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ORIGINAL ARTICLE

Spatial cueing effects do not always index attentional capture: evidence for a priority accumulation framework

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Abstract
The spatial cueing paradigm is a popular tool to investigate under what conditions irrelevant objects capture attention against the observer's intention. In this paradigm, finding better visual search performance when the target appears at the location of an irrelevant cue is taken to indicate that this cue summoned attention to its location, before the search display appeared. Here, we provide evidence challenging this canonical interpretation of spatial-cueing (or cue-validity) effects and supporting the priority accumulation framework (PAF). According to PAF, the cue can bias attention but such bias takes effect only when the relevant context for selection (the search display) appears: attentional priority accumulates over time at each location until the search context triggers selection of the location that has accumulated the highest priority. We used a spatial-cueing paradigm with abruptly onset cues and search displays varying in target–distractor similarity. We found that search performance on valid-cue trials deteriorates the more difficult the search (Experiment 1), and showed that this finding is explained by PAF but cannot be accommodated within the standard interpretation of spatial-cueing effects (Experiment 2). Finally, we assessed the priority accumulated at each location by using a combination of the spatial-cueing and dot-probe paradigms (Experiment 3). We showed that the similarity of the cued object to the target modulates probe detection performance, a finding that is at odds with the standard interpretation of cueing effects and supports PAF's predictions. We discuss the implications of the findings in resolving existing controversies on the determinants of attentional priority.

Public significance statement

Many studies aim at establishing whether certain objects mandatorily capture our attention. Here, we show that there is no "yes-or-no" answer to this question because the temporal context in which an object appears influences whether this object wins the competition for selection. We show that our attention is not shifted to the highest-priority object at *any given time*; instead, information about priority is collected across time until some signal indicates that the appropriate moment for deploying our attention has arrived.

Introduction

Striking failures to notice conspicuous events routinely illustrate how limited our attentional system is: we can attend to very few objects at any given time, and probably to just one. In natural conditions, when we move the focus of our attention from one object to another, we also shift our gaze towards the attended location: this allows us to place the object of most interest in the center of our fovea, which maximizes the quality of its perceptual processing. Tracking the locus of such *overt* attention is easily achieved by using eye-tracking devices. However, to isolate the benefits of attention from the benefits of visual acuity, one must study *covert* attention—that is, attentional shifts in the absence of eye movements. These shifts are not directly observable and must therefore be inferred using indirect measures of processing.

The spatial cueing paradigm

A particularly popular method for studying covert attention is the spatial cueing paradigm. In a typical experiment, observers search for a target among distractors. Shortly prior to the search display, a cue appears at one of the potential target locations. Spatial cueing effects, that is, faster search performance when the target appears at the same location as the cue than at another location,

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are taken to indicate that attention was shifted to the cued location (see Eriksen & Hoffman, 1974; Posner, Nissen & Ogden, 1978; Posner, Snyder & Davidson, 1980 for early examples of this inference).

This method has been especially useful to investigate under what conditions an irrelevant object captures attention against the observer's intention. For instance, Folk, Remington and Johnston (1992) asked participants to search for a color singleton target (e.g., a red target among gray distractors) in one condition, and for an abrupt onset, that is, a white target in an otherwise empty field, in a different condition. The location of the cue, also either a color singleton or an abrupt onset, was not predictive of the target location. Folk et al. (1992) observed a spatial cueing effect when the cue shared the target property (e.g., when it was an onset cue in search for an onset target), but not when it did not (e.g., when it was an onset cue in search for a color singleton target). This finding, which was replicated in numerous subsequent experiments (see Büsel, Voracek & Ansorge, 2018, for a meta-analytic review), led the authors to propose the contingent-capture view, according to which irrelevant salient objects do not capture attention unless they match the observers' search goals (Folk et al., 1992). This goal-driven account of attentional capture stands in sharp contrast with the stimulus-driven account, which stipulates that the most salient object within a display will capture attention independently of the observer's goals (e.g., Theeuwes, 2010).

Proponents of the stimulus-driven view have questioned the claim that failure to find a spatial cueing effect indicates that the cue did not capture attention. For instance, an alternative interpretation of Folk et al.'s (1992) finding is that a salient cue outside the observer's attentional set does capture attention, but because this cue does not match the search goals, attention can be quickly disengaged from its location during the cue-target interval. As a result, the spatial cueing benefit can no longer be observed when the target finally appears at the cued location (Fast-Disengagement hypothesis; e.g., Theeuwes, Atchley & Kramer, 2000; but see Chen & Mordkoff, 2007; Lamy, 2005). Others have suggested that attention dwells at the location of the cue until the search display appears, and that the spatial cueing effect mainly indexes the time it takes to reject the distractor at the cued location (attentional-dwelling hypothesis, Gaspelin, Ruthruff & Lien, 2016; Ruthruff, Faulks, Maxwell & Gaspelin, 2020). Specifically, these authors proposed that irrelevant onset cues routinely capture attention, but their effects may or may not be observed: spatial cueing effects are reliable when the distractors are similar to the target and thus difficult to reject, but not when the distractors are dissimilar from it and can be immediately rejected—as was typically the case in Folk and colleagues' studies and their replications.

Challenges to the traditional interpretation of spatial cueing effects

By contrast with the conflicting interpretations of null spatial cueing effects, the notion that, when found, spatial cueing effects indicate that *the cue triggered a shift of attention to its location, before the search display appeared*, is fairly unanimous—we henceforth refer to it as the standard or canonical interpretation of spatial cueing effects. However, several observations, three of which are detailed below, call this interpretation into question (see Gabbay, Zivony & Lamy, 2019; Toledano, Sasi, Yuval-Greenberg & Lamy, 2021; Yaron & Lamy, 2021 for additional findings).

Firstly, spatial cueing effects from irrelevant onset cues have been reported with cue–target SOAs as long as 300 ms (e.g., Lamy, 2005, Exp.3). Although the time it takes to shift attention from one object to another during visual search is debated (e.g., Duncan, Ward, & Shapiro, 1994; Eimer & Grubert, 2014; Woodman & Luck, 1999), the most conservative estimates rarely exceed 200 ms (e.g., Moore, Egeth, Berglan, & Luck, 1996). Finding a spatial cueing effect indicates that attention was not yet disengaged from the cued location when the search display appeared, according to the fast disengagement hypothesis (e.g., Theeuwes, 2010), or that it still dwelled at the cued location, according to the Attentional Dwelling hypothesis (Gaspelin et al., 2016). Yet, it is difficult to explain why observers would not shift their attention away from a to-be-ignored cue that did not match the observer's attentional set for 300 ms, as both accounts would have to assume to explain the spatial cueing effects over long cue–target SOAs.

Secondly, Gaspelin et al., (2016; see also Lamy, Darnell, Levi & Bublil, 2018; Ruthruff et al., 2020) manipulated search difficulty by varying target–nontarget similarity in the search display and measured the spatial cueing effects associated with an abrupt-onset cue. They found the spatial cueing effect to increase with search difficulty. Since according to the standard interpretation, the cue captured attention before the search display appeared, this finding entails that such capture occurred across levels of search difficulty (see Hilchey & Pratt, 2019 for additional evidence supporting the idea that attentional capture by abrupt onsets is latent in easy search). However, for easy search tasks, null spatial cueing effects (ranging from − 1 to 4 ms) were often reported (e.g., Chen & Mordkoff, 2007; Gaspelin et al., 2016, Exp.1; Folk et al., 1992, Exps. 3 & 4; Lamy et al., 2018, Exp.2), with cue-to-target distances spanning over 10° of visual angle.

Even if one conservatively assumes that the cue captured attention only on, say, one fourth of the trials, a 2-ms spatial cueing effect (e.g., Gaspelin et al., 2016, Exp.1) would entail that attention was disengaged from the cued distractor and shifted to the target in only 8 ms. This claim is difficult to reconcile with previous literature on attentional motion speed (e.g., Eriksen & Yeh, 1985; Tsal, 1983).

Finally, in the same studies (Gaspelin et al., 2016; Lamy et al., 2018; Ruthruff et al., 2020), response times increased with search difficulty when the target appeared at the cued location. According to the standard interpretation of spatial cueing effects, the reason why performance is better on valid- than on invalid-cue trials is that attention is already focused on the target location when the search display appears and observers can respond to the target without having to disengage their attention from a non-target location and move it to the target location. According to this rationale, on valid-cue trials responses to the target should be equally fast irrespective of what distractors (easy or difficult) surround the target. However, the standard interpretation can readily explain the effect of search difficulty on valid-cue trials, in two ways. First, as search displays were presented until the participants responded, these had the leisure to verify that the object currently in the focus of their attention was indeed the target, by comparing it to surrounding distractors. This double-checking procedure should take more time the more similar the distractors are to the target. Second, as the cue most probably did not capture attention on every trial, the effect of search difficulty on valid-cue trials may simply reflect what happened on trials in which the cue failed to capture attention: when the search does not start at the (validly) cued location, it obviously takes more time to find the target the more difficult the search.

However, as we describe next, we recently proposed a Priority Accumulation Framework (PAF, Gabbay et al., 2019; Lamy et al., 2018; Toledano et al., 2021; Yaron & Lamy, 2021) that provides an alternative account for the effect of search difficulty on performance for valid-cue trials, while also accommodating the extant findings with no need to postulate excessive Attentional Dwelling at irrelevant locations or cost-free shifts of attention.

