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Attentional priming: recent insights and current controversies

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Humans possess a primitive memory system for attention deployments that allows quick reorientation of visual attention to stimuli that are relevant to behavior at any given moment. We review recent evidence regarding such attentional priming effects from a number of different perspectives. We discuss recent findings on the time course and duration of such effects, the potential interaction of priming and top-down attentional guidance; how priming can be used to probe the nature of visual representations and attentional templates; findings on the basic nature of priming effects and recent relevant findings on so-called serial dependencies that share many characteristics with attentional priming. Our discussion shows that priming effects are strong and occur on many levels of perceptual processing, and that these effects cannot and should not be thought of as reflecting the operation of any single type of mechanism. Additionally, our overview shows the utility of these paradigms in answering questions about how we represent statistical regularities of stimuli in our environment.

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Given the limited amount of visual information that we can attend to and represent at a given moment, it is crucial for observers to reorient quickly to important stimuli. A key finding regarding this question is the 'priming of pop-out' effect (PoP). Maljkovic and Nakayama [1] tested visual search for an oddly colored diamond among 2 diamonds of another color. They found that the more often the same target and distractors were repeated on consecutive visual search trials, the faster the search. Notably, they also found that these attentional priming effects were impervious to top down influences, affecting attentional allocation irrespective of observers' goals in each case.

Nakayama *et al.* [2] suggested that this was evidence for a memory system for attention deployments allowing quick reorientation to stimuli of interest in a given context. An example could be as you try to keep track of your child wearing a green coat in a playground. You may chat with other parents, momentarily shifting gaze away from your child, but such a memory system would enable you to effortlessly reorient to green items.

Kristjánsson & Campana [3] reviewed research on attentional priming and our current aim is therefore to focus on more recent findings: on the time course of priming, how priming may guide visual selection, how priming reveals the contents of our representations of stimuli; what sort of activity priming reflects, and whether priming affects visual appearance. Finally, Kristjánsson & Campana proposed that priming can occur on many perceptual levels but the debate about whether priming reflects facilitated processing of repeated features, episodic memory traces, or response facilitation has gone on, a topic that we pick up here. Results since the 2010 review reiterate the point that trying to distinguish whether priming reflects one process or the other is not helpful. A far more interesting question is what cognition lead to which pattern of priming.

The time course and duration of priming

A highly interesting feature of attentional priming involves its time course. Maljkovic and Nakayama assessed the effects of a single target exposure over time, showing that a single exposure to a particular target color presented at least 5 trials in the past could influence the current one, irrespective of intervening target and distractor identity.

Martini [4••] assessed the priming influence of a single search trial on any future trials to measure the time course of priming, finding that color priming involved two components, a high-gain, fast-decay component and a low-gain, slow-decay component, consistent with the idea that priming occurs at more than one level. Brascamp *et al.* [5] similarly suggested that priming effects contain both rapid and more sustained components, while Kruijne *et al.* [6] suggested that priming involves short-lived facilitation that decays over approximately eight trials. Kruijne & Meeter [7•] then used the time course of priming to argue that both feature facilitation and episodic memory influence search times, and the relative influence of each depends on the search type (conjunction versus feature) in each case — a view that we sympathize with.

We can currently state with confidence that priming is long lasting, and survives intervening trials with different targets and distractors, but whether priming reflects different mechanisms operating on different timescales is still unclear. Highly interesting temporal patterns of attentional priming are regrettably often neglected when only switches versus repeats (sometimes called N-1 effects) are studied rather than longer-lasting effects.

Priming and top-down attention

Priming has been proposed as an alternative explanation for effects attributed to top-down guidance [8,9]. A good example involves the debate on so-called contingent capture. Folk *et al.* [10] proposed that unexpected items must be part of our attentional set to capture attention, so the degree to which items capture attention is contingent on task relevance. But according to Belopolsky *et al.* [11••], contingent capture findings reflect that the cues that Folk *et al.* [10] used may actually have primed the relevant items that therefore captured attention. Belopolsky *et al.* told observers to adopt a top-down set for a particular attribute on each trial during a cued response time task. Priming effects nevertheless dominated performance even though it went *against* the top-down attentional set. This finding (see also Ref. [12•]) led to the proposal that effects attributed to top-down attention, reflect feature priming [9]. In an overview of the available evidence, however, Lamy and Kristjánsson [13] argued conversely that while many effects could certainly be explained by intertrial priming, top-down guidance of attention could occur independently of priming.

