Top-down, bottom-up and selection-history-based control of attention: A failed trichotomy? The case of Priming of pop-out (PoP)

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RUNNING HEAD: Selection history and attentional guidance

Keywords: Selection history, priming of pop-out, attentional guidance, visual search.

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Abstract

When we search for an object, our performance is strongly influenced by our past experience. In the lab, this influence has been demonstrated by investigating a variety of phenomena, including inter-trial priming, statistical learning and reward history, and collectively referred to as selection history. The resulting findings have led researchers to claim that selection history guides attention, thereby challenging the prevailing dichotomy, according to which attentional priority is determined solely by top-down goals and bottom-up salience. The objective of the present review is to reexamine this claim by evaluating the evidence that specifically pertains to the role of selection history in attentional guidance, rather than in later processes occurring after the target is found. We focus on one selection history phenomenon, priming of pop-out (PoP). After demarcating the conditions under which PoP effects can be dissociated from top-down effects, we review the relevant findings, while distinguishing between the main experimental rationales adopted to address this question. We conclude that despite some inconsistencies that should be resolved by further research, most of the extant empirical evidence does not support the idea that PoP affects attentional priority. We call for similar reevaluations of other selection history phenomena and caution against burying the bottom-up vs. top-down dichotomy too hastily.

In a very influential study, Maljkovic and Nakayama (1994) reported a counter-intuitive observation. They asked their subjects to perform a simple task: to search for a uniquely colored object (or color singleton) that could be either the only red object among objects that were all green, or the only green object among objects that were all red (see Figure 1). This task is so easy that the target is said to pop out, that is, it is immediately spotted, no matter how many distractors surround it. In addition, the target's actual color should not matter, because it suffices to search for the most salient object, the odd-one-out, in order to find it. Yet, the authors found responses to be considerably faster when the target happened to have the same color on consecutive trials than when its color changed.

This effect, which was called priming of pop-out (or PoP), has been extensively replicated (see e.g., Kristjansson & Campana, 2010; Lamy & Kristjansson, 2013 for reviews) and extended to target singletons differing from distractors on a large variety of dimensions such as shape (e.g., Lamy et al., 2006; Pinto, Olivers & Theeuwes, 2005), orientation (e.g., Hillstrom, 2000; Lamy, Yashar & Ruderman, 2013), brightness (e.g., Becker, 2008a; 2008b), size (Huang, Holcombe, & Pashler, 2004; Kristjansson, 2006) and facial expression of emotion (Amunts, Yashar & Lamy, 2014; Lamy, Amunts, & Bar-Haim, 2008).

Since then, a myriad of additional effects of memory on visual search have been documented and are typically referred to as "selection history" (e.g., Brascamp, Blake & Kristjansson, 2011) or "attentional priming" effects (e.g, Kristjánsson & Ásgeirsson, 2019). These include other *intertrial priming* effects, such as dimension priming (e.g., Found & Müller , 1996; Olivers & Humphreys, 2003), the distractor preview effect (e.g., Ariga & Kawahara, 2004; Wan & Lleras, 2010), location priming (Maljkovic and Nakayama, 1996; Geyer & Müller , 2009) and singleton priming (Lamy, Bar-Anan & Egeth, 2008; Lamy, Carmel, Bar-Anan & Egeth, 2006), *statistical learning* effects, such as contextual cueing (Chun & Jiang, 1998; Sisk, Remington & Jiang, 2019), and probability cueing (e.g., Geng &

Behrmann, 2005; Ferrante et al., 2018), and *reward history* effects (Della Libera & Chelazzi, 2006; Failing & Theeuwes, 2018).

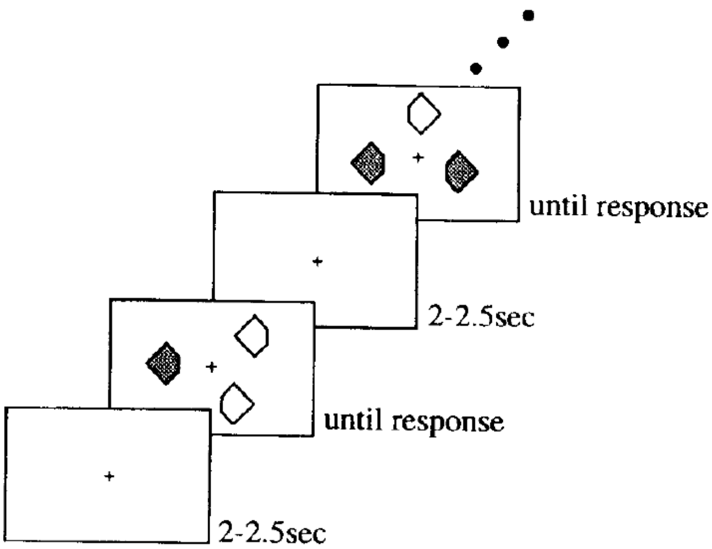

Figure 1. Sample sequence of trials in a typical PoP experiment (Maljkovic & Nakayama, 1994). The target is the diamond with the unique color.

A challenge to the bottom-up vs. top-down dichotomy in attentional guidance

The recent surge of research showing effects of memory on visual search has promoted the view that selection history strongly influences attentional priority (e.g., Awh et al., 2012; Belopolsky, 2015; Theeuwes, 2013; see also Anderson, 2016; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Goldstein & Beck, 2018; Jiang, 2018; Theeuwes, 2018; Todd & Manaligod, 2018; Wolfe, 2019; 2020). This is a far-reaching claim because it challenges a well-entrenched dichotomy, according to which two factors determine attention priority: stimulus salience (bottom-up or stimulus-driven guidance) and task goals (top-down or goal-directed guidance). Surprisingly however, the demise of the traditional dichotomic view has been widely and quickly embraced by the field, to the point where visual search models most identified with the distinction between bottom-up and top-down guidance of attention have come to incorporate selection history as a separate source of attentional guidance (e.g., Guided Search, Wolfe & Horowitz, 2017).

However, before we seal the fate of this “failed” dichotomy (Awh et al., 2012), it is important to review the evidence that specifically demonstrates that selection history influences attentional guidance, that is, the relative priority weights assigned to different objects in the visual field – rather than later processes, such as selection and response-related processes. The question arises because, as was the case in Maljkovic and Nakayama’s (1994) seminal experiments, selection history effects often manifest as faster search performance on a given trial when some aspect of the search array repeats from a previous trial (e.g., Chun & Jiang 2003; Druker & Anderson, 2010; Maljkovic & Nakayama, 1996; Sha & Jiang, 2016). Yet, faster performance on repetition trials does not necessarily indicate that the target is found earlier, and may instead denote that the target is processed faster *after* it is found.

In addition, selection history refers to a heterogenous collection of phenomena, and there is no a priori reason to consider that all the types of memory effects that are currently placed under the selection-history umbrella affect the same processes, as is typically assumed (Awh et al., 2012; Horowitz & Wolfe, 2017; Kristjansson & Asgeirsson, 2019) – and in particular, that they all affect attentional priority.

Objective of the present review

In the present review we evaluate the evidence that specifically pertains to the issue of whether selection history modulates attentional priority. We focus on one selection history phenomenon, PoP (Maljkovic & Nakayama, 1994), because it has been the most intensively studied, but the methodology used here can readily be applied to other instances of selection history. We first summarize the different accounts that were suggested in order to explain the mechanisms underlying PoP. We show that while these accounts have mainly contrasted perceptual and post-selective views, there has been a less structured effort to distinguish attentional guidance from later perceptual/selective processes - a state of affairs that prevails also for other selection history phenomena (see e.g., Sisk, Remington & Jiang, 2019 who contrasted an perceptual vs. post-perceptual locus of contextual cueing). Then, we delineate the phenomenon under scrutiny, by considering under what conditions PoP effects can be dissociated from top-down effects. We then proceed to review the evidence that is relevant to the question of whether PoP modulates attentional guidance, while distinguishing between the experimental rationales adopted to address this question. We conclude by reevaluating the current consensus on selection history's status as a source of attentional guidance and by suggesting guidelines for further research.

Theoretical accounts of PoP

Since Maljkovic and Nakayama's (1994) seminal study, researchers have actively debated the mechanisms underlying PoP. The models that have emerged from this debate fall into three broad categories, often referred to as the *independent feature-weighting*, *episodic retrieval* and *hybrid* accounts (see Milliken & Thomson, 2013; Kruijne & Meeter, 2015; Kristjansson & Asgeirsson, 2019 for recent reviews).

The independent feature-weighting account is based on the ideas initially developed by Maljkovic and Nakayama (1994; 1996) to account for PoP. During a search event, the features associated with the target become more activated, while the features associated with the distractors are suppressed. These activations persist for some time and then decay. The priority of the locations that share these features on subsequent trials is modified accordingly (e.g., Becker & Horstmann, 2009; Chun & Nakayama, 2000; Kristjansson, 2006; Lee, Mozer, & Vecera, 2009; Maljkovic & Martini, 2005; Martini, 2010; Theeuwes, 2018; Wolfe, Butcher, Lee, & Hyle, 2003). Thus, according to the feature-weighting view, an object sharing a previous target's feature is more likely to be selected, just as if it had become physically more salient and conversely, an object sharing a previous distractor's feature is less likely to be selected, just as if it had become less salient.

By contrast, the episodic retrieval model posits that PoP reflects mechanisms that occur after the target is found. Multiple aspects of each search trial are stored as bound episodic memory traces. On a new trial, these memory traces are automatically retrieved; they speed performance if they match the features of the current search episodes and impair performance otherwise. One of the main findings supporting this view is that the effects of repeating different features of the target interact. In particular, repeating the response feature speeds performance when the target-defining feature repeats but slows performance when this feature changes from the previous trial (e.g., Hillstrom, 2000; Huang et al., 2004; Lamy, Yashar & Ruderman, 2010; Lamy, Zivony & Yashar, 2013; see Thomson & Milliken, 2013 for additional evidence supporting the episodic retrieval account).