The priority accumulation framework

Several models of attention (e.g., Bundesen, Habekost, & Kyllingsbæk, 2005; Desimone & Duncan, 1995; Luck, Girelli, McDermott, & Ford, 1997; Zelinsky & Bisley, 2015) posit that objects in the visual field compete for neural representation in the visual cortex. They propose that such competition can be biased in favor of objects that are physically salient or match the observer's current goals, and that the winner is the first object to be selected. Resolving the competition is thought to take more time, the tougher the competition, that is, the smaller the winner's leading edge (see e.g., Barras & Kerzel, 2017).

The Priority Accumulation Framework rests on similar principles with one main difference: it suggests that the attentional priority accruing to each location in the visual field accumulates across time, until temporally relevant/contextual information signals that selection can occur. Thus, PAF incorporates the notion that attention can be allocated at the moment known to be most relevant for the task at hand (e.g., Coull & Nobre, 1998; Yaron & Lamy, 2021).

In the context of the spatial cueing paradigm, this moment is the onset of the search display: the priority weights assigned to locations across the trial (in the cueing display and then in the search display) are summed, and attention is allocated to the location with the highest *accumulated* priority, in the search display. Thus, important differences exist between PAF and other models as to how cue location and the competitive interactions prevailing in the search display affect performance in the spatial cueing paradigm. According to the standard interpretation, the search starts at the cue location on trials in which the cue captured attention (i.e., triggered an attentional shift to its location), whereas on trials in which the cue did not capture attention, search most often starts at the location of the highest-priority object in the search display (e.g., the target or nontargets resembling it). By contrast, according to PAF, the cue location and the objects in the search display jointly determine where the search starts, on each trial. Figure 1 illustrates how PAF differs from the standard interpretation of the spatial cueing effect (e.g., Folk & Remington, 1992; Gaspelin et al., 2016; Theeuwes, 2010).

This framework accounts for the aforementioned challenges to the traditional interpretation of spatial cueing effects. First, it explains why spatial cueing effects can be observed with long cue-target SOAs: since according to PAF, attentional shifts most often occur only after the search display appears, there is no need to assume that attention dwells at the location of an irrelevant object across long SOAs. Second, PAF also explains why spatial cueing effects increase with search difficulty and can be null for very easy search: when target-nontarget discriminability is very high, the target's advantage is so large that the added priority from an irrelevant-feature cue has no measurable effect. By contrast, when the distractors are similar to the target, the distractor benefitting from the cue is likely to win the competition and the spatial cueing effect indexes the time it takes to disengage attention from this distractor and shift attention to the target—hence the large effect (Fig. 1, lower panel). When search difficulty is moderate, PAF makes the novel prediction that spatial cueing effects may occur even if attention was never directed to the cue: if the target is

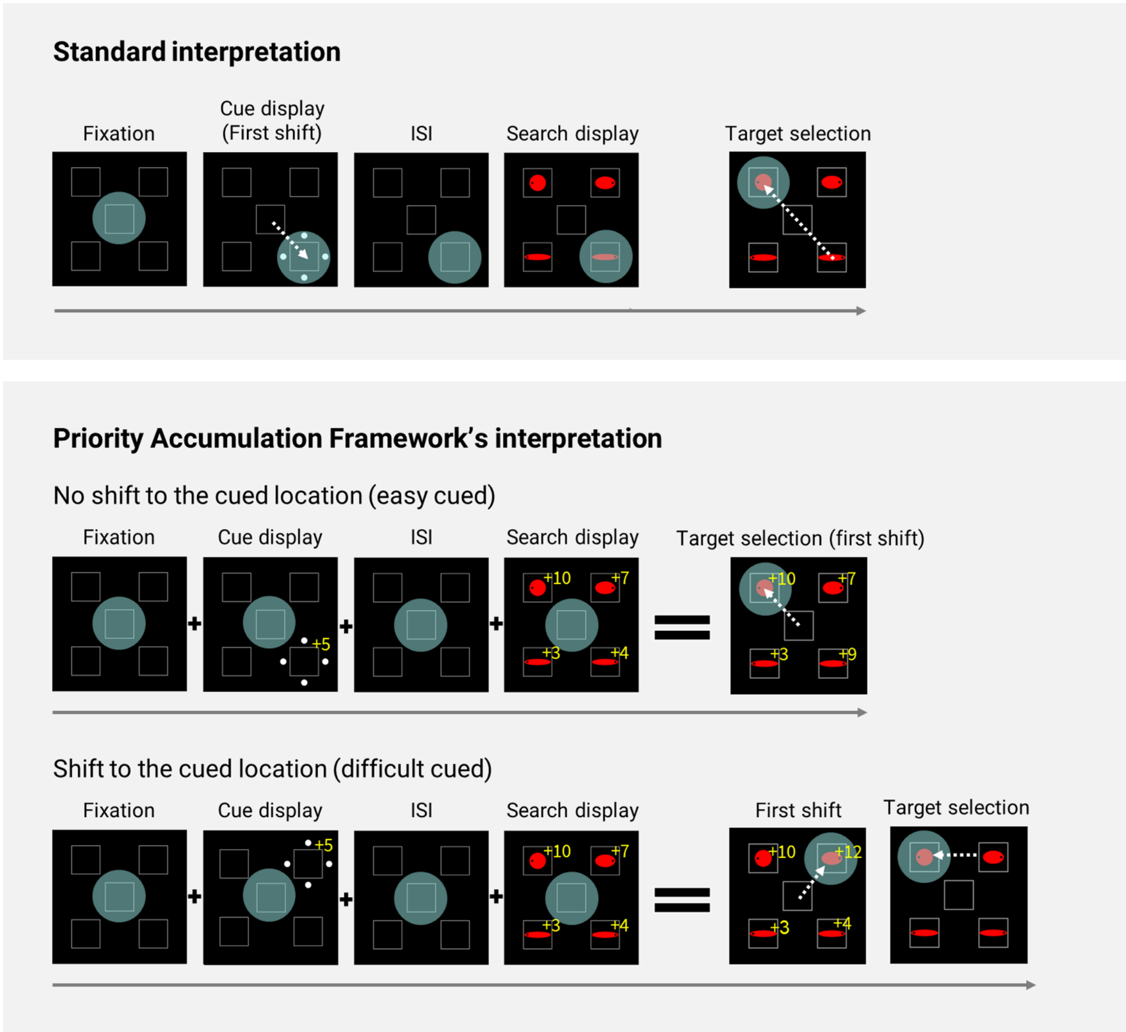


Fig. 1 Illustration of the competing interpretations of spatial cueing effects. According to the standard interpretation (e.g., Folk & Remington, 1992; Gaspelin et al., 2016; Theeuwes, 2010), finding a spatial cueing effect indicates that attention was shifted to the cue position shortly after cue onset, at least on a proportion of trials, and remained at its position until the search display appeared (*upper panel*). According to the Priority Accumulation Framework (PAF, e.g., Gabbay et al., 2019; Lamy et al., 2018; Toledano et al., 2021; Yaron & Lamy, 2021), attentional priority accumulates across time at different locations and attention is shifted to the location with the highest accumulated priority after the search display appears. Finding a spatial cueing effect may indicate that the cue speeded target selection when the cue was valid relative to when it was invalid, despite the fact that attention was never shifted to the cued location. This may occur if the target wins the competition with a substantially larger edge on valid- than on invalid-cue trials, for instance, when a distractor dissimilar to the target appeared at the cued location (*middle panel*). Alternatively, when the target loses the competition on invalid-cue trials, the spatial cueing effect also indexes the time required to disengage attention from the cued distractor and shift it to the target. This may occur if a distractor similar to the target appeared at the cued location (*lower panel*)

the highest-priority object both when it is cued and when it is not (Fig. 1, middle panel) spatial cueing effects simply indicates that the competition that leads to target selection is resolved faster when the target location benefits from the extra-priority provided by the cue (valid-cue trials) than when it does not (invalid-cue trials). Finally, PAF explains why performance on valid-cue trials deteriorates as search difficulty increases: while the target benefits from the cue's priority weight across search difficulty conditions, and is most often the first object to receive attention, target–distractor similarity still strongly determines how long it takes to resolve the competition.

