

Attentional cartography: mapping the distribution of attention across time and space

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Abstract Decades of research have shown that the orienting of attention follows a reliable pattern of facilitation and then inhibition following a peripheral cue. However, the literature lacks a high-resolution spatiotemporal map of this pattern. Moreover, the use of visual placeholders to highlight potential stimulus locations is inconsistent. This is puzzling, given attention's well-known predilection for objects. In this article, we remedy these outstanding issues with a large-scale investigation charting the spatiotemporal distribution of attention. Participants detected targets presented at 121 possible locations 100, 200, 400, or 800 ms following an uninformative peripheral cue. The cued locations were presented with or without placeholders. With placeholders, the classic pattern of early facilitation and late inhibition was observed for targets appearing within the placeholders, and the spread of inhibition was severely limited to within the placeholders. Without placeholders, we observed inhibition shortly after cue presentation, upsetting the famously reliable effect of facilitation following a cue. Moreover, inhibition spread from the cued location, unlike when placeholders were present. This investigation has produced an eminently detailed spatiotemporal map of attentional orienting and illustrated the consequences of placeholder stimuli, with surprising results.

Keywords Attentional capture · Space-based attention · Object-based attention

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For 35 years, researchers have fruitfully employed variations of the spatial cueing paradigm to learn how visual attention moves. This paradigm, designed and popularized by Posner (1980; Posner & Cohen, 1984), uses abrupt peripheral onsets (cues) to attract attention. Shortly thereafter, a target is presented at the same location as the cue or at a different location; the difference in the reaction times (RTs) to detect targets at cued and uncued locations indexes the orienting of attention. These types of cues produce two effects: a brief period of *facilitation*, in which targets are detected faster at the cued than at uncued locations shortly after the cue, followed by a longer period of *inhibition*, during which targets are detected slower at cued than at uncued locations (Klein, 2000; Posner & Cohen, 1984). This later inhibition is called *inhibition of return* (IOR; Posner, Rafal, Choate, & Vaughan, 1985).

Measuring the effect of cues by comparing the RTs from only cued and uncued locations may not fully describe the distribution of attention, since there have been compelling demonstrations of the spatially continuous nature of facilitation and inhibition. For example, IOR spreads to locations neighboring the cue and attenuates with distance, suggesting a graded inhibition centered on the cued location (Maylor & Hockey, 1985). In a similar study, in which stimuli were displayed on the perimeter of a circle, IOR appeared to be strongest at the location opposite the cue, and diminished around the perimeter (Pratt, Spalek, & Bradshaw, 1999). The most detailed spatial study of IOR to date used four cue locations and 441 potential target locations (Bennett & Pratt, 2001), producing a high-resolution map of the inhibitory aftereffect following peripheral cues. Inhibition was pronounced in the cued quadrant and spread in a Gaussian pattern, becoming facilitation in the opposite quadrant. Although the spatial resolution of this map is extreme, the researchers used only one cue–target onset asynchrony (CTOA; 800 ms). Thus, we possess only a snapshot of attention's spatiotemporal

distribution. In this article, we aimed to expand on this attentional cartography by generating a similarly high spatial resolution map of attention over multiple CTOAs.

Following the design of Posner and Cohen (1984), researchers employing variations of the spatial-cueing paradigm have typically used visual placeholders to indicate potential cue and/or target locations. The use of placeholders is so ubiquitous in studies examining the orienting of attention (cf. Wright & Ward, 2008) that their presence is taken for granted. This is odd, for two reasons. First, consider the widely known effect that objects limit the spread of attention. For example, cueing one end of a rectangle speeds target detection at the other end, as compared to an equidistant location in a separate object (Egly, Driver, & Rafal, 1994). Object-based effects are not limited to facilitation: Target detection on a moving object results in IOR, as though the inhibited region tracked the object through space (Tipper, Weaver, Jerreat, & Burak, 1994). Simply put, objects alter the spatial distribution of attention. Second, some of Posner's early contemporaries employed similar cue–target designs without placeholder boxes—with contrasting results. When the cues and targets were represented by LEDs affixed to an arc perimeter, such that the cue and target locations were not confined within the contours of a box stimulus, the reliable facilitative cueing effect reversed; at CTOAs as short as 100 ms, targets were detected *more slowly* at the cued locations (Berlucchi, Tassinari, Marzi, & Di Stefano, 1989; Tassinari, Aglioti, Chelazzi, Marzi, & Berlucchi, 1987). Given that attention operates qualitatively differently when objects are involved, it is important to examine how the presence of placeholders affects the spatiotemporal distribution of attention. Note that some examinations of the distribution of IOR have used placeholders (e.g., Maylor & Hockey, 1985; Pratt et al., 1999), whereas others have not (Bennett & Pratt, 2001); we aimed to disambiguate this inconsistency by manipulating the presence of placeholders in our display. Still other research has looked at IOR with and without placeholders (e.g., Birmingham & Pratt, 2005; Klein & McCormick, 1989), but not with short and long CTOAs, and never with the spatial resolution provided by our design (after Bennett & Pratt, 2001). Perhaps the most interesting product of this method is that we will be able to see the distribution of attention not just at the placeholder locations, as in existing studies, but also at the regions surrounding them.