Unlike feature-weighting and episodic-retrieval accounts, hybrid models of PoP suggest that PoP may occur at several stages during search. For instance, Meeter and Olivers (2006; see also Hickey, Olivers, Meeter & Theeuwes, 2011; Olivers & Meeter, 2006, 2008; Olivers & Hickey, 2010) suggested an interpretation of PoP, known as the *ambiguity account*. They argued that repetitions from previous trials benefit performance more the more ambiguous the task is, and that such ambiguity may arise at different levels. Accordingly, they suggested that ‘‘if it is ambiguous what the target is, visual selection will rely relatively more on what was selected in previous trials. If it is ambiguous what the response should be, response selection will rely more heavily on what response was coupled with a stimulus on previous trials" (Meeter & Olivers, 2006). In support for these claims, they showed that increasing perceptual ambiguity (e.g., by introducing a salient distractor in the search displays) and increasing response-related ambiguity (e.g., by alternating the response requirements) both resulted in larger priming effects.

Lamy et al. (2010) suggested a *dual-stage account* of PoP that also offers a compromise between the independent feature-weighting and episodic retrieval accounts. They tracked the time course of the interaction between PoP and response repetition that is the hallmark of episodic retrieval accounts. They reported a robust PoP effect at early stages of processing, before response-related processes could kick in (within 100ms from search display onset), and an interaction between pop-out feature repetition and response repetition later on (after 200-400ms). Moreover, later studies showed that this interaction results from repetition of the motor response, and not from repetition of the response feature (Yashar & Lamy, 2011; Yashar, Makovski & Lamy, 2013) - a finding that situates retrieval processes at play in PoP at a late stage. The authors concluded that PoP speeds both a perceptual stage and a response-related stage of visual search.

Processing stages in a typical PoP experiment

The brief foregoing review suggests that PoP operates at both early and late stages during visual search. However, further scrutiny of the literature reveals that there is quite some variance as to what these stages stand for. By integrating the various suggestions raised with regard to how PoP speeds performance in a typical PoP experiment, one can distinguish between five candidate stages, as illustrated in Figure 2. (1) When a search display comes on, the basic features present in the display are analyzed in parallel and attentional priority weights are assigned to each location / object (*attentional priority* stage, e.g., Maljkovic & Nakayama, 1994). (2) Attention is shifted to the object with the highest priority weight (*attention shifting/focusing* stage, e.g., Yashar & Lamy, 2010a). Note however, that the task may or may not require a shift of attention: for instance, the simple detection of a featural discontinuity does not require that attention be focused on its location, whereas making a fine discrimination at its location does. (3) Once attention is shifted/focused at the candidate location, it is engaged, that is, the features in that location are processed (*attentional engagement* stage, e.g., Yashar & Lamy, 2010b). (4) Then, prior to responding, comes a decision as to whether the selected object is indeed the target (*episodic retrieval* stage, e.g., Huang et al., 2004). (5) Finally, the appropriate response is selected and executed (*response-related* stage; e.g., Yashar & Lamy, 2011).

To determine whether selection history in general, and PoP in particular, should be integrated with current goals and physical salience to shape an integrated priority map, as suggested by Awh et al. (2012; see also Jiang, 2017; Wolfe, 2019), it is not enough to evaluate the evidence from studies that tested the independent feature-weighting, episodic retrieval and hybrid accounts against each other. Instead, a more focused review is necessary, that examines the findings from studies that used experimental strategies specifically suited to investigate whether PoP affects the attentional priority stage and guides attention as do bottom-up and top-down factors.

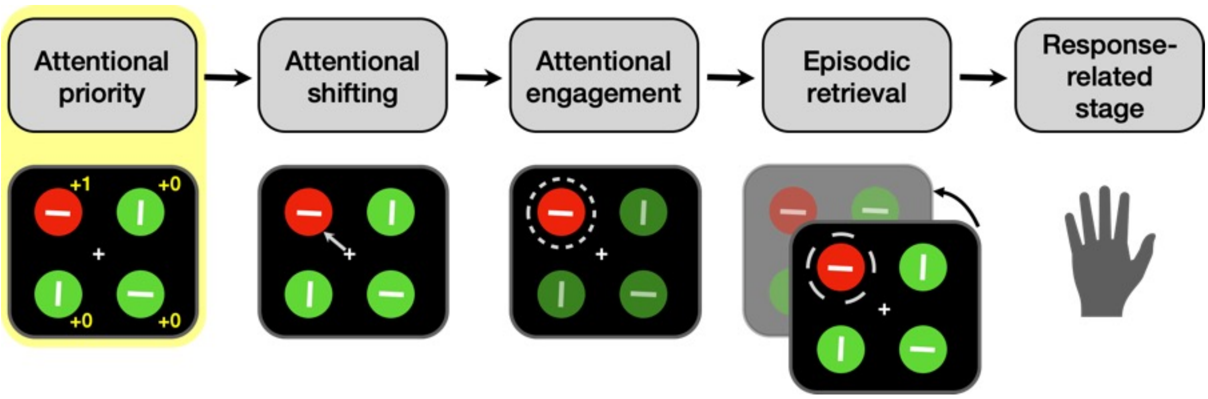

Figure 2. Schematic illustration of the processing stages that may be modulated by PoP. In the present review, we focus exclusively on the evidence pertaining to the effects of PoP on attentional guidance.

What counts for Priming of Pop-out?

Before we proceed to review the evidence pertaining to the role of PoP in attentional guidance, it is important to clarify what counts for selection history. The original PoP phenomenon described by Nakayama and colleagues (Maljkovic & Nakayama, 1994; 1996; McPeek et al., 1999; Chun & Nakayama, 2000) referred to the effect of repeating the target or the distractors' features on the target-defining dimension during pop-out search, that is, search for a target defined by its unique feature on a basic dimension and yielding either negative or flat search slopes. However, the studies that have investigated the mechanisms underlying PoP have extended the boundaries of the phenomenon to irrelevant features of the target and distractors, as well as to serial search. Although these search types are included in the present review, they are considered separately because they might reflect different mechanisms.

More crucially, the claim that the classical dichotomy between top-down and bottom-up factors should be updated to include selection history critically hinges on the premise that selection history and top-down control are different sources of attentional guidance. However, as we clarify below, selection history is often confounded with top-down control – not in the sense that selection history may be considered as an implicit or enduring form of top-down control, as has been extensively discussed elsewhere (e.g., Egeth, 2018; Jiang, 2018; Theeuwes, 2018; Wolfe et al., 2003), but in the sense that some manipulations of selection history are confounded with manipulations of top-down information, in its narrowest and most traditional definition.

While volitional control is sometimes put forward as a defining feature of top-down attentional guidance (e.g., Theeuwes, 2018), a more widely accepted definition links top-down control of attention to working memory (WM), with top-down information being defined as "some kind of short-term description in working memory of the information currently needed" (e.g., Duncan & Humphreys, 1989; Desimone & Duncan, 1995). Many studies convincingly demonstrated that when some information is held in WM for a memory test, attention is biased towards items matching this information in an unrelated search task that intervenes during the retention interval (e.g., Downing, 2000; Pashler & Shiu, 1999; Olivers, Meijer & Theeuwes, 2006; Soto, Heinke, Humphreys & Blanco, 2005; see also Li, Chen & Wolfe, 2020). Such mandatory guidance of attention by the information stored in WM is widely considered to reflect top-down attentional guidance even if it is not under volitional control. Accordingly, within this framework, *whether PoP is a form of top-down control depends on whether the features of the previous target are maintained in working memory*.

This possibility is unlikely with regard to Nakayama and colleagues' early studies. Bravo and Nakayama (1990) showed that search for unpredictable color singletons is salience-based, indicating that participants search for a feature-discontinuity rather than matching the visual input against one of two color templates held in WM. In addition, Maljkovic and Nakayama (1994) showed that selecting a target speeds performance for targets sharing its feature on the subsequent 5–8 trials (see Thomson & Milliken, 2012; 2013 for even longer-lasting effects), in the absence of explicit awareness of the repeated feature (Maljkovic & Nakayama, 2000) – two findings that also argue against the notion that PoP is mediated by representations stored in WM. In light of the above, it is reasonable to assume that in classical PoP studies, the effect reflects a mechanism that is distinct from top-down guidance.

However, there are many studies that claim to investigate PoP, but in which the involvement of working memory is difficult to reject. Consider an extreme case, reported by Theeuwes and van der Burg (2011), who claimed to pit inter-trial priming against top-down goals. They used a variant of the additional singleton paradigm (Theeuwes, 1991). On each trial, a precue indicated the color of the upcoming target and was followed by a search display that contained two color singletons among gray objects. One singleton (the target) shared the precue color, while the other singleton (the distractor) had a different color. The authors found that the salient distractor interfered with search when the target color on the current trial differed from the target color on the previous trial, and that this interference disappeared when the target color repeated on successive trials. They concluded that repeating the target, which they labeled "automatic bottom-up intertrial priming", biased the competition in favor of the repeated singleton.