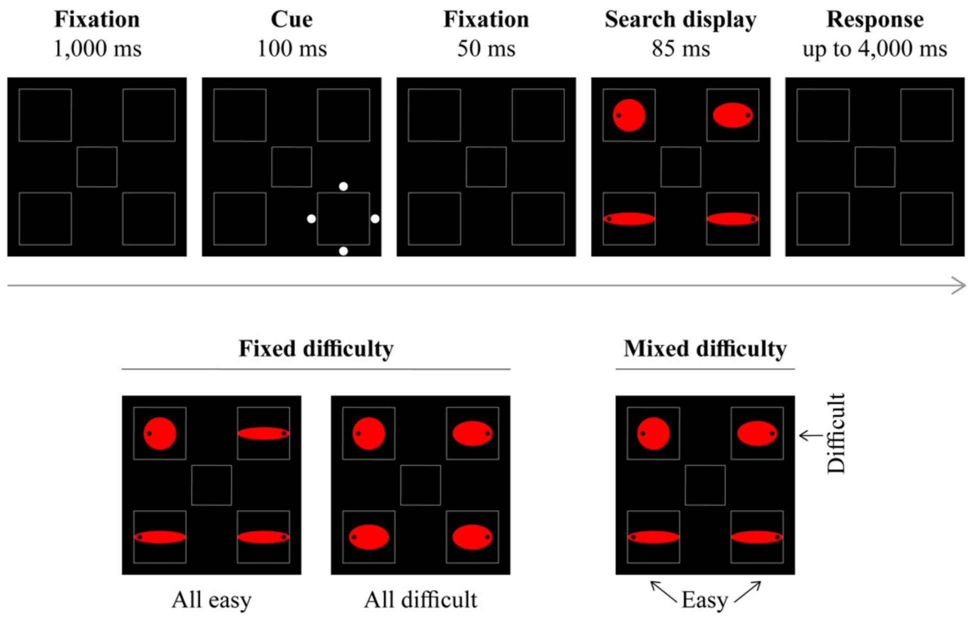


Fig. 2 *Upper panel*: sample sequence of events in Experiment 1. Participants searched for the circle in the target display and reported the side of the black dot inside the target (left or right). This example corresponds to an invalid-cue trial in the mixed-difficulty search condition. The cued distractor is an easy distractor. *Lower panel*: sample displays in each search type condition (all-easy, all-difficult, mixed-difficulty). The stimuli are not drawn to scale

Objective of the present study

In the present study, we further tested the Priority Accumulation Framework (PAF) against alternative models. In Experiment 1, we set out to replicate our previous findings supporting PAF (Lamy et al., 2018, Exp.1), with brief displays and relying on accuracy rather than on RTs as the dependent measure. In Experiment 2, we focused on the finding that target–distractor similarity modulates performance on valid-cue trials (Gaspelin et al., 2016; Lamy et al., 2018; Ruthruff et al., 2020) and tested PAF's interpretation of this finding against alternative accounts. Finally, in Experiment 3, we sought more direct evidence for PAF's hypothesis that on any given trial, whether an object in the search display is the first to receive attention jointly depends on whether the cue appeared at its location, on the similarity of that object to the target and on how difficult it is to resolve the competition with other objects in the search display.

Experiment 1

In Lamy et al.'s (2018) study, participants searched for a perfect circle among three elliptical shapes. A small black dot appeared on either the left or the right inside of each shape in the display. Participants had to report the side of the dot in the target circle. On any given trial, the search display included distractors that were all similar to the target (all-difficult search), all dissimilar from the target (all-easy search) or mixed (one similar and two dissimilar distractors—mixed-difficulty search). Prior to the search display, an abrupt onset was flashed randomly at one of the potential target locations. This study yielded three main findings. First, spatial cueing (henceforth, cue validity) effects increased with search difficulty. Second, in the mixed-difficulty condition, we found a cue validity effect both when the difficult or an easy distractor was cued, but the effect was larger in the former condition. These two findings are predicted by both PAF and the Attentional Dwelling hypothesis (Gaspelin et al., 2016) but are incompatible with either the contingent capture (e.g., Folk et al., 1992) or fast disengagement (e.g., Theeuwes, 2018) accounts, which predict that spatial cueing effects, if present, should be unaffected by search difficulty: according to the former account, a cue that does not share the target-defining feature should not capture attention altogether; according to the latter, attention is disengaged from the cue location before the search display appears. The third finding was that search difficulty strongly modulated performance on valid-cue trials. Testing PAF's interpretation of this finding against alternative accounts will be the objective of Experiment 2.

The main objective of Experiment 1 was to replicate the findings of Lamy et al., (2018, Exp.1) when search displays were presented briefly and accuracy instead of reaction time was the dependent measure. Accordingly, unlike in previous versions of this task (Gaspelin et al., 2016; Lamy et al., 2018), search displays were presented for 85 ms rather than until response. We selected an 85-ms exposure duration, based on a preliminary pilot experiment showing that with this exposure, participants' overall accuracy was approximately 80%. Beyond its value as a replication, this experiment was also important as a preliminary step towards Experiment 3, as will be explained later. A sample sequence of events is presented in Fig. 2.

Methods

Participants

We calculated the sample size required for the smallest relevant effect reported by Lamy et al., (2018, Exp.1) to be significant, namely, the RT difference between valid-cue trials and easy-distractor cued trials in the mixed-difficulty condition (η^2p = 0.55). We conducted this analysis using MorePower (Campbell & Thompson, 2012), with an alpha of 0.01 and power of 0.95. We found the minimum sample size required to be 18 participants. We were therefore confident that our experiments would be sufficiently powered with a sample of twenty-one participants. In this and the following experiments, all participants signed a consent form prior to the experiment. All protocols were approved by Tel Aviv University ethics committee.

In Experiment 1, all participants were undergraduate students who participated for course credit and reported normal or corrected-to-normal visual acuity. The final sample included 21 participants (age M = 23.34, SD = 2.48, 19 females) after three participants were replaced by new participants because their mean error rate exceeded the group's mean by more than two standard deviations (46.6%, 41.9%, and 40.8% vs. M = 21.6%, SD = 7.7%).

Apparatus

The experiment took place in a dimly lit room. Stimuli were presented on a 23-in. LED screen, using 1920 × 1280 resolution graphics mode and 120-Hz refresh rate. Responses were collected via the computer keyboard. Viewing distance was set at approximately 60 cm from the monitor using a chin rest.

Stimuli

The fixation display consisted of five gray (CIE-L*ab = 57.4, 0, 0) square outline placeholders (2.4° × 2.4° of visual angle), one centered at fixation and the remaining four equally spaced at the corners of an imaginary square, with the central-frame center to outer-frame center distance subtending 5°. All stimuli were presented on a black background. The onset-cue and search displays were similar to the fixation display, except for the following changes. In the onset-cue display, a cue consisting of four white dots (CIE-L*ab = 100, 0, 0; 0.5° in diameter) forming an imaginary diamond (3.3° × 3.3°) was added around one of the four outer placeholders. In the search display, a filled red shape (CIE-L*ab = 53.2, 80.1, 67.2) appeared in the center of each of the outer placeholders: one circle (the target, 1.3° in diameter) and three horizontal ellipses (the distractors). "Difficult" distractors subtended 1.6° × 1° and "easy" distractors subtended 2.1° × 0.5°. On fixed-difficulty search trials, all distractors were either difficult (all-difficult search) or easy (all-easy search). On mixed-difficulty search trials, each display contained one difficult distractor and two easy distractors. A black dot (0.1°) appeared on the left or right side of each shape (0.1° from the outside), with each display containing exactly two left-dot and two right-dot shapes. As the dot shared the background's color, it was likely to be perceived as a hole.

Procedure

Participants were instructed to search for the circle target and report on which of its sides (left or right) a black dot appeared. They were asked to respond as accurately as possible with no time pressure, and to guess if unsure. They were instructed to press the key Z with their left hands or M with their right hands on the computer keyboard if the dot appeared on the left or on the right, respectively. Each trial began with the fixation display for 1000 ms, followed by the cue display for 100 ms and then again by the fixation display for 50 ms. Then, the search display appeared for 85 ms. A new trial began following the participant's response or after 4000 ms, whichever came first. Following an incorrect response, participants heard an error beep (225 Hz) for 300 ms.

Design

The experiment consisted of 64 practice trials, followed by eight blocks of 80 trials each. All-difficult (25%), all-easy (25%) and mixed-difficulty (50%) search trials were randomly mixed within each block of trials. Conditions of onset-cue location, target location and location of the black dot in each shape (left or right) were equiprobable and randomly mixed within each block of trials. Thus, the cue location was not predictive of the target location. On mixed-difficulty trials the cue appeared randomly at each of the four locations independent of what object appeared at each location, thus producing twice as many easy-cued trials as difficult- and target-cued trials.

Results

Cue validity effects

Mean accuracy rates for each search condition are presented Fig. 3 separately for valid- and invalid-cue trials. An analysis of variance (ANOVA) with cue validity (valid vs. invalid) and search difficulty (all-easy, mixed, all-difficult) as factors was conducted on mean accuracy rates. The main effects of cue validity and search difficulty were

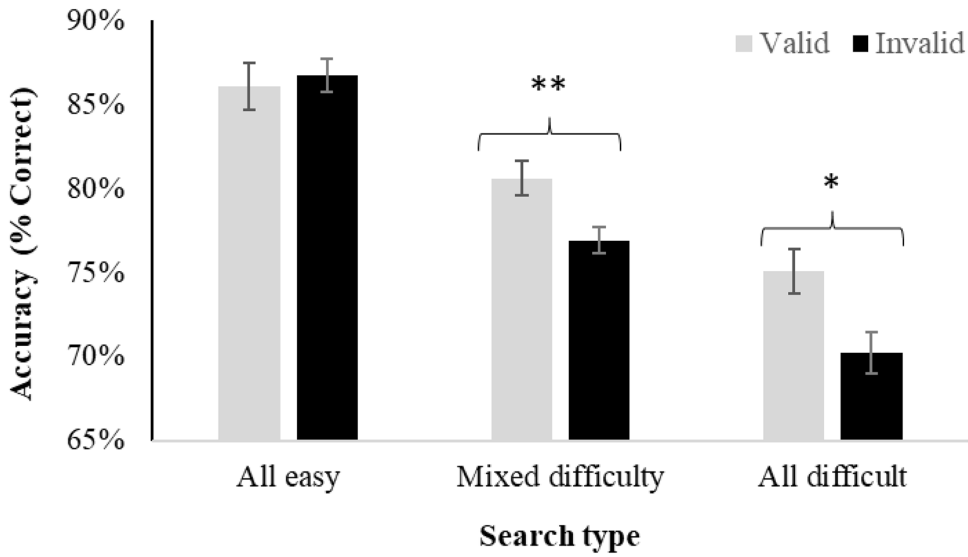


Fig. 3 Mean search performance accuracy (in percentage) on valid- and invalid-cue trials as a function of the search condition: easy (all distractors are easy), mixed difficulty (two easy distractors and one difficult distractor appear in the same display) and difficult (all distractors are difficult). Error bars represent condition-specific, within-subject standard errors (Morey, 2008)

significant, $F\ (1, 20) = 7.30$, $p = 0.01$, $\eta^2_p = 0.27$, and $F\ (2, 40) = 53.08$, $p < 0.0001$, $\eta^2_p = 0.73$, respectively. The interaction between the two factors was also significant, $F\ (2, 40) = 5.91$, $p = 0.006$, $\eta^2_p = 0.23$, indicating that the cue validity effect was larger on mixed-difficulty than on all-easy trials, $F(1, 20) = 8.78$, $p = 0.008$, $\eta^2_p = 0.31$, but similar on all-difficult and on mixed-difficulty trials, $F < 1$. The cue validity effect was significant in the all-difficult and mixed-difficulty conditions, $F(1, 20) = 7.78$, $p = 0.01$, $\eta^2_p = 0.28$ and $F(1, 20) = 10.19$, $p = 0.005$, $\eta^2_p = 0.34$, respectively, and non-significant in the all-easy condition, $F < 1$.