The present research is intended to provide an empirical demonstration of attentional orienting at high spatiotemporal resolution: attentional cartography. This expands on existing high-resolution spatial maps (e.g., Bennett & Pratt, 2001) by examining the way that maps change over time. These maps have additional methodological impact as demonstrations of what happens when we do or do not use placeholder stimuli in these types of displays. To produce these maps, we conducted a large-scale experiment in the spirit of Posner's spatial-cueing paradigm, with four cue locations and 121 target locations at

four CTOAs. Moreover, we manipulated the presence of placeholders at the cued locations. In doing so, we have obtained an eminently detailed map of the spatiotemporal distribution of attention.

Method

Participants

Eighty students from an introductory psychology class at the University of Toronto participated for course credit.

Apparatus

All stimuli were white on a black background. The display was divided into an invisible, square 11×11 grid, with 2° of visual angle separating each intersection (see Fig. 1a). The 121 intersections of this grid were possible target locations. A central fixation square (subtending 0.75°) was surrounded by four equally spaced cue locations that were located at the corners of an invisible $12^\circ \times 12^\circ$ square. On some trials, square outline placeholder stimuli subtending 0.75° were displayed at the cue locations. The target was a white dot subtending 0.5° , and the cue was a square outline subtending 0.75° , with an outline twice as thick as the placeholder stimuli (so that in the placeholder condition, one of the four placeholder stimuli appeared to thicken). The viewing distance was fixed at 44 cm using a chinrest. Participants made their responses on a keyboard placed directly in front of them.

Procedure and design

On every trial, the fixation appeared at the center location for 1,000 ms. Next, a cue appeared randomly at one of the four locations for 100 ms, whereupon a target would appear at one of the 121 possible locations 100, 200, 400, or 800 ms after cue onset. The participants' task was to detect the target as quickly as possible by pressing the space bar. On some trials, no target would appear. On these catch trials, no response was required; they were used to discourage participants from making anticipatory responses. A response made during a catch trial was considered an error and caused a feedback tone to be presented. Participants were told to respond as rapidly as possible while minimizing errors. The intertrial interval was 1,000 ms, and breaks were given periodically. Participants were told to fixate centrally throughout the experiment, and that the cue was completely uninformative. Data were collected in a single 2-h session. A closed-circuit camera was used to monitor eye movements and to ensure that participants remained fixated centrally.

Target Location was a within-subjects factor, and CTOA and Placeholder Presence were between-subjects factors,

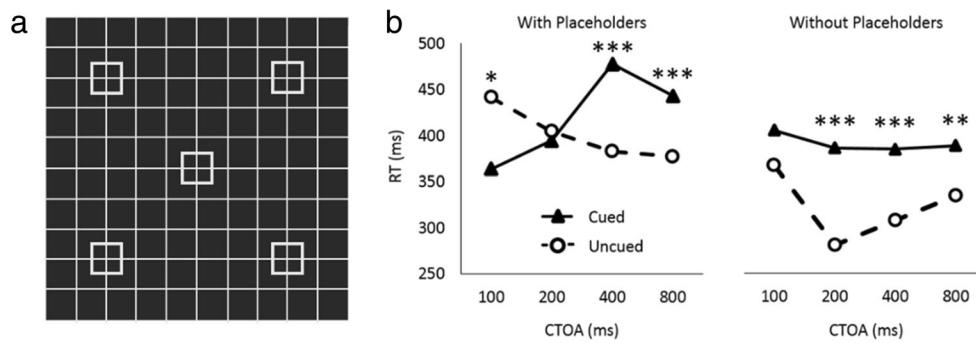


Fig. 1 **a** Display used in the experiment. The placeholders were present for half of the participants and were invisible for the other half, although the cues always appeared at these locations. Targets could appear at any of the 121 intersections of this invisible grid. The central box was always