This type of evidence is taken to support the notion that selection history guides attention, but our claim here is that it is irrelevant to the question at hand. In Theeuwes and van der Burg's (2011) study, the color of the target was stored in WM by design. Their results thus show that using the same feature template on successive trials enhances the representation of that feature in WM, and increases the competitive edge of objects sharing that feature[1]. These findings fall naturally within the realm of top-down control. They are interesting in their own right, and are particularly relevant to research on WM (e.g., Moore & Weissman, 2010; Olivers et al., 2011). However, they cannot be brought forward as evidence that selection history in general – and PoP in particular – is a source of attentional guidance that should be distinguished from bottom-up and top-down factors. Accordingly, in the review that follows, we single out the studies that suffer from this problem – that is, in which the task requires or encourages participants to maintain in WM the feature for which PoP is measured.

[1] In apparent contrast with this claim, Gunseli et al. (2016) presented findings suggesting that repeating the target of a search task *reduces* the strength of the representation of that target in WM, because this representation is transferred to LTM. However, in their study, (1) participants had to maintain an additional template in WM for a subsequent memory task and (2) they were informed that the search target would repeat on 20 consecutive trials (in Experiment 1) or on 6 consecutive trials (in Experiment 2). These characteristics created a strong incentive to transfer the search template to LTM. It is unlikely that such transfer should occur when the search template changes randomly from trial to trial and in the absence of the competition of a concurrent template, as was the case in Theeuwes and van der Burg's (2011) study.

Does PoP affect attentional guidance? Review of the evidence

Several different experimental rationales have been employed to investigate whether PoP modulates the attentional priority of a given object in the visual field. For each of these, we first explain why it can provide a diagnostic measure of attentional guidance and then review the studies in which it was used in the context of PoP. Note that, as we focused exclusively on the question of whether PoP modulates attentional priority, we do not review studies that address whether PoP affects perceptual processes (vs. post-perceptual processes) when their design does not allow one to distinguish between attentional guidance and later perceptual mechanisms (e.g. attentional shifting and engagement). In addition, our inclusion criterion was whether a given experiment included a manipulation that could isolate effects of PoP on attentional priority – even if it was not the authors' objective.

We first review studies that relied only on manual responses and then turn to describe studies that relied on eye movements, event-related potentials and single-cell recording, in separate sections.

PoP and search slopes

One of the most popular methods to study attentional guidance during visual search is to vary the number of distractors presented together with the target and measure the time it takes to respond to the target as a function of the number of distractors. The slope of the RT × set size function is a measure of the search efficiency: shallower search slopes are thought to indicate that fewer distractors are attended before the target is found (e.g., Horowitz & Wolfe, 2017).

The notion that positive search slopes are diagnostic of serial search has been sharply criticized (e.g., Townsend, 1990). The main objection is that adding distractors may prolong the pre-attentive processes that lead to target selection and thereby delay the deployment of attention, without requiring serial inspection of a larger number of distractors. This controversy is irrelevant for the present purposes, however, because there is a fairly wide consensus that any factor that reduces positive search slopes increases the target's attentional priority and ensures that it will be found faster (e.g., Duncan & Humphreys, 1989) – irrespective of whether distractors are rejected in parallel or serially (but see Christie, McDonald & Livingstone, 2014, for a different interpretation). Many previous studies have shown that both bottom-up and top-down factors modulate search slopes (e.g., Duncan & Humphreys, 1989; Treisman & Sato, 1990; Cave & Wolfe, 1990), in line with the idea that these factors guide attention.

In order to demonstrate that PoP reduces search slopes, it is necessary to use a task in which the addition of each distractor slows search (i.e., tasks with positive search slopes). However, in their original demonstration of PoP, Maljkovic and Nakayama (1994) used a pop-out search, in which search slopes were negative. Negative search slopes are taken to indicate that the target becomes more salient the more populated the displays (e.g., Bravo & Nakayama, 1992). In such tasks, the target is always the object with the highest priority and PoP is typically found to interact with display size: slopes become less negative with more repetitions (e.g., Leonard & Egeth, 2008; Meeter & Olivers, 2006). Since reaction times (RTs) become faster with each added distractor, there is less room for target repetition to speed RTs as set size increases (i.e., floor effects), hence the flatter search slopes.

Three studies used tasks in which the target was defined by a unique feature that randomly repeated or changed across trials, as in Maljkovic & Nakayama's (1994) study, but nevertheless generated positive search slopes (Amunts, Yashar & Lamy, 2014; Ásgeirsson & Kristjansson, 2011; Becker & Ansorge, 2013, Exp.2). None of them showed a reliable effect of PoP on search slopes (see Figure 3 for an example).

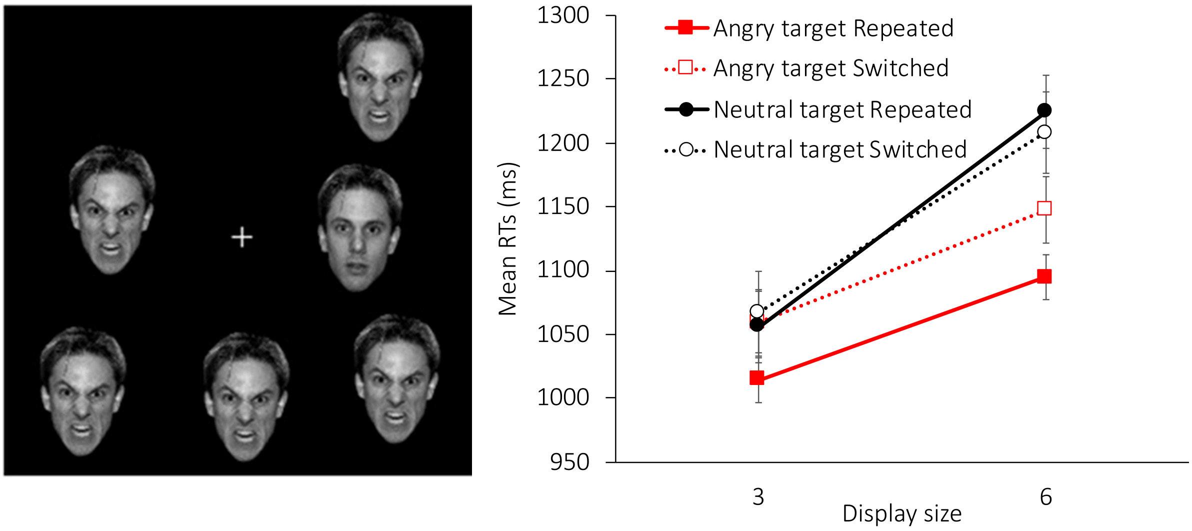

Figure 3. Sample display (left panel) and mean reaction times on target-present trials preceded by a target-present trial in the upright-face condition as a function of set size, target emotion and emotion repetition (right panel) in Amunts et al. (2014, Exp.1). Participants had to detect the presence of a face that differed from all others, unpredictably either a neutral face among angry faces (as depicted here) or an angry face among neutral faces. Repeating the target and distractors emotion speeded performance when the target was angry but not when it was neutral. While search slopes were positive, they were not modulated by emotion repetition.

Other studies examined the influence of PoP on positive search slopes by using a conjunction search task (Becker & Horstmann, 2009; Hillstrom, 2000; Exp.4; Geyer et al., 2006; Koshino, 2001; Kristjansson, Wang & Nakayama, 2002[2]; Lamy et al., 2008). These can be divided in three categories.

In some studies (e.g., Geyer et al., 2006; Kristjansson, Wang & Nakayama, 2002),

In one group of studies, participants were instructed to search for one of two conjunction targets (e.g., either a red horizontal or a green vertical bar presented among red vertical and green horizontal distractors) across the experiment (Becker & Horstmann, 2009; Hillstrom, 2000; Exp.4) or were instructed as to what target to search for on any given trial (Koshino,

[2] Wang, Kristjansson and Nakayama (2005, Exp.6) also used a conjunction search and found no interaction with set size but their finding is not informative for the present purposes because search slopes in their conjunction search were flat (4.5ms / item).

2001). Thus, in order to find the target participants had to maintain the templates of the candidate targets in working memory[3]. As explained earlier, feature repetition effects in this context may simply reflect top-down guidance: finding a match with one of the templates stored in WM on one trial may strengthen this template's competitive advantage in guiding attention on the next trial. Only one study in this group reported a reduction of search slopes when the target features repeated (Becker & Horstmann, 2009).

One conjunction-search study (Geyer et al., 2006) did not suffer from this problem: one of the target features was constant and the other could vary unpredictably. For instance, the target might be either a red vertical bar among green vertical bars and red horizontal bars or a red horizontal bar among green horizontal bars and red vertical bars. In this case, the task does not require maintaining the feature for which the repetition effect is computed (in this example, orientation) in working memory, because the target is always the orientation singleton within the red subset. In this study, search slopes did not interact with PoP.

Finally, one study (Lamy et al., 2008) examined the effect of repeating the target's color on search slopes when participants searched for a T among Ls in multi-color displays and reported its orientation. Color was thus an irrelevant dimension of the target. Although there was a robust color repetition effect on overall performance, it did not interact with set size.

To conclude, most of the current literature converges to show that PoP strongly reduces overall RTs but does not increase search efficiency measured by search slopes.

[3] As suggested by Hillstrom (2000), although this task is indeed likely to involve top-down guidance, it remains possible that participants may selectively search through one subset to find a discrepant item, the target (e.g., search through the green bars to find the only vertical bar among horizontal ones), and if unsuccessful, then search through the red bars to find the horizontal only bar among vertical ones.

PoP and high-priority distractors

The presence of a distractor that benefits from high attentional priority impairs search performance because this distractor competes with the target for attention. Thus, if feature inter-trial priming (i.e., PoP) affects attentional priority, repeating the target feature should increase the target's relative attentional weight and reduce the distractor's influence. Conversely, when the high-priority distractor takes on the previous target's feature, more weight should accrue to the distractor, which should increase its influence. Studies that adopted this logic relied on two main paradigms: the additional singleton paradigm and the spatial cueing paradigm.