Planned comparisons showed that in the mixed-difficulty condition, accuracy was lower when the difficult than when an easy distractor was cued, $M = 74.4\%$, SD = 1.1% vs. $M = 78.1\%$, SD = 0.8%, $t(20) = 2.82$, $p = 0.01$, Cohen's $d = 0.45$, with poorer performance in both conditions relative to the valid-cue condition, $t(20) = 4.22$, $p = 0.0004$, Cohen's $d = 0.7$, and $t(20) = 2.03$, $p = 0.05$, Cohen's $d = 0.3$, respectively.

Effects of search difficulty on valid-cue trials

On valid-cue trials, the effect of search difficulty was significant, $F\ (2, 40) = 18.91$, $p < 0.0001$, $\eta^2_p = 0.49$, with fewer errors the easier the search. Planned comparisons showed that accuracy was higher on all-easy than on mixed-difficulty trials, $t(20) = 3.07$, $p = 0.006$, Cohen's $d = 0.56$, and on mixed-difficulty than on all-difficult trials, $t(20) = 3.48$, $p = 0.002$, Cohen's $d = 0.55$.

Discussion

The results of Experiment 1 replicated the main findings reported by Lamy et al. (2018), using brief displays and relying on performance accuracy. First, the cue validity effect increased as overall target–distractor similarity increased. Second, in the mixed-difficulty condition, accuracy was higher when an easy than when a difficult distractor was cued. Third, performance on valid-cue trials became poorer as search difficulty increased.

As previously explained, the first two findings are in line with both PAF and the Attentional Dwelling hypothesis, but are incompatible with either the contingent capture (e.g., Folk et al., 1992) or fast disengagement (e.g., Theeuwes, 2018) accounts. Notably however, unlike in Lamy et al. (2018), the cue validity effect was not significant when all the distractors were easy in the present experiment. PAF predicts no cue-validity effect when target-nontarget discriminability is high enough. To explain why cue validity effects for all-easy trials were observed in Lamy et al., (2018, Exp.1) but not here, one may speculate that presenting the displays for short durations may have encouraged participants to maintain a stronger attentional set (thereby increasing the priority of the target relative to that of the easy distractors, hence the null effect). By contrast, to accommodate this finding, the Attentional Dwelling account would have to assume that disengaging attention from the cued easy distractor and moving it to the target incurred no cost at all—an unlikely conjecture (e.g., Posner & Petersen, 1990; Tsal, 1983).

As previously explained, several accounts are possible for the third finding. According to PAF, the cue increases the priority weight accruing to the target in all conditions of search difficulty, yet search difficulty still strongly determines how long it takes to resolve the competition. According to the standard interpretation (e.g., Folk et al., 1992; Gaspelin et al., 2016; Ruthruff et al., 2020; Theeuwes, 2010), a first possibility is that after participants' attention is drawn to the cue and the target appears at its location, they may scan the surrounding distractors in order to verify that the object in the focus of their attention is indeed the target—a

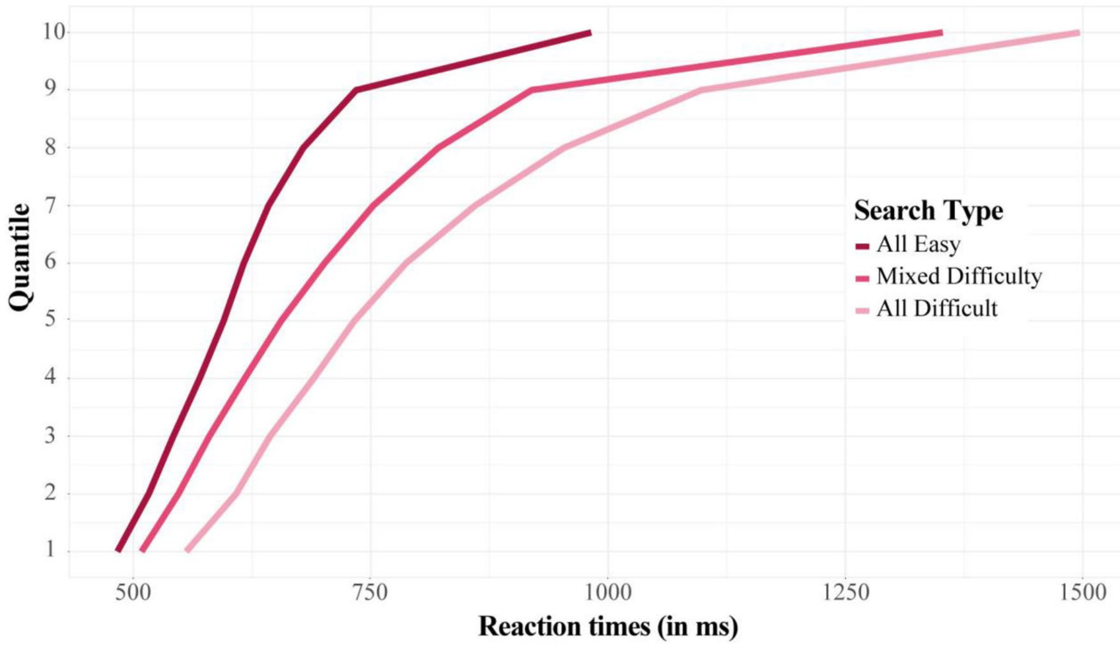


Fig. 4 Vincentized reaction time distribution (quantile means) in all-easy, mixed difficulty and all-difficult search conditions, on valid-cue trials (i.e., in which the target appeared at the cued location) in Experiment 2

double-checking procedure that should take more time the more similar the surrounding distractors are to the target. Because the search displays were presented very briefly, it is unlikely that participants had enough time to engage in such a behavior. However, since the search displays were not masked, the possibility that participants may have scanned the traces of the search display in iconic memory cannot be entirely dismissed. Second, the effect of search difficulty on valid-cue trials may result from the trials in which the cue did not capture attention: on these trials, the cue does not bias attention and performance should be poorer the more difficult the search, on valid- and invalid-cue trials alike. The objective of Experiment 2 was to further explore these two alternative accounts.

Experiment 2

In Experiment 2, we focused on the finding that performance on valid-cue trials deteriorates as search difficulty increases, and tested PAF's interpretation against alternative accounts. According to the standard interpretation, cue validity effects indicate that on a sizeable portion of the trials, the cue triggers a shift of attention to its location before the search display appears. Accordingly, on valid-cued trials in which the cue *did* capture attention, attention should be already focused at the target location when the search display appears (see Fig. 1). On some of these trials, participants may nevertheless move their attention around before selecting the target, whereas on the remaining trials, they may respond to the target in the focus of their attention, without searching any further. The latter subset of trials (i.e., trials in which the cue brought the target location into the focus of the participants' attention and these immediately selected the target) should be the fastest trials. Thus, according to the standard interpretation, performance should be equally fast in the three conditions of search difficulty on these (fastest) trials. By contrast, according to PAF, distractor competition should modulate search performance across the RT distribution, that is, even on the fastest valid-cue trials.

To test these predictions against each other, we conducted new analyses on the data from Lamy et al.'s (2018) first experiment. This experiment was identical to Experiment 1 except that the search display was presented until response and responses were speeded. We plotted the distribution of the trials in which the target appeared at the same location as the cue. To do that, we used a vincentization procedure (Ratcliff, 1979): quantiles of RT distributions were computed for each participant, each summarizing 10% of the cumulative RT distribution, and were then averaged to produce the group distribution (Rouder & Speckman, 2004). This nonparametric procedure was applied on valid-cue trials separately for the all-easy, mixed-difficulty and all-difficult conditions. As is clear from Fig. 4, the effect of search difficulty was present across the RT distribution. In particular, it was already large and significant for the 10% fastest trials, F (2, 46) = 47.59, $p < 0.0001$, $\eta^2_p = 0.67$. Thus, to explain these data by invoking the argument that the effect came from trials in which the cue failed to capture attention, one would have to assume that the cue captured attention on much fewer than 10% of the trials. Such a conjecture would considerably weaken the relevance of cue validity effects as indicators of involuntary capture of attention.