because of the large amount of data required to produce detailed maps with 121 locations. Ten participants were assigned to each of the eight combinations of CTOA and placeholder presence; each participant completed 968 target trials and 184 catch trials. Because the cue was uninformative, and because the 121 target locations were equally likely to contain the target on a given trial, the ratio of cued (i.e., the target appeared precisely at the cued location) to uncued trials was 1:120. The likelihood of the target appearing in the cued quadrant was 25/121, versus 75/121 in the uncued quadrants (with 21 of the locations being along the horizontal and vertical meridians).

Results

To ensure that we obtained typical IOR effects, we compared mean RTs in order to detect targets at the cued and uncued locations with and without placeholders at each CTOA. Thus, we performed a 2 (cued vs. uncued; within subjects) \times 4 (100, 200, 400, and 800 ms; between subjects) \times 2 (placeholders present vs. absent; between subjects) analysis of variance (ANOVA). The results revealed a three-way interaction between target location, CTOA, and placeholder presence: $F(3, 70) = 5.71, p = .001, \eta^2 = .197$. To probe this interaction further, we ran paired-samples t tests comparing the mean RTs at cued and uncued locations for each combination of CTOA and placeholder. Significant comparisons are noted in Fig. 1b. Inspecting Fig. 1b, we can see a typical pattern of facilitation and then inhibition when placeholders were present: RTs are faster at the cued than at uncued locations at the earliest CTOA, representing facilitation, and this pattern reverses at the later CTOAs, representing IOR. The pattern is very different when placeholders were absent: RTs are slower at the cued than at uncued locations for all CTOAs, indicating a very early and sustained inhibition (although note that the trend at the 100ms CTOA did not reach significance). To

present. Placeholders are not drawn to scale. **b** Mean reaction times (RTs) for cued and uncued locations at different cue–target onset asynchronies (CTOAs), with and without placeholders. * $p \leq .05$. ** $p \leq .01$. *** $p \leq .001$

further illustrate the effect of placeholders on the typical crossover pattern, we compared the mean cueing effects ($RT_{\text{Uncued}} - RT_{\text{Cued}}$) with and without placeholders at each CTOA with independent-samples t tests. The placeholders influenced the cueing effects at 100 and 200 ms after the cue ($t_s > 2.67, p_s < .016$; all other $t_s < 0.64, n.s.$), indicating that placeholders alter the time course of attention shortly after cue presentation.

To illustrate the spread of attention over space and time, we also created scatterplots and heat maps of the data, depicted in Fig. 2. On the heat maps, the fastest of responses are represented by white squares, the slowest are represented by black squares, and the intermediate RTs are represented by shades of gray. On the scatterplots, the cued locations are highlighted by red circles, the opposite uncued locations by blue triangles, and the mean of the other uncued locations by green diamonds.

When placeholders are present, there is a steady, positive relationship between RT and distance from the cued location at the shortest CTOA. This relationship disappears at 200 ms and reverses at 400 and 800 ms. Note, however, that IOR (inhibition at 400 and 800 ms) is sharply confined to the cued placeholder, and to a lesser extent the other uncued placeholders: RTs to detect targets within the placeholders are dramatically lengthened relative to all surrounding locations. For a visual representation, examine the heights of the red, blue, and green points on the scatterplots in Fig. 2. They appear as outliers; RTs to targets within placeholders are highly exaggerated, indicating that they limit the spread of IOR.