PoP in the additional singleton paradigm

In the additional singleton paradigm pioneered by Theeuwes (1991), participants search for a target on a given dimension (say, shape). All the items in the display share the same feature on an irrelevant dimension (say, color) except for one, the singleton distractor. Distractor interference refers to poorer performance when the singleton distractor is present relative to when it is absent. This cost is generally taken to indicate that the singleton distractor enjoys higher priority than the target, and that as a result, spatial attention is automatically shifted to the distractor's location before it is redirected to the target (but see Ester & Awh, 2008; Mathot, Hickey & Theeuwes, 2010, for alternative interpretations). Several studies showed that both bottom-up and top-down factors affect singleton-distractor interference. On the one hand, increasing the target's salience decreases interference, whereas increasing the singleton distractor's salience increases such interference (e.g., Theeuwes, 1991; 1992). On the other hand, decreasing the match between the singleton distractor and the target-defining feature reduces the interference (e.g., Bacon & Egeth, 1994), thus demonstrating a role for top-down factors. If PoP affects attentional guidance, repeating the target should reduce the singleton distractor's interference. Three groups of studies are relevant for testing this prediction. The differences between them are highlighted in Figure 4.

Repetition on the target-defining (task-relevant) dimension

One group of studies used Theeuwes' (1991) original paradigm and examined the effect of repeating vs. swapping the target and distractors' features on the target-defining dimension (Figure 4A). The target was a shape singleton that could unpredictably be either the unique circle among diamonds or the unique diamond among circles, and the critical distractor was a color singleton (e.g., it was red, whereas all the other items, including the target, were gray). Pinto et al. (2005) showed that distractor interference (i.e., the performance cost when the color-singleton distractor was present relative to when it was absent) was reduced when the target and nontarget shapes happened to repeat relative to when they swapped, whereas Lamy et al. (2006) found no such reduction using a similar task.

Lamy and Yashar (2008) showed that the inconsistency between the two studies is entirely explained by the fact that conditions of distractor presence were blocked in the former study and randomly mixed in the latter. If feature repetition strengthened the priority weight of the target relative to the distractor, it should not matter whether distractor presence is blocked or mixed. Thus, taken together, these findings are inconsistent with the idea that PoP affects attentional priority and suggest that participants use a different strategy in the distractor-present and -absent conditions, when these are blocked. Note that that even when conditions of distractor presence are blocked, target repetition does not always reduce distractor interference: using a blocked design, Becker (2008a) showed that repetition of a target defined by its size did not reduce the large interference produced by a color singleton distractor (Exps. 1 and 3, but see Exp.4 where repetition of a target defined by its color did reduce the small interference produced by a size singleton distractor).

In summary, most of the extant evidence shows that repetition of the defining feature of a target singleton does not reduce the interference from a distractor unique on a different dimension.

Repetition on the salient distractor's (task-irrelevant) dimension

A second group of studies used a variant of Theeuwes' (1991) paradigm in which the color singleton distractor had one color and all the remaining items (including the target, that is, the shape singleton) another, with the colors either repeating or swapping unpredictably across trials (Figure 4B). These studies focused on whether color repetition (i.e., repetition on a task-irrelevant dimension) reduces distractor interference (Graves & Egeth, 2015; Hickey & Theeuwes, 2011; Hickey, et al., 2011).

The critical reduction was reported in all three studies. However, Hickey and Theeuwes (2011) contested the conclusion that the smaller distractor interference resulted from feature repetition modulating the target and distractors' relative attentional priorities. In addition to the cost of the distractor's presence, they also measured the distance effect. The distance effect refers to the finding that a salient distractor slows search more when it is close to the target than when it is far from it. The interpretation of this effect is that it takes longer to resolve the competition between the target and distractor and shift attention to the winner, the closer the salient distractor is to the target (e.g., Desimone & Duncan, 1995; Mathot, Hickey & Theeuwes, 2010; Mounts, 2000). Hickey and Theeuwes (2011) found that while color repetition reduced distractor interference, it did not modulate the distance effect. They suggested that attention might dwell longer on the distractor on swap trials (i.e., when this distractor has the previous target's color) and concluded that whether the target and distractor colors repeat vs. swap has no impact on competitive target–distractor interactions (see Müller et al. (2016) for related ideas with regard to the modulation of distractor interference by reward).

A similar interpretation can also apply to Graves and Egeth's (2015) findings. They used a task in which the target was defined by its shape and participants could not search for a singleton to find the target (feature-search mode). The authors reported two main findings. First, when the target and color singleton colors could never swap, that is, when both colors were fixed, or when either the target color was fixed and the singleton distractor took on different other colors unpredictably, or vice-versa, the color singleton distractor did not interfere with search. Interference emerged only when the colors could swap. Second, in the latter case, the interference was substantial even when the colors repeated from the previous trial, but was smaller than when the colors swapped. The authors concluded that participants can simultaneously inhibit several possible distractor colors, and do so only when the sets of target and singleton distractor's colors do not overlap (see also Stilwell & Vecera, 2018). When inhibition is not possible because the color sets do overlap, attention is drawn more strongly to a color singleton when it has the previous trial's target color. Thus, according to Graves and Egeth (2015), PoP affects attentional priority, in line with the feature weighting account (e.g., Maljkovic & Nakayama, 1994; Wolfe, 2007). However, in this study also, the larger distractor interference observed on swap trials does not necessarily reflect that the distractor captured attention on a higher proportion of trials (i.e., that its attentional priority increased). Instead, it may indicate that when a salient distractor's color cannot be inhibited, this distractor is indeed more likely to capture attention and that it is more difficult to disengage attention from it on trials in which it takes on the previous target color.

In summary, the extant evidence is ambiguous with regard to whether PoP on an irrelevant dimension modulates distractor interference. On the one hand, by contrast with a priority-based account of PoP, a repetition vs. a change in the target and distractor colors does not modulate distractor interference. On the other hand, in line with a priority-based account a swap between these colors increases the interference. The most parsimonious account of these findings is that when the target takes on distractor's color or vice-versa, the decision to select the target / reject the distractor is delayed. According to this account, PoP on an irrelevant dimension does not affect attentional guidance. However, further research is required to establish this conclusion.

Repetition of the target-defining feature with a singleton distractor in the same dimension

In a third group of studies, both the target and the critical distractor were singletons on the same dimension (Figure 4C). In this case, it is necessary to let participants know which one is the target. In some studies, this was achieved by using non-overlapping target and distractor color sets: throughout the experiment, the target might be either red or green and the distractor either yellow or blue, among gray items (Olivers & Hickey, 2010; Meeter & Olivers, 2006, Exp.3; Olivers & Meeter, 2012). In other studies, the target feature was specified by a precue on a trial-by-trial basis: on a given trial, the precue might indicate that the color of the upcoming target is red and the search display would include one red item (the target) and a green item (the distractor) among gray items (Theeuwes & van der Burg, 2011). In all these studies, distractor interference was reduced when the target color was the same on consecutive trials relative to when it changed (but see Asgeirsson & Kristjansson (2019) for a failure to replicate Theeuwes & van der Burg's (2011) findings). However, these studies fall into the category where the task requires participants to maintain in working memory the feature for which PoP is measured. Therefore, they are likely to reflect effects mediated by top-down control rather than by selection history as a separate source of attentional guidance.

To conclude, the studies that measured manual responses in the additional singleton paradigm do not provide strong support for the idea that PoP reduces distractor interference by modulating the relative attentional priorities of the target and critical distractor. Most of the extant evidence shows that repetition of the defining feature of a target singleton does not reduce the interference from a distractor unique on a different dimension. The studies where the feature repetition occurred on the (irrelevant) dimension on which the distractor was salient revealed that swapping between the target and distractor features modulated distractor interference. However, the most parsimonious account is that this finding does not reflect attentional guidance but a later decision stage, because a repetition vs. change, (instead of a swap), did not reduce distractor interference. Finally, studies in which both the target and the critical distractor were singletons on the same dimension are irrelevant to the question of selection history as a third source of attentional guidance, because in these studies, PoP cannot be dissociated from top-down guidance.

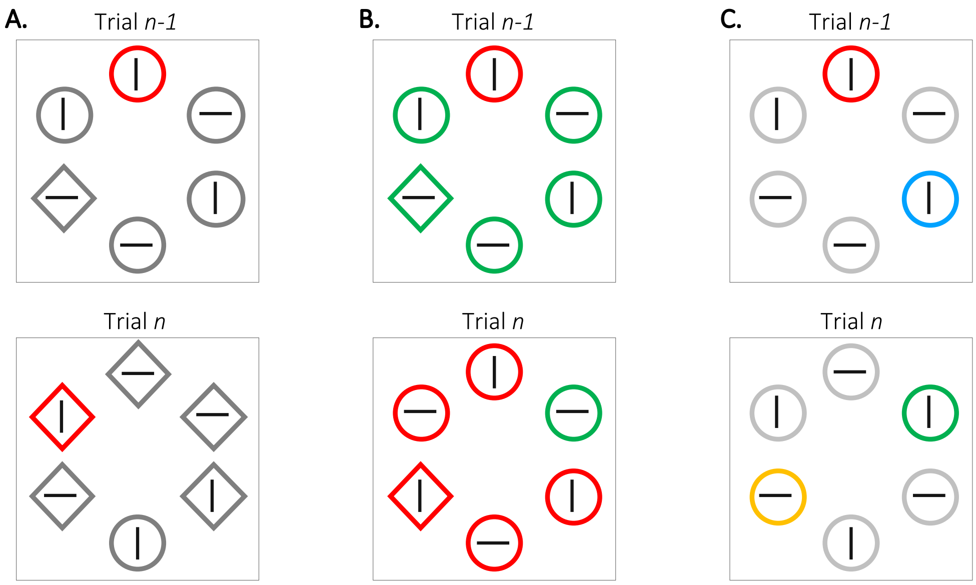

Figure 4. Schematic displays illustrating the different measures of PoP using the additional singleton paradigm. Panel A: Participants search for the unique shape and the salient distractor is a color singleton. PoP is measured for repetitions vs. swaps on the shape (task-relevant) dimension. Panel B: The task is the same but PoP is measured for repetitions vs. swaps on the color (task-irrelevant) dimension. Panel C: Participants search for a target that is either red or green and the salient distractor is either blue or yellow. PoP is measured for repetitions vs. changes of the target color. The lower panels depict a swap/switch on trial *n* relative to trial *n-1* (upper panels).