However, one could still claim that some of the participants were rarely if ever captured by the cue, and for these, even the fastest valid-cue trials should be slower the more difficult the search. To examine this possibility, we considered participants with a cue validity effect smaller vs. larger than the median (median = 78 ms), separately. If the alternative account is correct, the effect of search difficulty on the fastest valid-cue trials should be observed for participants with cueing effects below the median (low-capture participants), but not for participants with cueing effects above the median (high-capture participants, mean cuing effect = 117 ms): for these, it is conservative to expect that attention was captured on at least 10% of the trials. However, the effect of search difficulty on the fastest 10% valid-cue trials was highly significant for the high-capture group, $F(2, 22) = 16.70$, $p < 0.001$, $\eta^2_p = 0.60$. The vincentized data for this group are presented in the "Appendix".

Taken together, the outcomes of the new analyses presented here strongly support PAF's interpretation, according to which the cue and the objects in the search display jointly determine how fast the competition for selection is resolved, even on valid-cue trials.

Experiment 3

In Experiments 1 and 2, we relied on overall search performance in order to assess the relative priority at each location in the search display. However, as search performance is not determined solely by where the search begins but also by subsequent processes, different accounts for the findings are possible. Consider, for instance, the finding that performance is better when an easy vs. a difficult distractor is cued in the mixed-difficulty condition (Fig. 1, middle vs. lower panel). According to PAF, the cued location enjoyed lower priority when it was occupied by an easy than by a difficult distractor. By contrast, according to the Attentional Dwelling hypothesis, the cued location enjoyed the same priority level in both conditions, and the difference in performance reflected a later operation, namely, how long it took to disengage attention from the cued distractor.

In Experiment 3, we sought a more direct measure of attentional priority, that would allow us to assess the relative priority at each location across the search display (rather than inferring it indirectly, based on responses made to the target,) and to test PAF against competing accounts. To do that, we used the dot-probe paradigm. Previous studies have used the dot-probe paradigm in order to obtain a snapshot of the distribution of attention during visual search (e.g., Kim & Cave, 1995; Lamy, Tsal & Egeth, 2003; Watson & Humphreys, 2000; see also Gaspelin, Leonard & Luck, 2015, for a novel variation of this paradigm). In a typical dot-probe study, the search display is immediately followed, on a portion of the trials, by a probe that is equally likely to appear at each of the previously filled locations. Participants are required to make a non-speeded response to the target on each trial, but also to first press a key as fast as possible whenever they detect a probe. The crux of this paradigm is that, because participants do not know on any given trial whether they will have to respond to the target (probe-absent trials) or to the probe (probe-present trials), they search for the target on both types of trials. Therefore, probe-detection performance should provide an indication of how often the first shift of attention landed at each location, during search.

In Experiment 3, we combined the spatial cueing and dot-probe paradigms. It was similar to Experiment 1, with two notable changes. A probe immediately followed the offset of the search display on half of the trials and participants had to respond as fast and accurately as possible to its presence before making their non-speeded response to the target. In addition, only the mixed-difficulty condition was included. A sample sequence of events is presented in Fig. 5.

According to the Attentional Dwelling hypothesis, after the cue appears, attention is allocated to the cue location on most trials (capture trials) and the cue fails to capture attention on the remaining trials (no-capture trials). On capture trials, attention remains at the cued location until the search display appears and is then disengaged from that location more or less slowly, depending on how similar the distractor appearing at the cued location is to the target. Thus, on those trials, performance at detecting a probe flashed shortly enough after the search display, should be best when the probe appears at the cued location, irrespective of what object occupies this location. On no-capture trials, probe-detection performance should be better the more similar the object on which the probe lands, is to the target, irrespective of where the cue appeared. Thus, the Attentional Dwelling hypothesis predicts that probe detection performance should be influenced by (a) whether or not the probe appears at the cued location, and (b) what type of object is probed, but should not depend on (c) what type of object is cued (that is, what object is cued and what object is probed should not interact). Finally, if an onset cue most often captures attention (as postulated e.g., Gaspelin et al., 2016; Theeuwes, 2018), probe detection performance when an easy distractor is cued should be better when the probe appears at the location of this distractor than when it appears at the target's location.

While PAF shares the first two predictions, it is at odds with the last two. First, it predicts that what type of object is cued should affect the competition, that is, how strong the

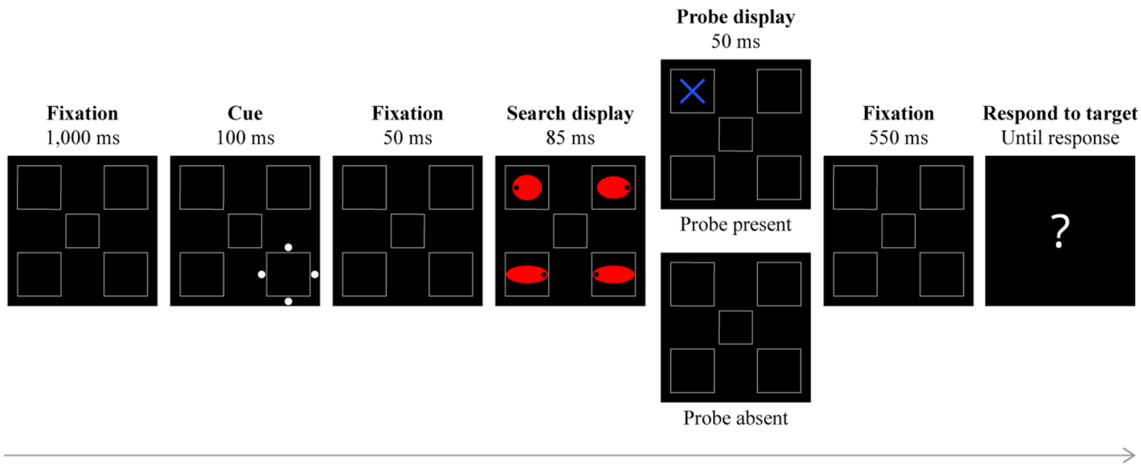


Fig. 5 Sample sequence of events in Experiment 3. It was similar to Experiment 1 except that a probe-detection task was added. Prior to responding to the target, participants had to press a key within 600 ms when the probe was present (probe-present trials, 50% of all trials) and to refrain from pressing this key when the probe was absent (probe-absent trials, 50% of all trials). The stimuli are not drawn to scale

priority advantage of the winning object is, and therefore, that it should modulate probe detection performance. More specifically, PAF predicts that the extent to which the identity of the probed object (target, easy distractor or difficult distractor) modulates probe-detection performance should be maximal when the target is cued (with fast resolution of the competition), intermediate when an easy distractor is cued and minimal when the difficult distractor is cued (with slow and inconsistent resolution of the competition). Second, PAF predicts that probe detection performance when an easy distractor is cued should be better when the probe appears at the location of the target than when it appears at the cued easy distractor's location (see Fig. 6).

Methods

Participants

Participants were undergraduate students who participated for course credit and reported normal or corrected-to-normal visual acuity. The final sample included 11 females and 10 males (age $M=25.73$, SD = 3.76) after five participants were replaced by new participants because their performance deviated from the group's mean by more than 2 standard deviations: % of misses on the probe task (one participant, 79% vs. $M=14.6\%$, SD = 9.1%), % of false alarms on the probe task (three participants, 40.6%, 44.5% and 35.7% vs. $M=7.8\%$, SD = 6.3%) and % of errors on the search task on probe-absent trials (one participant, 48.2% vs. $M=25.8\%$, SD = 8.9%). No participant met the exclusion criterion on % errors on the search task when the probe was present ($M=33.4\%$, SD = 10.1%).

Apparatus, stimuli, procedure and design

The apparatus, stimuli, procedure and design were similar to those of Experiment 1, except for the following changes. Only the mixed-difficulty condition was included. All shapes in the search display were ellipses, subtending $1.4°\times1.21°$ for the target, $1.6°\times1.06°$ for the high-similarity (difficult) distractor and $2°\times0.84°$ for the two low-similarity (easy) distractors. The target was defined as the object that most resembled a circle.[1] The probe was a small blue X (CIE-L*ab = 32.3, 79.2, -107.9) subtending 0.3° inside.

On 50% of the trials (probe-present trials), a probe appeared for 50-ms at the center of one of the four possible stimulus locations, immediately following the search display offset. Then, the fixation display appeared for 550-ms, followed by a question mark. On the remaining 50% of the trials (probe-absent trials), the fixation display replaced the probe display and thus appeared for 600 ms. Participants were instructed to report the presence of the probe, as quickly as possible within the 600-ms response window, by pressing "0" on the numerical keypad using their right-hand index fingers, and to respond to the target after the

[1] In both Gaspelin et al.'s study (2016, Exp.7) and our replications of their experiment (e.g., Exp.1 of the present study), similarity to the target and surface size were confounded, because the target was larger than difficult distractors, which were larger than easy distractors. In addition, when the search display was presented briefly (in Exp.1), some participants reported that in the context of the horizontal ellipses, the perfect circle appeared to be a vertical ellipse. This illusion may have rendered the instruction to look for a perfect circle difficult to follow. To address these issues, all objects were horizontal ellipses occupying the same surface and varying in elongation. Participants were instructed to search for the ellipse that was closest to a circle.