When placeholders are absent, there is a negative, exponentially decreasing relationship between RTs and distance at every CTOA. These curves indicate that inhibition is strongest at the cued location and diminishes rapidly with distance. This relationship is strongest 400 and 800 ms after the cue. Importantly, RTs at the four potential cue locations are not unlike those at their neighbors when no placeholders are present. On the heat maps, this effect is visible in that the cued location is not confined. Rather, inhibition spreads without constraint. On

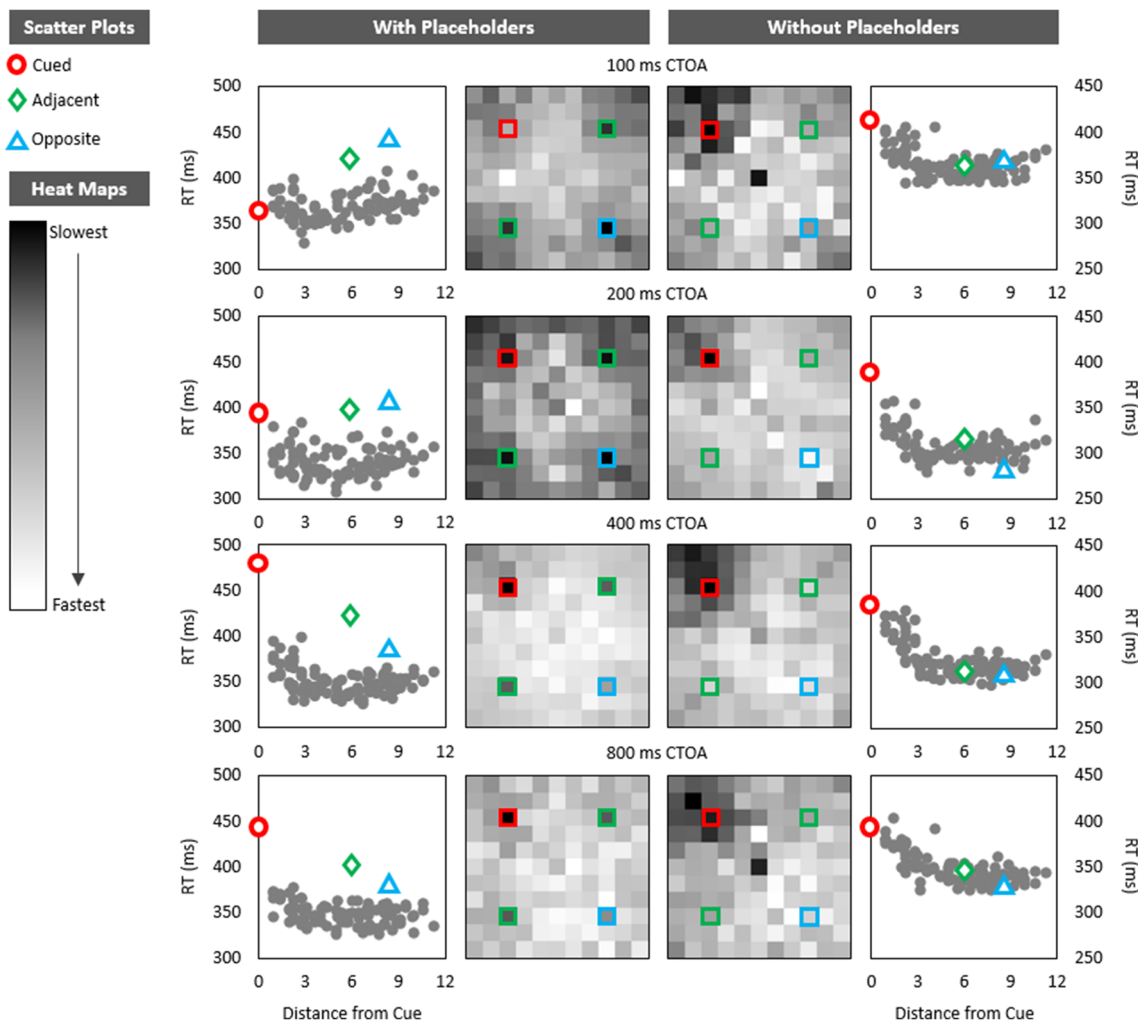


Fig. 2 Scatterplots and heat maps displaying the spatial distribution of attention at different CTOAs, with and without placeholders for cued locations. The scatterplots display the mean reaction times (RTs) at a given location as a function of how far that location was from the cue (distance is measured in grid units; each target location was 2° from its neighbor). RTs for the cued location and the opposite, uncued location are shown as red circles and blue triangles, respectively; the green diamonds represent the mean RTs for the other two uncued locations. Note that the axes represent the same intervals, but different values, for placeholders