PoP in the spatial cueing paradigm

The other paradigm used to study the effect of PoP on attentional capture is the spatial cueing paradigm (e.g., Folk, Remington & Johnston, 1992). In a typical experiment, observers search for a target among distractors and shortly prior to the search display, a spatially uninformative cue appears at one of the potential target locations. Faster search performance when the target appears at the same location as the cue (valid-cue trials) than at another location (invalid-cue trials) is taken to indicate that attention was shifted to the cue (e.g., Folk et al., 1992; Gaspelin, Ruthruff & Lien, 2016) or that the cue was effective in later biasing attention in favor of its location (Lamy, Darnell, Levi & Bublil, 2018; Gabbay, Zivony & Lamy, 2019; Yaron & Lamy, 2020).

Early studies using this paradigm demonstrated that top-down factors strongly modulate the cue validity effect (e.g., Folk et al., 1992). They showed that a cue produces a validity effect only when it matches the target-defining feature, for example, in search for a red target, when the cue is red but not when it is green (e.g., Folk & Remington, 1998; see Büsel, Voracek & Ansorge, 2020 for a review). Moreover, only slightly larger effects were reported when the matching cues were made more salient (e.g., Schoeberl, Goller, & Ansorge, 2019; Lamy, 2005; Lamy, Leber & Egeth, 2004). However, recent studies revealed that bottom-up guidance also plays an important role in the spatial cueing paradigm: cue validity effects from cues not matching the search set emerge during difficult search (Gaspelin, Ruthruff & Lien, 2016; Lamy, et al., 2018) but only when these cues are abrupt onsets and not when they are static color cues (Ruthruff, Faulks, Gaspelin & Maxwell, 2020).

The effect of PoP on attentional guidance can be probed using the spatial cueing paradigm by examining whether a cue produces larger validity effects when it shares the feature of the target on the previous trial relative to when it does not (see Figure 5). When the target feature is constant, effects of PoP are confounded with top-down guidance (see Folk & Remington, 2008, for the first formulation of this idea): a cue sharing the previous target's color always matches the target template, whereas a cue that does not share the previous target's color never matches the target template. This problem is avoided in two types of studies.

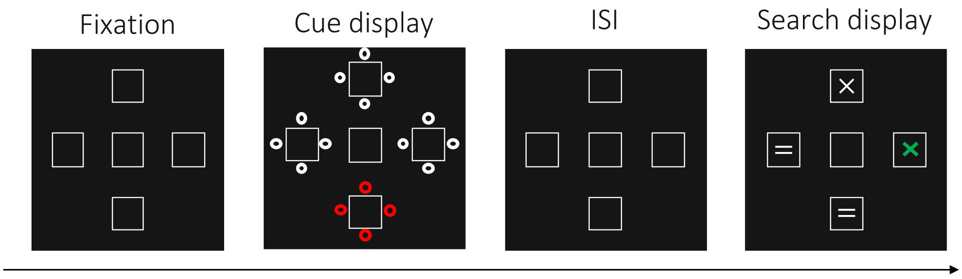

Figure 5. Sample sequence of events in a typical spatial cueing paradigm adapted to examine the effect of PoP on the cue validity effect. In this example, the target is either the red or green singleton in the search display (here, it is green) and the cue is either the red or green singleton in the cue display (here, it is red). The comparison of interest is whether the cue validity effect is larger when the cue on trial *n* shares the color of the target on trial *n-1* than when it has the alternative color.

Two-feature search tasks

In some studies, participants searched for two possible targets, for example, either a green or a red object. The critical question was whether a red cue would produce larger validity effects when the target on the previous trial had been red than when it had been green. The evidence is mixed: some studies reported the critical interaction (Beloposlky et al., 2010, Exp. 2; Folk & Remington, 2008, Exp.1; Schoeberl, Goller & Ansorge, 2019, Exp.1), whereas other studies did not (Biderman et al., 2017; Irons et al., 2012; Eimer & Kiss, 2010; Schoeberl et al., 2019, Exp.3 - see also Yashar, White, Fang & Carrasco, 2017). To explain these discrepancies, one may rely on Folk and Remington's (2008) suggestion that priming might modulate capture only when participants adopt singleton-detection mode, that is, "only under the condition that the primed features are left unspecified in the overall attentional set" - but this account cannot accommodate Yashar et al.'s (2017) findings. Irons et al. (2012) suggested that the critical modulation may be observed when only cues with potential target features are used (i.e., red and green cues with targets that can be either red or green) but not when cues with features that never characterize the target are also included (i.e., red, green and blue cues with targets that can be either red or green) - but this account cannot accommodate Schoeberl et al.'s (2019) findings.

It is important to note that with the spatial cueing paradigm, PoP measured as the effect of target-cue feature repetition is sometimes confounded with top-down guidance. This is true when participants cannot simply search for the most salient object and are required to store the possible features of the target in WM. In that case, the competitive advantage of the WM template corresponding to the feature of the target on trial *n-1* may be strengthened relative to the competing template when this target is selected, which would explain why the cue on trial *n* produces larger spatial cueing effects when it shares this feature on trial *n* than when it does not. This alternative account does not arise when the participants' task is to search for an unpredictable singleton (i.e., in singleton-detection mode).

Go – no go tasks

The other group of studies used go no-go tasks. Displays contained one of two possible targets (say, either a red or a green color singleton) but participants had to respond if the target had one feature and refrain from responding if it had the other. The question of main interest was whether a cue sharing the *go* feature would produce a larger validity effect when the target on the previous trial had been a go vs. a no-go target. The findings showed that it did not (Eimer & Kiss, 2010, Exp.2; Folk & Remington, 2008, Exp.2).

To conclude, there is mixed evidence from spatial cueing studies as to whether PoP guides attention. It is also important to keep in mind that with this paradigm, unless the task requires searching for an unpredictable singleton, the repetition effect can be accounted for by top-down attention.

Prior-entry effects

According to the law of prior entry (Titchener, 1908) "the objects of attention come more quickly to consciousness than the objects which we are not attending to". Empirical evidence for this phenomenon comes from studies using Temporal Order Judgement (TOJ;

e.g., Stelmach & Herdman, 1991) and Simultaneity Judgement (SJ, e.g., Carver & Brown, 1997) tasks. In both tasks, two objects appear at a variable Stimulus Onset Asynchronies (SOA) from one another. In the TOJ task, participants report which of the objects appeared first; the prior-entry effect is quantified by the Point of Subjective Simultaneity (PSS), that is, the average SOA at which participants are equally likely to report that the object that appeared first was the attended or the unattended object. In the SJ task, participants report whether or not the two objects appeared simultaneously. The typical finding in both tasks, is that the attended object must be presented later for participants to judge the two objects as simultaneous (e.g., Schneider & Bavelier, 2003; Stelmach & Herdman, 1991). Accordingly, several authors have relied on prior entry effects to investigate which objects enjoys higher priority (e.g., Born, Kerzel & Pratt, 2015; Donk & Soesman, 2011).

Two studies relied on this rationale to examine the role of PoP. Theeuwes and Van der Burg (2013) used both TOJ and SJ tasks and reported that an object primed by a same-color cue was attended first. However, unlike in classical PoP studies, where a benefit is observed for the target color although both the target and distractor colors repeat, here, only the cued color repeated. Thus, the findings may reflect simple perceptual priming.

Burnham (2015) used visual arrays more similar to the classical PoP search displays and therefore did not suffer from this problem. He relied on a ToJ task: on each trial, four task-irrelevant squares appeared, either one red among green ones or one green among red ones, randomly. Two probes, flashed one after the other at various SOAs, were superimposed on two of these squares and participants had to determine which appeared first. Probes appearing on the color singleton needed to be presented earlier on switched than on repeated-color trials to be perceived simultaneously with a probe appearing on a nonsingleton. It is noteworthy, however, that PSS calculated from TOJ tasks have been criticized because they might reflect decision biases that emerge more strongly the more ambiguous temporal order is (Shore et al., 2001; Spence & Parise, 2001). In Burnham's (2015) study, such decision bias may have manifested in participants' selecting the same object color on successive trials (see also Brascamp et al., 2011). Further research is therefore needed to ensure that his findings are replicated when response biases are prevented (see Spence & Parise, 2001 for procedures allowing such prevention).

To conclude, while the two studies relying on prior-entry suggest that PoP affects attentional priority, their findings are open to alternative accounts. Therefore, further research is required in order to establish this conclusion.

PoP and search accuracy with brief displays

A small group of studies investigated whether PoP affects perceptual processing by measuring search performance accuracy in the typical PoP task with briefly presented, masked search displays. They relied on the idea that reaction times with extended viewing times index both perceptual and post-perceptual stages, whereas accuracy under data-limited conditions indexes only perceptual stages. Any factor that increases the attentional priority accruing to the target relative to the distractors should help participants find the target faster and therefore improve search accuracy under such brief exposure conditions. Crucially, such improvement should be observed both when the task requires attention to be focused on the target in order to report its response feature and when it requires only detecting the target.