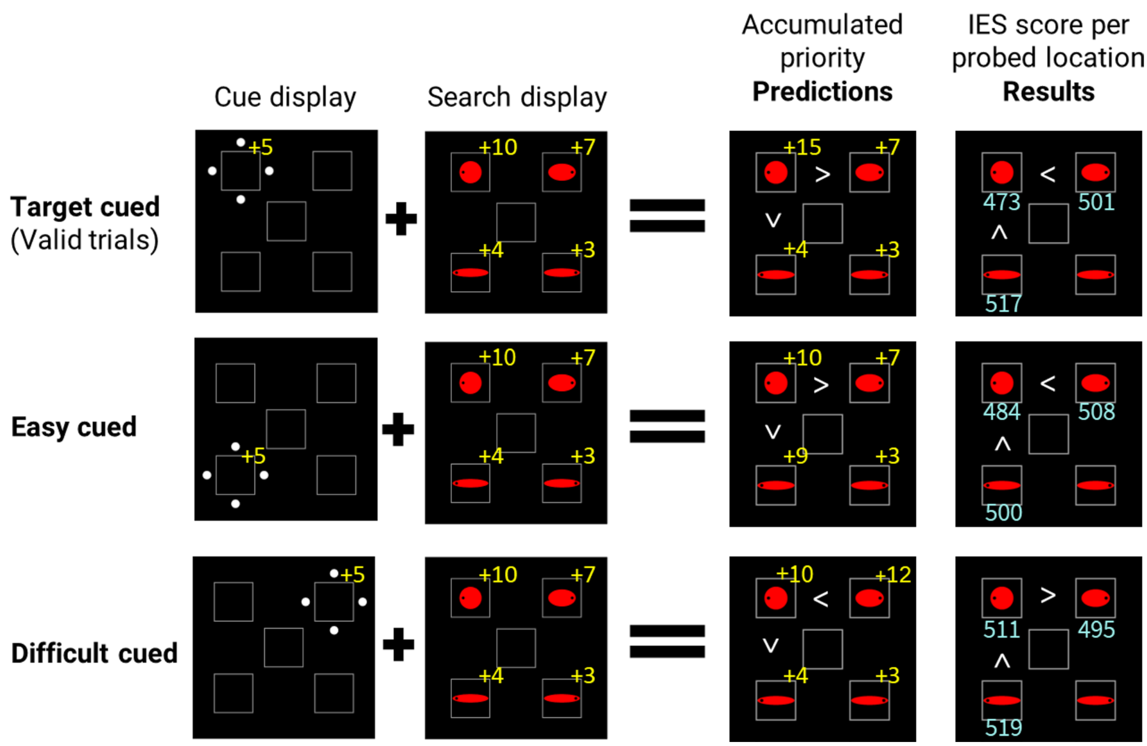


Fig. 6 Illustration of the predictions and results in Experiment 3. Each row represents a different cued-item condition (target cued, easy cued and difficult cued). The first two columns from the left show the sequence of events, with illustrative priority weights. The third column shows the accumulated priority at each location. The last column shows the IES (turquoise numbers) from Experiment 3 for each probed-item condition (probe on target, easy or difficult). The pattern of results closely conformed to PAF's predictions: the higher the priority, the better the performance (i.e., the lower the IES). In particular, in the easy-cued condition, although the easy distractor's location received extra priority from the cue, its accumulated priority did not exceed the target's, hence the shorter IES in response to the probe when it appeared at the target's location vs. at the easy distractor's location

question mark appeared (by pressing "Z" for left, and "X" for right, using their left hands). The error beep was sounded if a participant's response was wrong for either the probe or the search task.

The experiment started with two 15-trial practice blocks. In the first practice block, participants were required to respond only to the target. The second practice block was similar to the experimental blocks: the probe appeared on 50% of the trials and participants responded first to the probe and then to the target. There were nine experimental blocks of 96 trials each. On probe-present trials, the probe was equally likely to appear at each of the four possible locations. All conditions were randomly mixed within each block of trials.

Results

Search task performance

Performance on the search task was significantly impaired when participants also had to respond to the probe (probe-present trials) relative to when they did not, F (1, 20) = 34.89, $p < 0.0001$, $\eta^2_p = 0.63$. To verify that we replicated the findings observed in the mixed-difficulty condition of Experiment 1, we first analyzed performance on the search task when the probe was absent and participants correctly refrained from hitting the zero number-key (92.2% of the trials). Mean accuracy rates are presented in Fig. 7.

A one-way ANOVA with cued object (target, easy distractor, difficult distractor) as a within-participant factor and accuracy as the dependent measure revealed a significant main effect of cued object, $F(2,40) = 18.26$, $p = 0.0001$, $\eta^2_p = 0.47$. Follow-up analyses revealed that performance was better when the target was cued than when either an easy distractor, $t(20) = 4.36$, $p = 0.0003$ Cohen's $d = 0.77$, or a difficult distractor, $t(20) = 4.67$, $p = 0.0001$, Cohen's $d = 1.19$, was cued, with significantly higher accuracy in the former than in the latter condition, $t(20) = 2.7$, $p = 0.01$, Cohen's $d = 0.44$.

Probe-task performance

Probe-absent trials were excluded from all the following analyses. Preliminary analyses on probe-present trials

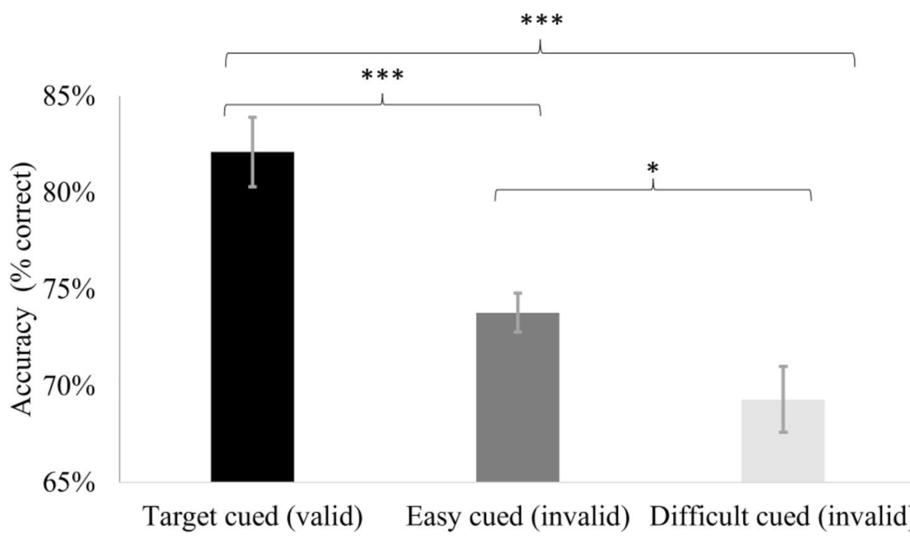


Fig. 7 Mean accuracy rates (in percentage) on the target search task in Experiment 3 as a function of which object was cued (target, easy or difficult). Error bars represent condition-specific, within-subject standard errors (Morey, 2008)

Table 1 Mean reaction times (in milliseconds), accuracy rates (in percentage) and inverse efficiency scores (IES, in milliseconds) on the probe detection task in Experiment 3, as a function of cued object (target, easy distractor or difficult distractor) and probed object (target, easy distractor or difficult distractor)

	Probe on target		Probe on easy		Probe on difficult	
RTs						
Target cued	418	[3]	427	[3]	429	[5]
Easy cued	415	[2]	420	[3]	421	[4]
Difficult cued	425	[3]	426	[3]	417	[3]
Accuracy						
Target cued	89.6%	[1.4%]	84.1%	[1.3%]	86.7%	[1.8%]
Easy cued	86.8%	[0.8%]	85.7%	[1.0%]	84.5%	[1.0%]
Difficult cued	85.8%	[1.8%]	84.2%	[1.3%]	86.0%	[1.1%]
IES						
Target cued	473	[9]	517	[8]	501	[13]
Easy cued	484	[5]	500	[8]	508	[8]
Difficult cued	511	[15]	519	[10]	495	[8]

The numbers between square brackets represent condition-specific, within-subject standard errors (Morey, 2008). Note that the mean IES are different from the ratio of the mean RT by the mean accuracy score because this ratio was calculated separately for each subject and then averaged

indicated that there was no speed-accuracy trade-off, with a strong negative correlation between probe RTs and accuracy. We could thus integrate the two measures into a single measure, the Inverse Efficiency Score (IES; Townsend & Ashby, 1978), which is obtained by dividing the mean RT by the mean accuracy rate for each participant for each condition. It has been suggested that this measure can be useful to detect small effects, provided that the speed and accuracy data are also inspected (e.g., Vandierendonck, 2017). As is clear from a comparison of the probe-detection mean RTs, accuracy and IES presented in Table 1, all the relevant effects (i.e., the ranking of the scores within each row of Table 1) followed the same pattern on RTs and accuracy.