The automaticity of priming

Maljkovic and Nakayama ([1]; Experiment 2) found strong evidence that color priming was strong enough to overshadow any effects of expectation, or top-down guidance, on search performance. They reasoned that if expectations determined performance, foreknowledge of target identity on upcoming trials, should interfere with the effects of priming. They manipulated color switch probabilities during odd-one-out search, and found that performance was slowest when the probability of a color switch was 1, even when observers always knew the color of the upcoming target. This result suggested that priming is largely impermeable to top-down influence. However, more recent findings suggest that priming can be modulated by reward association [14,15], and expectation. Pascucci *et al.* [16••] ran a brief presentation (104 and 234 ms) version of the Maljkovic and Nakayama [1] search task, where stimuli were followed by a metacontrast mask. They manipulated the length of fully predictable color runs, and compared them to random color runs of the same length. Participants were more likely to correctly discriminate the target diamond when color contingencies were predictable. Shurygina *et al.* [17], then found that predictable color contingencies yielded faster RT's, higher accuracy and more accurate saccade performance than randomly generated runs of the same length. In sum, these studies demonstrate that expectations can modulate priming. Note however, that top-down processes did not completely override priming in either study. Expectations seem only to attenuate or amplify priming.

Using priming to probe the nature of visual representations and attentional templates

Just as aftereffects have been called the psychophysicists electrode [18], priming has similarly been used in recent investigations to assess the nature of our internal representations of the world.

Chetverikov *et al.* [19] have used so-called role reversal effects [20,21] to study representations of distractor sets following visual search for targets among distractors. When observers expect distractors to have specific features, they respond more slowly than otherwise when these features belong to the target instead. In Chetverikov *et al.* [22••], observers searched for an odd-one-out bar among 36 distractor bars differing in orientation that were drawn from a specific orientation distribution. During several adjacent trials, the parameters of the distractor distribution were kept constant and target orientation varied randomly but always came from outside the distractor distribution. After these *learning* trials, *test* trials followed where distractor distributions and the target had different distances in orientation space from the mean of the previous distractor distribution. By measuring RTs as a function of this distance in feature space, Chetverikov *et al.* could assess representations of previously encountered distractor set distributions and expectations about successive ones. They compared where in the preceding distractor distribution a target belonged, to the size of the role-reversal effect. Their results showed that not only could observers learn the mean and variance of orientation and color [23•] distributions, but showed for the first time that they could also represent their shape.

Related techniques were used by Geng *et al.* [24••] who found that the probability of a distractor being similar to the target affected the sharpness of the tuning of templates guiding search. Won and Geng [25•] then used a similar approach to argue that distractor templates have broader representations than target templates, allowing generalized suppression instead of the sharper tuning of target templates.

The basic nature of priming effects

The nature of priming effects, their locus and potential behavioral benefits, has also been addressed in recent research. Brascamp *et al.* [26••] noted that while the role of priming in attentional selection had been assumed, it had never been explicitly tested. They speculated that the real function of priming could be to steer *where* observers orient (such as to important features like the green color

of your child's coat). Priming paradigms typically predesignate targets but Brascamp *et al.* introduced *choice* trials in-between the search trials, where only two items appeared, one each of the preceding target and distractor colors. Priming determined attentional selection, since participants chose the primed target color on a large majority of trials. Conversely choice trials also determined subsequent priming arguing that priming involves facilitation of attentional selection.

Considerable debate has centered around whether priming reflects feature facilitation or episodic memory of preceding trials. Huang *et al.* [27], observed priming when both target brightness and size were repeated, while when only one feature was repeated and the other changed, RTs were longer than when neither repeated. They argued that priming in visual search reflected episodic retrieval of previous trials (see also Ref. [28]). But Ásgeirsson & Kristjánsson [29••] showed that this finding only applied to difficult searches that did not involve pop-out. Again this suggests that different forms of priming operate at different processing stages. As mentioned before, Kristjánsson & Campana [3] proposed that priming can occur on many perceptual levels, so definitive answers to such questions, may neither exist nor be needed. The available neural evidence indicates that several distinct neural mechanisms are involved in priming [30–36]. Note, that priming has also been observed for locations (Maljkovic and Nakayama, 1996) and recently, Tower-Ricardi et al (2016) found that spatial priming operates within ecologically relevant coordinate frames rather than retinotopic ones, which suggests that spatial priming serves an adaptive role in human behavior.