present versus absent, because RTs were slower overall when placeholders were present. For each heat map, the fastest value is white (RGB: 255, 255, 255), the slowest value is black (RGB: 0, 0, 0), and the mean RT is in mid-gray (RGB: 128, 128, 128). All other values are in intermediate shades of grays. Although the cue location was random, these heat maps have been normalized such that the cued location is always at the top left. The boxes represent the possible cue locations, and their colors correspond to the highlighted points on the accompanying scatterplots

the scatterplots, this effect is visible in that the colored points appear well within the trends.

To describe the spatial distribution of attention over time, we used an exponentially decreasing function to predict the mean RTs at different locations ($RT = ae^{-b(\text{Distance})} + c$). We conducted this regression with and without placeholders for every CTOA. The best-fit regression parameters for every condition are described in Table 1. Smaller *b* values indicate a broad distribution of attention (a shallower bend to the curve), whereas larger *b* values indicate a tighter distribution surrounding the cue (a steeper bend). The parameters were bound at zero, and this function cannot be increasing, which explains why the one plot without a negative relationship

(placeholders present, 100 ms CTOA) outputs parameters describing a flat line.

Discussion

These maps illustrate the spatiotemporal distribution of covert attention elicited by peripheral cues with unsurpassed detail. Furthermore, they highlight the dramatic impact that placeholder stimuli have on this distribution. Consider the data from the cued locations. When placeholders were present, we replicated the well-known pattern of early facilitation and late inhibition. In contrast, when placeholders were absent, we

Table 1 Regression parameters for the distribution of attention

Cue–Target Onset Asynchrony (ms)	<i>a</i>	<i>b</i>	<i>c</i>	<i>R</i> ²
With Placeholders				
100	<0.01	1.50	369.28	.09
200	53.83	1.72	341.05	.10
400	127.25	1.34	348.20	.49
800	95.27	1.37	345.61	.44
Without Placeholders				
100	56.48	0.66	360.04	.35
200	90.39	0.86	301.25	.52
400	88.69	0.55	313.60	.65
800	67.77	0.46	337.09	.60

The parameters describe an exponentially decreasing function: $RT = ae^{-b(\text{Distance})} + c$. These parameters were discovered with an iterative model and were bounded as greater than or equal to zero

observed early and late inhibition at the cued location, inconsistent with the typically espoused time course of covert orienting (e.g., Posner & Cohen, 1984). By comparing the sizes of the cueing effects at each CTOA, we found that covert orienting was dramatically altered in the presence or absence of placeholder stimuli at short (100 and 200 ms) CTOAs.

Turning next to the spatial distribution of the cueing effects, our results demonstrate that the placeholders in our study acted as visual anchors that confined the spread of inhibition. This is evident on the scatterplots and heat maps, which clearly demarcate the placeholder locations as outliers relative to their surroundings. This observation is further supported by the regression analyses: The high *b* values and low *R*²s relative to the no-placeholder condition indicate that the curve quite literally bent over backward accounting for the cued location, and that the cued locations were more prominent outliers. In contrast, when placeholders are absent, inhibition spreads over much of the visual field (replicating the findings of Bennett & Pratt, 2001, at the longest CTOA). The spread of inhibition is curvilinear, rapidly decreasing at short distances and smoothing out after about three grid units (~6°). In addition to replicating existing data from Bennett and Pratt at the longest CTOA (800 ms), this investigation adds maps for three other CTOAs, bringing this high-resolution cartography into the temporal dimension. The results also complement similar high-resolution spatiotemporal maps of attention derived using change detection procedures, which have also revealed an opposite-hemifield boost (although those authors did not implicate IOR; Tse, Sheinberg, & Logothetis, 2003). Furthermore, they complement new research demonstrating that structured arrays of placeholder stimuli can alter the shape of the distribution of attention (e.g., Jefferies & Di Lollo, 2015, who showed that attention can be deployed in an annulus when the display is populated with placeholders in that shape).