We conducted an ANOVA with cue-probe location (same vs. different) and probed object (target, easy distractor or difficult distractor) as within-subject factors, and IES as the dependent measure. The main effect of cue-probe location was significant, $F\ (1, 20) = 6.27$, $p = 0.02$, $\eta^2_p = 0.24$, with better performance when the probe appeared at the cued than at an uncued location. The main effect of probed object was also significant, $F(2, 40) = 7.60$, $p = 0.002$, $\eta^2_p = 0.28$, indicating that performance was better when the probe appeared at the location of the target than at the difficult distractor's location, $F(1, 20) = 9.25$, $p = 0.006$, $\eta^2_p = 0.32$, and was similar when the difficult vs. an easy distractor's location was probed, $F(1, 20) = 1.11$, $p = 0.3$, $\eta^2_p = 0.01$. There was no significant interaction, $F < 1$. These results confirm that, as predicted by both PAF and alternative accounts, probe detection performance was improved both when the probe appeared at the location of the cue and the more similar the probed object was to the target—although the numerical

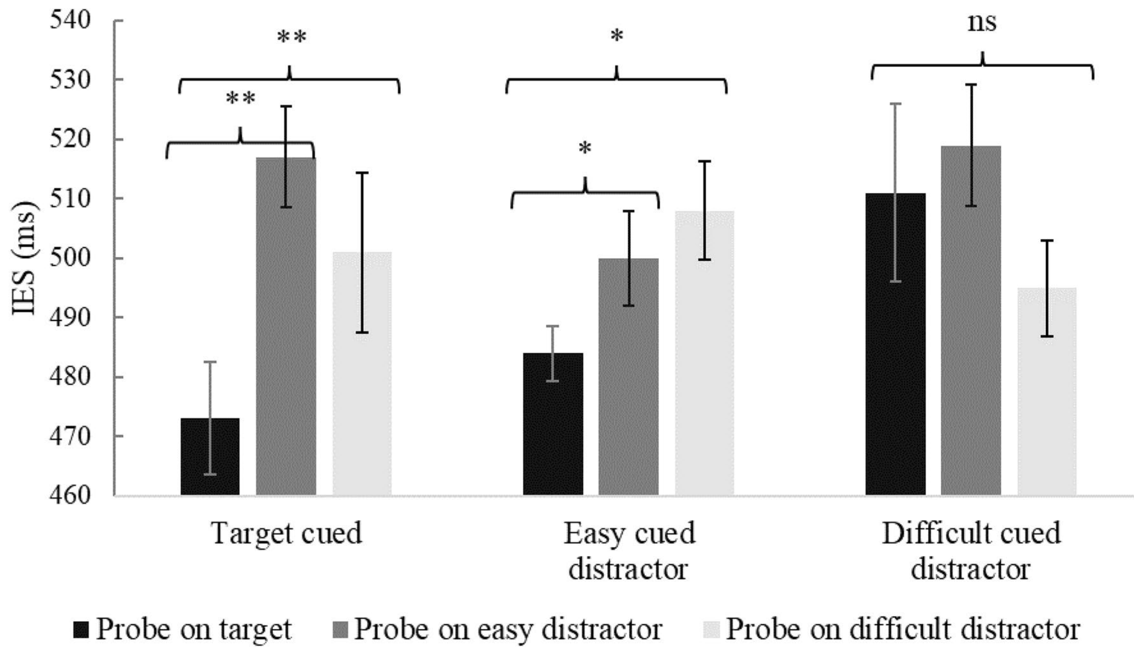


Fig. 8 Mean inverse efficiency scores (IES, in milliseconds) in Experiment 3, as a function of cued object (target, easy distractor or difficult distractor) and probed object (target, easy distractor or difficult distractor). Error bars represent condition-specific, within-subject standard errors (Morey, 2008)

difference between difficult—and easy-distractor probed trials (500 vs. 508 ms, respectively) did not reach significance.

Next, we conducted an ANOVA with cued object (target, easy distractor or difficult distractor) and probed object (target, easy distractor or difficult distractor) as within-subject factors, and IES as the dependent measure, excluding trials in which an easy distractor was probed and the other easy distractor was cued. The IES for each condition of cued object and probed object are presented in Fig. 8. This exclusion was necessary in order to perform a balanced comparison between the target and difficult distractor on the one hand, of which there was only one, and the easy distractor on the other hand, of which there were two.

The main effect of probed object was significant, $F(2, 40) = 4.55$, $p = 0.02$, $\eta^2_p = 0.19$, indicating that probe detection was better when the target than when either the difficult or an easy distractor was probed, $F(1, 20) = 3.43$, $p = 0.04$, $\eta^2_p = 0.15$ and $F(1, 20) = 9.05$, $p = 0.0006$, $\eta^2_p = 0.31$, respectively, with no difference between the latter two conditions, $F < 1$. Crucially, the interaction between cued object and probed object was significant, $F(4, 80) = 2.46$, $p = 0.05$, $\eta^2\text{p} = 0.11$, as predicted by PAF. Planned comparisons revealed that the effect of probed object was highly significant when the target was cued, $F(2, 40) = 5.69$, $p = 0.007$, $\eta^2_p = 0.22$, marginally significant when an easy distractor was cued, $F(2, 40) = 3.14$, $p = 0.05$, $\eta^2_p = 0.14$, and non-significant when the difficult distractor was cued, $F(2, 40) = 1.27$, $p = 0.29$, $\eta^2_p = 0.06$.

Finally, a planned comparison indicated that when the easy distractor was cued, probe detection was better when the target's location than when the easy (cued) distractor's location was probed, $t(20) = 2.19$, $p = 0.04$, Cohen's $d = 0.20$. This finding supports PAF's prediction.

Discussion

As was expected, the results of Experiment 3 replicated the findings observed in the mixed-difficulty condition of Experiment 1: the cue-validity effect on the search task was larger when the cued distractor in the invalid-cue condition was difficult than when it was easy. In addition, the results conformed to the predictions common to PAF and to the Attentional Dwelling hypothesis: both the cue location and the probed object's shape influenced probe detection performance. With regard to the latter finding, it is noteworthy that the expected advantage when the probe appeared at the location of the difficult vs. of an easy distractor showed only a numerical trend in the predicted direction. However, as is clear from Fig. 8, this advantage failed to emerge only on trials in which an easy distractor was cued, a finding that is entirely consistent with PAF's predictions (because according to PAF, the cue added some priority to the easy distractor's location on those trials).

The result that most strongly supports PAF's predictions against alternative models is that the effect of the probed object (namely, better probe detection performance when the target vs. the difficult or an easy distractor was probed) was modulated by what object was cued (target, difficult distractor or easy distractor). This finding indicates that the easier it was to resolve the competition (which was determined here by what object was cued), the larger the benefit when the probe appeared at the target's location relative to the difficult or easy distractors' locations.

In addition, we found that when an easy distractor was cued, performance was higher when the probe appeared at the location of the target than when it appeared at the cued easy-distractor location. This finding is in line with PAF's prediction that the target is most often the first object to receive attention when a cue not matching the current attentional set appears at the location of an easy distractor.

Our selection of the search display exposure duration and search-probe SOA in this experiment was guided by two objectives: maintain the overall accuracy rate on the search task above chance but below ceiling, and take a snapshot of the distribution of attentional priority shortly after the search display was presented to catch the first shift of attention. However, one may argue that during the 85-ms between search display onset and the probe onset, participants had time to shift their attention away from the cued easy distractor and redirect it to the target (e.g., Gaspelin et al., 2016; Ruthruff et al., 2020). According to this scenario, (1) in the easy-distractor-cued condition, attention was most often already focused on the target when the probe was flashed, hence the better probe detection performance at the target than at the cued (easy distractor) location (middle columns in Fig. 8). By contrast, (2) when the difficult distractor was cued, disengagement took longer and attention was redirected to the target only on a portion of the trials, hence the null effect of the probed object on probe detection (rightmost columns in Fig. 8). However, if attention was shifted to the target location within 85 ms when an easy distractor was cued, accuracy on search trials should be similar when the target was cued and when an easy distractor was cued—yet, this was clearly not the case (see Fig. 7).

Nevertheless, additional research with a time interval between the search display and probe onsets shorter than 85 ms may be useful to further test this alternative account.

General discussion

Spatial cueing effects have shaped attention theories, based on the premise that they provide a reliable indicator of attentional allocation. In this paper, we contrasted two interpretations of this effect. According to the canonical interpretation, better performance on valid- vs. invalid-cue trials indicates that the cue triggered a shift of attention to its location on a large proportion of trials. On the remaining trials—in which the cue failed to capture attention—search starts at the location of the highest-priority object in the search display, with no impact of the cue. Such interpretation implies a dichotomic view of attentional allocation: certain objects (salient objects or objects sharing the target-defining feature) capture attention, whereas others do not. This view has generated decades-long controversies over the question of which objects possess the intrinsic ability to capture our attention (e.g., Luck, Gaspelin, Folk, Remington & Theeuwes, 2021).

We suggested a different interpretation, based on the Attentional Priority Framework (Gabbay et al., 2019; Lamy et al., 2018; Toledano et al., 2021; Yaron & Lamy, 2021), which rests on two main tenets. The first is that, in line with the biased competition model (e.g., Desimone & Duncan, 1995; see also Barras & Kerzel, 2017), some objects enjoy more priority than others, but the strength of the competition prevailing in the visual field determines how likely these objects are to be selected, and how long it takes to resolve the competition for selection. The second tenet, which distinguishes PAF from previous models, is that priority weights accumulate at each location of the visual field across time, and attention is shifted to the location with the highest accumulated priority, at the moment relevant for selection. In the context of the spatial cueing paradigm, this entails that (a) the first attentional shift most often occurs after rather than before the search display appears and (b) although the cue and search items do not appear at the same time, they nevertheless compete. Thus, the impact of the cue is not all-or-none, and instead, interacts with the characteristics of the search display: it is larger the more difficult the search.