Recently, Thomson & Milliken [37••], reported that PoP effects can last for up to 16 trials for rare trials that involve different target and distractor colors than on more frequent trials. They also showed that such long-term priming can depend on contextual cues, such as whether the rare trials differed from frequent trials in location or configuration [38•]. These results were used to argue for an episodic view of priming over a feature-based one. Cochrane *et al.* [39••], then showed how, given enough preparation time, an imagined target color different from the primed one, can interfere with priming. These findings are interesting, but appear consistent with the conclusion that priming occurs on many levels and cannot be attributed to a single mechanism. Broadly, the findings involve further demonstrations of a vast capacity for learning, but do not rule feature facilitation accounts out by any means. A strong version of their claims contrasts, for example, with recent findings showing how priming affects masking and visibility [16••,40] and crowding [41•]. Episodic memories of recent trials are unlikely to have such direct effects on perception.

A strong case for pure perceptual priming can be made from the literature on feature repetition during brief presentation. Such paradigms remove the speeded response inherent to RT experiments and can be interpreted as clean measures of perception without contamination from speeded decision making or motor-processes. Ásgeirsson *et al.* [42•,43••], demonstrated reliable priming of repeated color in masked letter displays (<= 200 ms exposures) that, importantly, were independent of the response variable, implicated in several episodic priming accounts [27,28]. Comparing accuracy-based, and RT measures strongly suggests that priming occurs at multiple stages, and that as the number of cognitive processes required to perform a task increases, increasingly multifaceted priming can be observed.

Peremen *et al.* [44••] argued that feature-priming benefits on RTs or accuracy only occurred when subjects were aware of the target during both what they called encoding of priming and at retrieval of priming (prime and probe trials respectively). This was surprising as it contrasts with other results, of unconscious priming from neglected items in hemispatial neglect [36,45]. In general, priming effects can be unconscious [46], and it would be surprising if attentional priming involved an exception.

Serial dependencies

Recent findings on so-called serial dependencies have renewed interest in priming effects in vision and attention. Fischer & Whitney [47••] showed how the perception of an oriented Gabor patch is biased towards the orientation of Gabor patches presented on previous trials. While some have argued that this may reflect a response bias [48], recently Cicchini *et al.* [49••] showed how serial dependencies occur both for perceptual and decision processes. Serial dependence shows how repetition can change appearance. Interestingly, these effects depend on attention [47••], increasing the likelihood that there is a relation between serial dependence and priming (see Ref. [50]). The main difference between serial dependence and priming seems to be that the former alters appearance while the latter affects response times and accuracy. But recent findings indicating that priming can affect visibility [41•,40,16••] complicate this. A challenge for future research will be to determine the relation between serial dependence effects and attentional priming.

Conclusions

Ever since the seminal findings of Maljkovic and Nakayama [1], attentional priming has captured the interest of researchers in vision and visual attention. Priming has a surprisingly large influence on how we orient attention. These repetition benefits are seen for simple features or even-specific episodes. Notably, nothing suggests that the two effects cannot co-occur. Any account that is too restrictive is almost certain to fail. Priming may

simply be a feature of cognitive mechanisms that applies universally, and other history effects occur that are covered better elsewhere than here, such as reward expectation (Failing & Theeuwes, 2018); spatial or featural probability cueing Geng & Behrmann, [51] or contextual cuing Chun, [52]. Utilizing regularities makes good sense since processing of previously encountered stimuli that are still relevant for behavior is faster. The mistake we make is when we try use one repetition benefit to account for another. This overview indicates that priming effects occur at various stages of perceptual processing. These effects are highly reliable, and continue to provide us with information about the operational principles of the visual system while they also raise intriguing questions about visual perception.

Conflict of interest statement

Nothing declared.

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Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

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