The early and sustained inhibition reported in our no-placeholder condition is surprising, because it seems to contradict an established literature. However, we endorse an explanation that is consistent with the earliest descriptions of the biphasic, facilitation-then-inhibition pattern (Klein, 2004). In the seminal study of the components of visual orienting, Posner and Cohen (1984) explained the biphasic pattern of attentional orienting by positing an interaction between separate, but simultaneous, facilitative and inhibitory processes. The typical spatial-cueing task invokes an early and sustained inhibition along with an early and ephemeral facilitation that is stronger than the inhibition. Cueing effects are described by the summation of these processes, such that early CTOAs yield facilitation (on account of this being stronger than the inhibition), but later CTOAs yield inhibition, because that process outlasts the facilitation. In accordance with this model, early inhibitory cueing effects should be observed if the facilitative component can be erased or quickly terminated. For example, when observers are given a strong incentive to disengage from a peripheral cue, inhibitory cueing effects are observed at CTOAs as short as 50 ms (Danziger & Kingstone, 1999). Similarly, Collie and colleagues observed facilitation by peripheral cues only when the cue presentation overlapped with the target; when the cue was flashed briefly and offset, they observed no facilitation, even at short (<200-ms) CTOAs (Collie, Maruff, Yucel, Danckert, & Currie, 2000). Although Collie et al. did not comment on this finding, we propose that it can be considered as a manifestation of the aforementioned rapid disengagement: Perhaps the transient nature of those cues speeded disengagement, relative to the longer-duration cues that did elicit facilitation. Similarly, we propose that the absence of placeholders in our display made it easier or more likely for observers to disengage attention from the cued locations, expediting decay of the facilitative component.¹ The corollary to this explanation is that when placeholders are present, observers default to a mode in which they anchor attention to those high-contrast contours. This seems likely, given that observers automatically allocate attention within the contours of objects' edges in well-known demonstrations of object-based attention (Egley et al., 1994). It is not clear why exactly we did not observe facilitation without placeholders, but the aforementioned studies (Collie et al., 2000; Danziger & Kingstone, 1999), and others not showing early facilitation with placeholder stimuli (e.g., Samuel & Kat, 2003; Samuel & Weiner, 2001), illustrate that this violation of the typical cross-over pattern cannot be the only factor in our finding.

Why, then, did placeholder boxes in our study attract such attentional priority? Perhaps because they were the only objects (besides the fixation box) in the display, observers defaulted attention to them. Another possibility is that attention has a predilection for edges, which is consistent with the

¹ We thank an anonymous reader for proposing this idea.

object-based literature (Scholl, 2001). Placeholder stimuli also bring a lot of perceptual baggage when they are inserted into an otherwise blank display, and this complicates interpretations of the effect of such placeholders. Consider that the relative change in luminance in the display caused by the appearance of a cue or target is greater in the placeholder condition than in the no-placeholder condition.² Thus, the observed differences between the placeholder and no-placeholder conditions could be caused by perceptual factors independent of attention (e.g., salience, sensory adaptation, etc.). This idea is also consistent with early reports of inhibitory cueing effects at short CTOAs (200 ms) in displays without placeholder boxes (e.g., Berlucchi et al., 1989; Tassinari et al., 1987). These researchers used LEDs as their stimuli instead of placeholder boxes. Like our no-placeholder condition, the sudden illumination of an LED would produce a much larger relative change in luminance than Posner and Cohen's (1984) brightening boxes. In any event, the present results offer a clear demonstration of the consequences of a paradigm-typical placeholder display on the covert orienting response.

Another theoretical complication produced by elements of our display is the potential confound of target eccentricity with the results. Because our goal required the examination of many target locations over a wide area, we were unable to control for target eccentricity when producing our map. We are not too concerned, though, because Bennett and Pratt (2001), after whom our display was designed, conducted a small study to examine the effect of eccentricity and found no effect with their display. They used a similar display, without cues, and targets appeared at 40 different locations along the four diagonals extending from fixation (ten locations on each diagonal). Because they found no effect of eccentricity on simple target detection with their display, and because our display (i.e., very bright stimuli on a black background) and procedure were practically identical, we are confident that there was no influence of eccentricity on our data.