Summary of the study's novel findings

The findings of the present study supported PAF's predictions. In Experiment 1, we replicated the findings that Lamy et al., (2018; see also Gaspelin et al., 2016) reported for search speed with unlimited viewing, but measured search accuracy with brief displays: we found the cue validity effect from an irrelevant onset cue to increase with search difficulty and responses to be less accurate when the cued distractor was similar to the target than when it was dissimilar. Both findings are predicted by PAF and by the Attentional Dwelling hypothesis (Gaspelin et al., 2016), but are inconsistent with either the contingent capture (e.g., Folk et al., 1992) or fast disengagement (e.g., Theeuwes, 2018) accounts: these predict that spatial cueing effects should be unaffected by search difficulty.

Most importantly for the present purposes, we again found performance on valid-cue trials to deteriorate as search difficulty increased. This finding is predicted by PAF: on valid-cue trials, the target benefits from the cue priority across search difficulty conditions, but it should take more time to resolve the competition for selection, the more difficult the search. However, this finding can also be explained if one assumes, contrary to PAF, that attention is shifted to the cue before the search display appears. First, even though search may often start at the cued location, participants may scan the distractors to verify that the object in the focus of their attention is indeed the target—and this should take more time the more similar the distractors are to the target. Second, most proponents of the standard interpretation of spatial cueing effects would agree that the cue should fail to capture on at least some trials, and on these trials performance should be poorer the more difficult the search.

We refuted both arguments in Experiment 2. We reanalyzed the data from Lamy et al. (2018) and looked at the RT distribution on valid-cue trials. We reasoned that according to the standard interpretation, trials in which the cue captured attention and participants selected the target in the focus of their attention without further verifications should be the fastest trials, and on these, search difficulty should have no impact on performance. Yet, such impact was evident throughout the RT distribution (and was significant even for the 10% fastest trials), in line with PAF.

In Experiment 3, we tested novel predictions of PAF by combining the spatial cueing paradigm with a dot-probe paradigm that provided a proxy of the distribution of attention across the search display. On each trial, the target appeared among two easy and one difficult distractor (mixed-difficulty condition). Both PAF and competing accounts predict that probe performance should be better at the cued vs. uncued locations and when the probe appears at the location of an object that is similar vs. dissimilar to the target. However, only PAF predicts that *what object* is cued (i.e., how similar the cued object is to the target) should also affect probe detection performance, because it should modulate this object's priority. The results confirmed this prediction. In addition, we found that when the cue appeared at the location of an easy distractor, probe detection performance was better at the target's than at the cue's location—in line with PAF's prediction that search should most often start at the target location when the combined weight of the cue and cued distractor is too low to override the target's weight.

Bridging the gap between stimulus- and goal-driven accounts of attentional priority

Although the experiments presented here all used cues that did not match the target's defining feature, PAF can readily accommodate the findings on which the contingent-capture account relies (see Büsel et al., 2018 for a review). According to PAF, the priority boost from a matching cue suffices to create strong competition from an easy distractor, whereas the priority boost from a non-matching cue does not. This explains why during easy search (e.g., search for a red target among gray distractors), target-matching cues (e.g., red cues) produce large cue-validity effects, whereas non-matching cues (e.g., onset cues) do not. Thus, PAF bridges the gap between stimulus- and goal-driven accounts of attentional priority. On the one hand, it assigns a role for both salience and search goals in determining attentional priority. On the other hand, however, it stipulates that even the object category held to be most salient, abrupt onsets (e.g., Jonides & Yantis, 1988), can be entirely overridden by goal-directed factors (e.g., during easy search).

Priority accumulation vs. attentional dwelling

As noted by Ruthruff et al. (2020), "Attentional Dwelling following capture and priority accumulation are both plausible mechanisms and both fit much of the data…there is no obvious reason why they could not both contribute to capture costs" (p. 3062). Indeed, PAF does not dispute that it should take more time to disengage one's attention from the location of a distractor, the more closely this distractor resembles the target. However, the two accounts differ in how they construe the effect of search difficulty on the allocation of attention. Gaspelin et al. (2016) and Ruthruff et al., (2020) invoked the notion of *latent* capture to explain why onset cues produce cue-validity effects during difficult search but not during easy search. They claimed that because attention can be disengaged very fast from the cued location "easy visual search provides an insensitive test for stimulus-driven capture by abrupt onsets: even though onsets truly capture attention, the effects of capture can be latent" (Gaspelin et al., 2016).[2] Accordingly, they suggested that search difficulty modulates only the *cost* of capture (disengagement speed), but not the *probability* of capture. By contrast, PAF suggests that search difficulty modulates the probability that search should start at the cued location: when search is easy, where the cue appears has little bearing on what location will receive attention, whereas when search is difficult, the cue strongly determines what location wins the competition for selection.

[2] Hilchey and Pratt (2019) also claimed to expose latent capture by onset cues through statistical learning. Relying on the notion of learned predictiveness (LePelley, Mitchell, Beesley, George & Wills, 2016), they reasoned that participants should pick up on the statistical regularities that exist between an onset cue and the target location only if this onset cue reliably captures attention. However, the learned predictiveness principle stipulates that "attention is biased toward stimuli that predict their consequences reliably" (LePelley et al., 2016) and not that associative learning is possible only for attended stimuli. Thus, it is unclear whether there was "latent capture" by the onset cue before learning occurred.

What event triggers attentional deployment?

An important assumption of PAF is that some event must trigger the deployment of attention to the highest-priority location: if attentional priority weights accumulate at each location across time, such accumulation must stop at some point and a signal must indicate when attention should be shifted to the winner of the competition for selection. That we should wait for clues indicating that the appropriate moment has arrived for us to deploy our limited attentional resources to the highest-priority location, is a reasonable assumption: it would shield our attention against relentlessly shifting to potentially irrelevant events. The theory does not yet specify what the triggering event might be, yet two main candidates that are not mutually exclusive, come to mind.

First, temporal expectations may indicate the appropriate time for deploying attention. For instance, in the present study (as well as in Lamy et al., 2018), the temporal sequence was fixed across trials, such that participants could rely on such regularity and deploy their attention at the time when the search display was expected to appear. This suggestion is consistent with previous research showing that temporal expectations are powerful determinants of attentional deployment (see Nobre, 2010 for review). Second, the stimulus characteristics of the search display may signal that the time has come to deploy attention, provided that these can be easily discriminated from the stimulus characteristics of the events that preceded the search display. For instance, here, participants may have waited for filled red shapes to appear to deploy their attention to the highest-priority location.

Findings from a recent study by Yaron and Lamy (2021) provide support for the latter possibility. In a spatial cueing paradigm, the stimuli in the cue and search displays were colored arrows that were either small or large, and participants were asked to search for a color-defined target. In the cue display, one arrow shared the target color (target-color matching cue). In the strong-context group, one arrow size was consistently paired with the cue display and the other with the search display. Participants could thus wait for the arrows characterizing the context relevant for selection to deploy their attention. In the weak-context group, size-to-display pairing was random, and participants could only rely on the order of the displays (the search display always came after the cue display) to deploy their attention. The results showed that participants more often shifted their attention to the cue itself instead of waiting for the search display, in the weak- than in the strong-context condition (see Yaron & Lamy, 2021, for details about how attentional deployment was measured).

Although these findings are strongly suggestive of the role of stimulus-based contextual information in the timing of attentional deployment, further supporting evidence is required, especially using non-matching cues.

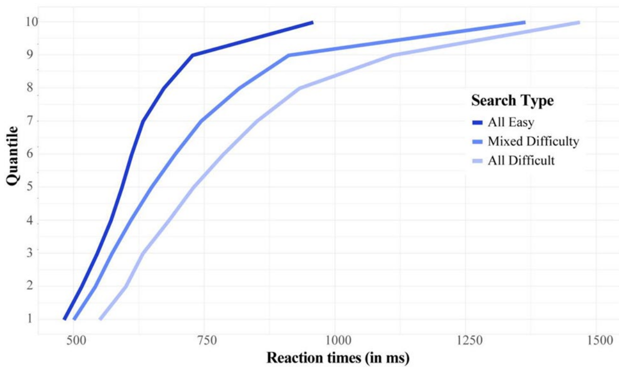
Conclusions

The evidence presented here provides novel support for the Priority Accumulation Framework (PAFGabbay et al., 2019; Lamy et al., 2018; Toledano et al., 2021; Yaron & Lamy, 2021). This model has two central implications for studies of attentional capture. First, it suggests that the question "Does object category X automatically capture our attention?", which has motivated intense empirical research and theoretical debate, is an ill-posed question. Specifically, the attempt to respond by "yes" or "no" is futile, because whether a given object receives attention depends on the competition context. Such context is determined by what other objects surround the critical stimulus (Desimone & Duncan, 1995), but also by what happened at each location of the visual field in the recent past. In this sense, "the notion of attention-as-capturable leads to a forced dichotomy with respect to the occurrence of capture" (Anderson, 2021, p.1), a dichotomy that perpetuates the debate (see Lamy, 2021, for a similar argument).

Second, PAF raises a question that has been largely neglected so far: is attention automatically moved to the ever-changing location with the highest priority, at any given moment? Or does the deployment of attention to the highest-priority location await a trigger that signals the appropriate moment? While most researchers implicitly assume the former to be true, as is clear from the canonical interpretation of spatial cueing effects, PAF assumes the latter. Additional research is needed to further explore this important issue.

Appendix

Vincentized reaction time distribution (quantile means) in all-easy, mixed difficulty and all-difficult search conditions, on valid-cue trials (i.e., in which the target appeared at the cued location) in Experiment 2 for participants with an overall cuing effect *larger* than the median.



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Declarations

Conflict of interest Maya Darnell declares that she has no conflict of interest. Dominique Lamy declares that she has no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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