The findings of several studies do not confirm this prediction. Repetition of the target and distractors features (PoP) improved accuracy only when the task involved fine discrimination of the response feature (e.g., Kristjansson, 2016; Pascucci et al., 2012; Sigurdardottir et al., 2008; Yashar & Lamy, 2010) but not when the task was a left/right hemifield localization the target feature (Huang et al., 2004; Yashar & Lamy, 2010). These findings suggest that PoP affects processes that occur after the target is found and therefore does not modulate attentional priority. Note, however, that it would be useful to further evaluate this conclusion by investigating whether bottom-up and top-down factors affect accuracy in both the discrimination and left/right hemifield localization tasks, as predicted if both tasks are indeed sensitive to attentional guidance.

PoP and eye movements

Eye movements (or saccades) that bring an object in the fovea are often interpreted as an overt marker of attentional shifting (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995). As a result, many visual search studies have used eye-tracking methodology to study the factors that contribute to attentional priority, relying on three main measures.

Measures of attentional priority in eye-movement studies

The proportion of first saccades is thought to be the most straightforward measure, based on the premise that the first object to which the gaze is shifted is the object with the highest priority. Accordingly, the proportion of first saccades to an object was found to increase the more salient this object is (e.g., Irwin et al., 2000; Theeuwes et al., 1998, 1999; van Zoest & Donk, 2005 and when it matches the search template relative to when it does not (e.g., Ludwig and Gilchrist, 2002; 2003a; 2003b; Wu & Remington, 2003).

Another popular measure is saccade latency to the target: the higher the attentional priority of the target, the faster one should be to select it. Saccades latencies to a target are typically faster the more salient it is (e.g., Theeuwes et al., 2003) and when it matches the search template compared to when it does not (e.g., Al-Aidroos and Pratt, 2010). However, saccade latencies are likely to also be modulated by post-guidance processes, such as deciding to shift attention and launch a saccade after the target is located. As such, they are less diagnostic of attentional guidance than proportion of first saccades.

Finally, deviations of saccade trajectory from a straight line to the target can also be used to assess the target's attentional priority relative to other objects in the visual field. Accordingly, the presence of a distractor leads to a more substantial deviation in the saccade path the more salient this distractor is (e.g., Theeuwes et al., 1998) and when this distractor matches the search-relevant feature relative to when it does not (e.g., Ludwig & Gilchrist, 2003). Thus, saccade trajectories may reveal changes in the relative attentional priority accruing to a target when a distractor competes with it for attention, changes to which the proportion of first saccades may not be sensitive.

PoP in saccade tasks and free-viewing manual response tasks

The studies that relied on eye-movements to examine the role of PoP on attentional guidance can be divided into two broad categories. In one group of studies, participants were required to make a saccade towards the location of the target. There were fewer erroneous saccades when the target repeated from the previous trial than when it switched, and correct saccades (to the target) were faster (Becker, 2008b; McPeek, Maljkovic & Nakayama, 1999). In addition, on correct-saccade switch trials, saccades were more likely than on correct-saccade repeat trials to deviate in the direction of a distractor before being corrected "in-flight" and landing at the actual target's location (McPeek, Skavenski, & Nakayama, 2000; see also Song & Nakayama, 2006; 2008, for more frequent in-flight corrections of manual reaching responses on switch trials). Similar findings were reported when monkeys served as participants (e.g., McPeek & Keller, 2001).

However, concerns have been raised that eye movements may not closely follow attentional shifts in saccade tasks because of speed-accuracy trade-offs (e.g., Becker, 2008a; Findlay, 1997): in order to minimize errors, observers may refrain from making saccades until they have enough confidence that they correctly located the target. This issue is particularly relevant in the present context, because it resonates with the claim that PoP may affect search after the target is located rather than guiding search prior to that stage (e.g., Huang et al., 2004; Huang & Pashler, 2005; Yashar & Lamy, 2011).

This concern is alleviated in a second group of studies where participants were required to make a manual response and allowed to move their gaze freely while their eye movements were recorded. These studies relied on a variety of search tasks similar to those used in the studies reviewed in the foregoing sections, in which only manual response performance was measured.

Pop-out search. With the standard pop-out task, target fixation latencies (i.e., the time that elapses from the onset of the search display until the target is fixated) were found to be faster when the target repeated than when it switched (Becker, 2008c; Becker & Ansorge, 2013). Importantly, in the latter study, both target repetition and target salience increased the proportion of first fixations to the target, irrespective of whether the target was defined on the color dimension or on the shape dimension. The attention-guidance account further predicts that the effects of PoP and target salience should interact, because if PoP increases the target's competitive advantage, its influence should be larger the less salient the target. Yet, while this prediction was confirmed with color-defined targets, the opposite pattern was observed with size-defined targets.

Conjunction search. One study (Becker & Horstmann, 2009) examined PoP in a conjunction search (see the section *PoP and search slopes* for more details). Mirroring their RT data, PoP reduced search slopes measured on target fixation latencies. In addition, the first fixation was more likely to land on the target on repeated- than on changed-feature trials. However, although increasing the number of distractors decreased the proportion of first saccades to the target, priming did not reduce this set size effect, as would be expected if repeating the target feature increased its attentional priority. Moreover, the priming effect on the proportion of first saccades to the target interacted with response repetition. Interpreted within the retrieval-based account of PoP, the latter finding suggests that first saccades may not be driven by attentional priority alone but also by post-selection processes.

Additional singleton search. Becker (2008a, 2010) used the additional singleton paradigm to examine whether PoP affects attentional guidance while measuring eye movements. When repetition was measured on the target-defining dimension (Becker, 2008a), first saccades were more likely to land on a non-target on switch than on repetition trials, and on distractor-present than on distractor-absent trials, in line with the attentional guidance account of PoP. However, in contradiction with this account, the effect of distractor presence on the proportion of first saccades to a non-target was equally large whether or not the target repeated. To explain why the expected interaction was not observed, Becker (2008a) suggested that the effects of priming may have been too weak to override the large competitive advantage of the salient distractor over the target (p.338). While this argument is valid, it cannot be easily applied to Becker's (2008a) results: in Experiment 1, for instance, an interaction would be expected because the magnitude of the priming effect was similar to that of the distractor-presence effect: the average number of non-target fixations per trial rose from .57 to .86 on repetition vs. switch trials, respectively, and from .53 to .81 on distractor-absent vs. distractor-present trials.

In a later study, Becker (2010) measured effects of feature repetition on the salient distractor's (irrelevant) dimension, but relied on a different index to gauge capture. The salient distractor was present on all trials, and attentional capture by this distractor was measured as a larger proportion of first saccades to this distractor relative to other nontargets. This effect was larger when the target (and salient distractor's) features switched than when they repeated, suggesting that repeating the target and distractor's features decreased the salient distractor's attentional priority relative to nontargets'.

To conclude, most of the evidence relying on eye movements shows that repeating the target feature increases the probability that the first fixation should land on the target and reduces target fixation latencies, both in saccade tasks and in a variety of manual response tasks. In addition, the probability of making the first saccade to a salient distractor decreases when the target-defining feature repeats, or when the irrelevant feature on which the distractor is salient repeats. These findings support the view that PoP guides attention. However, inconsistent with this conclusion, this PoP effect did not interact with other factors known to reflect attentional guidance, namely, search slopes and distractor interference. In addition, it is noteworthy that all the findings involving manual response tasks with free viewing were conducted in the same lab (Becker, 2008a, c; Becker, 2010; Becker & Ansorge, 2013; Becker & Horstmann, 2009). Further research is therefore required to strengthen the conclusion that PoP guides eye movements. In particular, it would useful to conduct manual-response studies probing the effect of PoP on saccade deviations, as none were published to date.

PoP and Event-Related Potentials

Event-related potentials (ERPs) are ongoing electroencephalogram (EEG) waveforms that are temporally locked to a specific event and averaged across many trials. Unlike behavioral studies, in which the end outcome of the processes that precede the response is measured, ERP studies provide a direct window into how these processes unfold in time, with high temporal precision.

Studies that used ERPs to clarify the mechanisms underlying PoP have mainly investigated whether PoP affects perceptual or response-related processes (e.g., Becker, Grubert & Dux, 2014; Eimer, Kiss & Cheung, 2010; Olivers & Hickey, 2010). To answer this question, they mostly relied on the N2pc component. The N2pc is an enhanced negativity over the posterior electrodes contralateral to the presentation of the critical stimulus, and is typically observed between 180 and 330ms after the visual array is presented. This component has become the gold standard ERP marker of attentional allocation in visual search tasks (e.g., Eimer, 1996; Luck & Hillyard, 1994; Luck, Woodman & Vogel, 2000; Mazza et al., 2007). Accordingly, several studies have reported that the amplitude and latency of the N2pc are modulated by top-down factors (e.g., Eimer & Kiss, 2010; Lien, Ruthruff & Cornett, 2010) and by bottom-up factors (e.g., Hickey McDonald & Theeuwes, 2006).

Because the N2pc is strongly linked to attentional processes, finding that PoP modulates the N2pc is taken as evidence that PoP affects processes that occur prior to response selection. In line with behavioral evidence for a perceptual component of PoP, most ERP studies reported that a target elicits an N2pc with an earlier onset (Becker et al., 2014; Christie et al., 2014; Tay et al., 2019) sometimes accompanied by higher amplitude (Eimer et al., 2010; Olivers & Hickey, 2010) when this target repeats relative to when it does not[4].

