necessarily restricted to spreading along the object structure. Attention spread from the cued location to other possible target locations, which happened to be along the cued object in Experiment 3. As Experiment 3 was designed as a control that we can show attentional spreading with our method when we strongly encourage it, by design, it leaves open whether or not the object itself had a role in the spreading of attention for the particular case of Experiment 3.

It has been suggested that OBA effects depend, at least partially, on whether the attentional spreading crossed interhemispheric or intrahemispheric boundaries (e.g., Barnas & Greenberg, 2019). This might raise questions regarding the decision to use only vertical rectangles in the current study. However, the critical comparison—cue on the gray end of the dark rectangle versus cue on the gray end of the light rectangle in the no-target condition—only required intrahemispheric spreading. Therefore, any difference between intra- and interhemispheric crossing has no bearing on the present findings. Vertically oriented rectangles were used in this study because a pilot experiment suggested that with this orientation the object-based advantage in RT was slightly more reliable.

One of the spreading account's main propositions is that object-based effects should occur even under spatial certainty, when the spreading of attention is not necessary. In other words, according to this account, the spreading of attention occurs automatically, even if the task characteristics favor a narrow focus of attention. Some studies have indeed demonstrated object-based effects under spatial certainty (e.g., Chen & Cave, 2006, 2008; Richard et al., 2008). Yet, others have shown that cue–target contingencies modulate object-based effects (e.g., Shomstein & Behrmann, 2008; Shomstein & Yantis, 2002, 2004). This challenges the proposition that attention spreads automatically along objects, suggesting that target location probabilities modulate attentional spreading. In contrast, the prioritization account incorporates a flexible component to attentional selection (e.g., Shomstein, 2012). This ostensibly allows for current goals and environmental contingencies to affect the way in which attention is deployed. Thus, although generating precise predictions for our experiments based on the prioritization account was not possible because it is unclear when exactly this flexible component comes to action (i.e., before or after target onset), our findings that cue–target contingencies influence the spread of attention are in line with the flexibility principle.

The current results are also in line with other recent studies that have examined how cue–target probability distributions affect object-based effects. For instance, using the two-rectangle paradigm Chou and Yeh (2018) varied the validity of location- and object-based cues. They found a spatial cueing effect when location-based cues were informative and a same-object advantage when object-based cues were informative. Thus, they demonstrated that the magnitude of object-based effects can be affected by strategic control. Similarly, Nah and Shomstein (2020) also manipulated the probability of the different target locations with the same paradigm and found that object-based effects were affected by cue–target contingencies, and could even be reversed if the uncued object is the most likely target location. O'Bryan and Scolari (2021) also demonstrated object-based effects that were contingent on the cue–target relationship. In their study, when the cue was highly predictive of target location no object-based effect was observed, but when the cue was only mildly predictive of target location (and invalid trials were more common) then an object-based effect emerged. Additionally, they used pupillary dilation as an indication of top-down control and showed that object-based effects co-occurred with greater pupillary dilation. These studies, like the current study, support the notion that object-based effects are contingent on cue validity and not only object representation.

Attentional shifting is the remaining major mechanism proposed to underlie OBA. This account proposes that object-based effects emerge because disengaging from an object is a costly process that is required in the invalid-different condition but not in the invalid-same condition thus giving the latter its behavioral advantage. Strictly speaking, according to this account we would not expect to find any evidence of spreading along the object. This is because the shifting account is only concerned with the cost of disengaging from an object when shifting attention—shifting that occurs following target onset not beforehand. Thus, the findings of our study are consistent with this account. Indeed, we have recently obtained direct evidence from the attentional modulation of the PLR in favor of this account using slightly different methods (Luzardo et al., 2022).

Conclusion

In the current study, we examined whether attention spreads automatically along a cued object. By continuously tracking attentional allocation using the PLR, we showed that attention spreads to uncued areas of an object only when cue–target contingencies strongly encourage such a strategy. These results provide clear response-free evidence that attentional spreading does not happen automatically but instead is contingent on the cue–target relationship.

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Correction to Luzardo et al. (2023)

In the article "Attention Does Not Spread Automatically Along Objects: Evidence From the Pupillary Light Response" by Felipe Luzardo, Wolfgang Einhäuser, Monique Michl, and Yaffa Yeshurun (*Journal of Experimental Psychology: General*, 2023, Vol. 152, No. 7, pp. 2040–2051. https://doi.org/10.1037/xge0001383), the target stimuli were missing from Figures 1 and 2 and have now been included.

The online version of this article has been corrected.

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