By dramatically increasing the number of target locations, we produced an eminently detailed map of the orienting response. But this also had the effect of reducing the reliability of the cue stimulus. Whereas most studies use a handful of cue and target locations, making even uninformative cues somewhat reliable, the likelihood of the target appearing at the cued location in our study was low: 1/121, to be exact (or a 25/121 likelihood of appearing in the cued quadrant). It is reasonable to suppose that the unreliability of the cue affected the distribution of attention (e.g., Druker & Anderson, 2010). However, even though the likelihood of the target appearing at the cued location was very low (1/121), we still replicated the typical facilitation-then-inhibition crossover pattern at the cued versus the opposite location (see Fig. 1b) in the

placeholder conditions, so it seems unlikely that the cue unreliability upset typical orienting behavior.

Because the number of trials required for sufficient power at 121 target locations was so high (>1,000 trials/participant), CTOA and placeholder presence were manipulated between subjects. Since all participants had experience with only one CTOA, the repeated temporal context might have influenced the surprising results observed in the no-placeholder condition. As we noted above, we would expect any effect of temporal context to be equipotent across placeholder conditions; given that we observed a highly paradigm-typical pattern of results in the placeholder condition, we do not expect that temporal context caused the surprising results in the no-placeholder condition. With respect to placeholder presence as a between-subjects manipulation, we wanted to ensure that participants in the no-placeholder condition never had exposure to the objects, since uncertainty in the trial-to-trial object structure can increase object-based selection (e.g., Shomstein, 2012), which may influence the orienting response.

This investigation was not the first on covert orienting to systematically manipulate the presence of placeholder stimuli. Other researchers have examined the effect that placeholder stimuli have on IOR (e.g., Birmingham & Pratt, 2005; Jordan & Tipper, 1998; Klein & McCormick, 1989; McAuliffe, Chasteen, & Pratt, 2006; McAuliffe, Pratt, & O'Donnell, 2001; Paul & Tipper, 2003; Pratt & Chasteen, 2007), but only at longer (>500-ms) CTOAs and with fewer stimulus locations (e.g., 2–8), often using multiple sequential-cueing paradigms, and never investigating cases in which a cue occurs at a placeholder location and the target does not (preventing fine-grained analyses of spatial distribution). Notwithstanding, they served as a useful reference for the effect of placeholder stimuli on spatial orienting. A common thread throughout these studies is that IOR is weakened without as compared to with placeholders (Jordan & Tipper, 1998; McAuliffe et al., 2006, with young adults; McAuliffe et al., 2001; Pratt & Chasteen, 2007; although some have shown no difference—e.g., Klein & McCormick, 1989; McAuliffe et al., 2006, with old adults), which seems at odds with our finding of significant IOR at 200 ms without placeholders, versus no IOR with placeholders. We do not contend that IOR was greater without placeholders, but rather that the time course of facilitation and inhibition was altered by the placeholders' presence. Had previous investigations examined the effect of placeholders on peripheral cueing at earlier CTOAs, they might have found similar results, and if we had extended our investigation to CTOAs greater than 1,000 ms, we might have observed greater IOR with placeholders as time progressed, as in these earlier studies. Interestingly, Birmingham and Pratt (2005) found no or minimal IOR at all without placeholders in a sequential-cueing paradigm with CTOAs between 1,000 and 3,000 ms. Given the accelerated pattern of inhibition observed in our no-placeholder condition, it may be possible that

² We thank an anonymous reader for proposing this idea.

the IOR that we observed was short-lived and did not extend past the 800-ms CTOA (although further investigation is warranted to resolve these differences).

The results from this large-scale, high-resolution study of the effects of peripheral cues on attention have shown the enormous effect that placeholders can have on both the time course and spatial distribution of attention. In other words, the spatiotemporal dynamics of attention are heavily influenced by something that is usually regarded as a feature of experimental design rather than an independent variable. By looking at more locations, across a larger range of time, than ever before, the present study not only highlights the critical role of placeholders, but also reconciles a longstanding discrepancy in the cueing literature and provides detailed information about how peripheral cues affect behavior over time and space. In light of the present findings, one wonders what would now be considered the “classic” pattern of cueing effects, had the early studies (Maylor & Hockey, 1985; Posner & Cohen, 1984) not used placeholders.

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