However, the N2pc is widely thought to index processes that occur after the competition for attentional priority is resolved. For instance, Tay et al. (2019) suggested an ERP chronometry of visual singleton detection, according to which the N2pc reflects the allocation of attention to the singleton's location "after the relevance and localization

[4] Another study using a variant of the standard PoP paradigm (Burra & Kerzel, 2013) reported no effect of shape repetition on the N2pc but did not report whether shape repetition had a behavioral effect. Hickey et al. (2011) also measured the N2pc elicited by the target and salient distractor in the additional singleton paradigm, but the large variability of the temporal windows used for the various comparisons does not allow one to draw strong conclusions from the findings (see Hickey and Theeuwes (2011) for additional criticisms of this study).

of the singleton are established and encoded" (p.12). These authors further suggested that parsing of the incoming information based on local contrast and task relevance to form a map of attentional priority occurs earlier, via processes indexed by neural modulations in the N1 range (see also Wascher & Beste, 2010). Likewise, Kiss, Velzen and Eimer (2008) proposed that "N2pc triggered in response to pop-out visual search targets does not reflect processes involved in covert shifts of spatial attention, but is instead linked to spatially selective attentional mechanisms that occur after such shifts are completed" (p.248). Accordingly, the N2pc seems to reflect processes akin to what we referred to as attentional engagement in the section titled *Processing stages in a typical PoP experiment* (see Zivony, Allon, Luria & Lamy, 2018 for related evidence).

To summarize the argument, although the feature-guidance account predicts that PoP should modulate the N2pc, such modulation does not necessarily indicate that repeated targets enjoy higher priority than non-repeated targets. Instead, it may only indicate that the selection process, which occurs after priority weights have been assigned, is faster for repeated targets. According to this rationale, in order to defend the idea that PoP affects attentional priority, one has to show that PoP also affects ERP waveforms prior to the N2pc (see Olivers & Hickey, 2010 for a similar argument). However, there is scarce evidence for such modulation.

Only three studies examined effects of PoP on components that precede the N2pc. While two of them (Christie et al., 2014; Tay et al., 2019) reported no modulation of either P1 nor N1-related components, Olivers and Hickey (2010) reported an earlier P1 on repeated- relative to changed-target color trials. However, as explained earlier, in the latter study, there were two color singletons – the target and a salient distractor, drawn from non-overlapping color sets - such that it was necessary to keep the possible target features in WM in order to perform the task. Therefore, effects of target repetition were potentially confounded with effects of enhanced top-down feature-based attention – which have been associated with modulations of the P1 component (e.g., Zhang & Luck, 2009).

To conclude, evidence from ERP studies indicates that PoP affects processes that occur after the target is located and therefore, does not affect the earlier stage of attentional guidance.

PoP and single-cell recordings

The theoretical concept of “priority map” is invoked by many models of attention to designate a representation of space that codes the relative priority of objects present in the visual field (e.g., Itti & Koch, 2001; Treisman, 1988; Wolfe, 1994; Zelinsky & Bisley 2015). These objects compete for attentional selection and the most highly prioritized object is chosen for enhanced processing in a winner-take-all fashion. Several brain regions have been singled out as potential priority maps, among them the superior colliculus (SC), the lateral intraparietal area (LIP) and the frontal eye fields (FEF) and, recently, the posterior inferotemporal cortex (PITd) (for reviews see Bisley & Goldberg, 2010; Krauzlis et al., 2013; Stemmann & Freiwald, 2019; Thompson & Bichot, 2005).

Finding that PoP modulates the activity of neurons in priority maps would provide direct evidence that PoP affects attentional guidance. Bichot and Schall (2002) published the first study that examined the effects of PoP on single-cell activity (see also Thompson, Bichot & Sato, 2005), and focused on FEF neurons. The task was similar to Maljkovic and Nakayama’s (1994) classical pop-out search task. When the target and distractor colors repeated over a sequence of trials, FEF cell activity increased when the target fell in its receptive field and decreased when a distractor was in its receptive field (see also Westerberg, Maier & Schall, 2020 for similar findings with single-cell recordings from area V4, and Muggleton et al., 2009 for increased RTs on switch trial when left FEF activity was disrupted using TMS).

While these findings align with behavioral reports of target facilitation and distractor suppression (Lamy, Antebi, Aviani & Carmel, 2008; Kristjansson & Driver, 2008; Maljkovic & Nakayama, 1994), it is not clear whether they reflect PoP or effects of top-down expectations. Indeed, in Bichot and Schall's (2002) study, the modulation of cell activity by feature repetitions and swaps was reported across a heterogenous combination of short search blocks, randomly intermixed: the color of the target and distractors switched across trials with a probability of 50 or 33%, or in blocks of 10 trials. Thus, overall, a color repetition was far more probable than a color switch. The other single-cell studies of PoP suffered from a similar problem (Muggleton et al., 2009, Thompson et al., 2005; Westerberg et al., 2020). Although Maljkovic and Nakayama (1994) initially claimed that expectations with regard to repetition and switch probabilities do not affect PoP, later studies provided strong evidence to the contrary (e.g., Cochrane & Pratt, 2020; Shurygina, Kristjánsson, Tudge & Chetverikov, 2019).

To conclude, the evidence from single-cell recording studies showing that PoP modulates the activity of neurons in brain areas held to serve as priority maps is ambiguous: in these studies, PoP was confounded with expectations. In addition, since they all used saccade tasks, whether their findings can be replicated for manual tasks with free viewing remains an open question.

Discussion

The claim that selection history is a third source of attentional guidance that should be distinguished from bottom-up and top-down factors enjoys a wide consensus in the current literature (e.g., Awh et al., 2012; Wolfe & Horowitz, 2017). The main conclusion that emerges from the present review is that this consensus is premature, at least with regard to one selection history phenomenon, priming of pop-out (PoP). We reviewed the main experimental rationales that have been used to determine whether PoP affects attentional priority and found no strong evidence that it does.

The first observation that arises when exploring the status PoP as a source of attentional guidance is that PoP is often defined in a way that does not allow one to dissociate it from effects of top-down control. In Maljkovic and Nakayama's (1994) initial demonstration, the target feature repetition occurred incidentally and was statistically uninformative. However, some later studies moved away from the initial PoP paradigm, and broader definitions of the phenomenon have surfaced. For instance, Ásgeirsson and Kristjánsson (2019) recently defined attentional priming (or PoP) as "… the finding that as observers repeatedly search for the same target, the search becomes faster" – a definition that is inclusive of feature repetitions that occur in streaks (e.g., Bichot & Schall, 2002), manifest as the repetition of one of the two possible target features or feature combinations held in WM (e.g., Olivers & Hickey, 2010), or result from the consecutive presentation of the same informative precue indicating the feature of the upcoming target (e.g., Theeuwes & van der Burg, 2011). In all these cases, the task requires or encourages participants to maintain in WM the feature for which PoP is measured, and PoP effects are therefore confounded with effects of top-down control. An important guideline for future studies investigating whether PoP affects attentional guidance is that they should avoid the experimental designs that suffer from this confound.

The different rationales reviewed here yielded conflicting results (see Table 1). On the one hand, research relying on search slopes, distractor interference and ERPs invalidated the notion that PoP biases competition for attentional priority. Most PoP studies generate negative or flat search slopes leaving no room to test whether feature repetition might decrease the time required to reject distractors and locate the target. However, the studies in which performance did deteriorate as the number of distractors increased showed that while PoP strongly reduced overall RTs, it did not increase search efficiency measured by search slopes – both during feature and conjunction search, and irrespective of whether the repetition pertained to relevant or irrelevant features of the target. Likewise, distractor interference studies showed that repetition of the defining feature of a target singleton did not reduce the interference from a distractor unique on a different dimension. However, when feature repetition occurred on the (irrelevant) dimension on which the distractor was salient, the interference decreased when the target and distractor features repeated relative to when they swapped – but not when either the target or distractor repeated vs. changed without swapping. The most parsimonious account of these findings is that PoP reflects processes that follow attentional guidance. Finally, all ERP studies aimed at testing a perceptual account of PoP against a response-related account and thus focused on the N2pc component. However, they typically did not report PoP effects on the earlier components that are relevant to the issue of attentional priority.

On the other hand, research relying on eye movements clearly supports the feature-weighting account: the strongest evidence comes from studies showing that repeating the target feature increases the proportion of first saccades to the target, when participants make a manual response and are free to move their eyes. However, in contradiction with the feature-weighting account, this effect did not increase when the competition was made stronger (i.e., by increasing the number of distractors or introducing a salient distractor). Further research is clearly needed, because if replicated, these observations would challenge the view that proportion of first saccades is an index of attentional priority.

The remaining rationales produced a more ambiguous picture, mostly because there were relatively few studies, some of which were open to alternative accounts. The spatial cueing studies that used singleton search and where therefore not open to a top-down alternative account, reported conflicting results. The findings from the only two prior-entry studies could result from either perceptual priming or response biases. The few studies using brief displays did not support the feature-weighting account, but further research is needed to determine whether, unlike PoP, bottom-up and top-down factors affect both detection and fine discrimination accuracy. Finally, all single-cell studies of PoP used designs in which a repetition was far more likely that a switch, thereby introducing an expectation confound.

The main contribution of the present review is to caution the field against burying the bottom-up vs. top-down dichotomy too hastily. We showed that although more research is required, most of the relevant evidence to date weighs against the idea that PoP affects attentional priority. It will be useful to conduct similar reevaluations of the processing stage at which other selection history phenomena affect visual search, in order to determine whether any of them is allowed as an additional player on the attentional priority map (Figure 6). The present review also revealed that different measures yielded conflicting outcomes (e.g., search slopes vs. proportion of first saccades). It therefore encourages further research that directly confronts different measures held to index attentional guidance, in order to help us refine our interpretation of these measures.

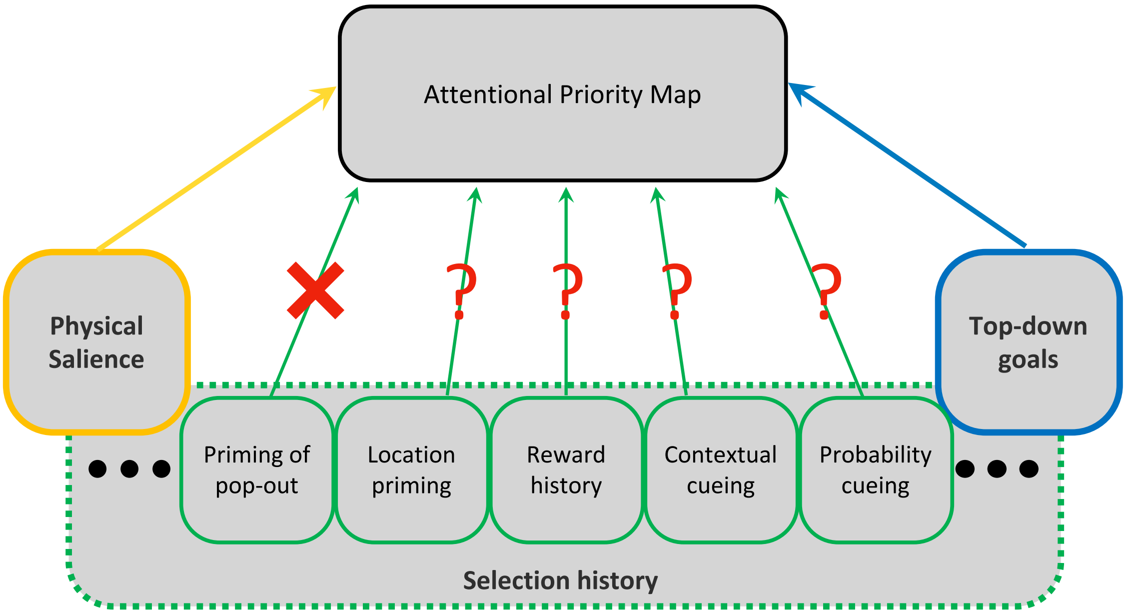

Figure 6. A schematic representation of the attentional priority map. Our review shows that priming of pop-out (PoP) does not affect the priority map. A similar reevaluation of the role of other selection history phenomena is required to determine which of them, if any, should be allowed as an additional player on the attentional priority map.

Table 1. Studies investigating the effect of Priming of Pop-out (PoP) on each of the reviewed measures of attentional priority.

Experiment	Measure	Paradigm	Repetition dimension relevance	Repetition dimension	Finding
Manual Responses					
Amunts, Yashar & Lamy (2014)	RT slope	Typical PoP	Target-defining	Facial expression	No
Ásgeirsson & Kristjansson, 2011)	RT slope	Typical PoP	Target-defining	Size	No
Becker & Ansorge (2013, E2)	RT slope	Typical PoP	Target-defining	Color	No
Becker & Horstmann, (2009)	RT slope	Conjunction search	Target-defining	Color and orientation	Yes*
Geyer et al. (2006)	RT slope	Conjunction search	Target-defining	Orientation	No
Hillstrom, (2000, E4)	RT slope	Conjunction search	Target-defining	Color and texture	No
Koshino (2001)	RT slope	Conjunction search	Target-defining (pre-cued)	Color and form	No
Lamy et al. (2008)	RT slope	Letter search	Irrelevant	Color	No
Becker (2008a, E3)	Distractor presence X PoP	Additional Singleton	Target-defining	Size	No
Becker (2008a, E4)	Distractor presence X PoP	Additional Singleton	Target-defining	Color	Yes
Lamy et al. (2006)	Distractor presence X PoP	Additional Singleton	Target-defining	Shape	No
Lamy & Yashar (2008, E1)	Distractor presence X PoP	Additional Singleton	Target-defining	Shape	Yes*
Lamy & Yashar (2008, E2)	Distractor presence X PoP	Additional Singleton	Target-defining	Shape	No
Pinto et al. (2005)	Distractor presence X PoP	Additional Singleton	Target-defining	Shape	Yes*
Hickey et al. (2011)	Distractor presence X PoP	Additional Singleton	Irrelevant	Color	Yes

Hickey & Theeuwes (2011)	Distractor presence X PoP Distance X PoP	Additional Singleton	Irrelevant	Color	Yes No
Graves & Egeth (2015, E1)	Distractor presence X PoP	Feature search	Irrelevant	Color	Yes
Meeter & Olivers (2006, E3)	Distractor presence X PoP	Additional Singleton, same dimension	Target-defining	Color	Yes*
Olivers & Hickey (2010)	Distractor presence X PoP	Additional Singleton, same dimension	Target-defining	Color	Yes*
Olivers & Meeter (2012)	Distractor presence X PoP	Additional Singleton, same dimension	Target-defining	Color	Yes*
Asgeirsson & Kristjansson (2019)	Distractor presence X PoP	Additional Singleton, same dimension	Target-defining (pre-cued)	Color	No
Theeuwes & van der Burg (2011)	Distractor presence X PoP	Additional Singleton, same dimension	Target-defining (pre-cued)	Color	Yes*
Belopolsky et al. (2010, E2)	Cue validity X PoP	Spatial cueing	Target-defining	Color/onset	Yes*
Biderman et al. (2017, E1)	Cue validity X PoP	Spatial cueing	Target-defining	Color/Shape	No
Biderman et al. (2017, E2)	Cue validity X PoP	Spatial cueing	Target-defining	Color/Size	No
Biderman et al. (2017, E3)	Cue validity X PoP	Spatial cueing	Target-defining	Color /Orientation	No
Folk & Remington (2008, E1)	Cue validity X PoP	Spatial cueing	Target-defining	Color	Yes
Folk & Remington (2008, E2)	Cue validity X PoP	Spatial cueing Feature search	Target-defining	Color	No
Irons et al. (2012)	Cue validity X PoP	Spatial cueing	Target-defining	Color	No
Schoeberl, Goller & Ansorge (2019, E1)	Cue validity X PoP	Spatial cueing	Target-defining	Color	Yes*

Schoeberl, Goller & Ansorge (2019, E3)	Cue validity X PoP	Spatial cueing	Target-defining	Form	No
Yashar, White, Fang & Carrasco (2017)	Cue validity X PoP	Spatial cueing	Target-defining	Color	No
Eimer & Kiss (2010, E2)	Cue validity X PoP	Spatial cueing (Go No-go)	Target-defining	Color	No
Folk & Remington, (2008, E2)	Cue validity X PoP	Spatial cueing (Go No-go)	Target-defining	Color	No
Burnham (2015)	Point of subjective similarity	Temporal order judgement	Target-defining	Color	Yes
Theeuwes & Van der Burg (2013, E1)	Point of subjective similarity	Temporal order judgement	Target-defining	Color	Yes
Theeuwes & Van der Burg (2013, E2)	Point of subjective similarity	Simultaneity judgment	Target-defining	Color	Yes
Eye-movements					
Becker (2008b, E1&E3)	Saccade latency	Typical PoP (saccade task)	Target-defining	Size	Yes
Becker (2008b, E2&E4)	Saccade latency	Typical PoP (saccade task)	Target-defining	Color	Yes
McPeek, Maljkovic & Nakayama (1999)	Saccade latency	Typical PoP (saccade task)	Target-defining	Color	Yes
Becker (2008c, E1)	Target fixation latency	Typical PoP (manual task)	Target-defining	Size	Yes
Becker (2008c, E3)	Target fixation latency	Typical PoP (manual task)	Target-defining	Orientation	Yes
Becker & Ansorge (2013, E1)	Target fixation latency	Typical PoP (manual task)	Target-defining	Color	Yes
Becker & Ansorge (2013, E2)	Target fixation latency	Typical PoP (manual task)	Target-defining	Size	Yes
Becker & Horstmann (2009)	Proportion of saccades to target Target fixation latency	Conjunction search (manual task)	Target-defining	Color and orientation	Yes* Yes*
Becker (2008a, E1)	Proportion of saccades to target	Additional singleton	Target-defining	Size	Yes

Becker (2008a, E2)	Proportion of saccades to target	Additional singleton	Target-defining	Color	Yes
Becker (2010)	Proportion of saccades	Additional singleton	Irrelevant	Orientation	Yes
Event-related Potentials					
Becker et al. (2014)	N2pc onset latency N2pc amplitude	Typical PoP	Target-defining	Color /Size	Yes[#] No
Christie et al. (2014 E2; one-singleton condition)	N2pc onset latency N2pc amplitude P1/N1 amplitude	Typical PoP	Target-defining	Color	Yes[#] No No
Tay et al. (2019)	N2pc onset latency N2pc amplitude N1pc amplitude	Typical PoP	Target-defining	Orientation	Yes[#] No No
Eimer et al. (2010)	N2pc onset latency N2pc amplitude	Typical PoP	Target-defining	Color	Yes[#] Yes[#]
Olivers & Hickey (2010)	N2pc peak latency N2pc amplitude P1 amplitude	Additional Singleton, same dimension	Target-defining	Color	Yes*[#] Yes*[#] Yes*
Single-cell recordings					
Bichot & Schall (2002)	FEF activity	Typical PoP	Target-defining	Color	Yes*
Westerfield, Maier & Schall (2020)	V4 activity	Typical PoP	Target-defining	Color	Yes*

* The effects of PoP could cannot be dissociated from top-down effects (see text for details).
\# Recent literature suggests that the N2pc indexes processes that occur *after* the competition for attentional priority is resolved (see text for details).

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