Comparing apples and oranges in priming of attentional selection?

Árni Kristjánsson

¹ Icelandic Vision Lab, University of Iceland

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Correspondence:

Árni Kristjánsson PhD
Professor of Vision Sciences
Icelandic Vision Lab
University of Iceland
207 Nýi Garður, 101, Reykjavík, Iceland
ak@hi.is
www.visionlab.is

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Abstract

Priming of attentional selection involves speeded selection of task-relevant visual search items when search stimuli remain constant from one search to the next. In the literature, diverse attentional priming effects have often been assumed to reflect the same mechanisms. Priming effects in various different paradigms (from lower-level to higher-level features) have been used interchangeably to study the nature of priming, even when tasks differ vastly in difficulty and neural mechanisms involved. Another view is that priming is a characteristic of all perceptual mechanisms, that operate at different processing levels. Here, this issue was addressed by contrasting time courses and relative sizes of priming effects for repetition of a lower-level and higher-level feature (colour vs. facial expression). Attentional priming was tested in two odd-one-out search tasks, one involving discrimination, the other a present/absent judgment. The main research question was whether the sizes and temporal profiles of priming for the two features would be similar or not. Firstly, the sizes of the priming effects were very different for colour and expression and secondly, colour priming effects lasted for much longer than expression priming, as measured with memory kernel analyses, suggesting that the mechanics behind the effects differ. These two forms of priming should therefore only be compared with great caution. Generally, the results suggest that priming occurs at many levels of processing and can take many forms. This view is highly consistent with research on the neural mechanisms of priming. Attentional priming should be thought of as a general principle of perceptual processing.

Public significance statement: Attentional priming has very strong effects upon how we organize the world and select from the visual field. This highlights the need to understand its basic underpinnings. Such priming (sometimes called “priming of pop-out”) is often considered to be a unitary mechanism. We approach the question of the nature of priming from the perspective that priming is a general feature of attentional and visual mechanisms. Consistent with this, we show that two different forms of priming effects (for colour and facial expression) show very different profiles both in terms of time-course and size.

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Over the last 60 years, or so, visual attention has been considered to be primarily influenced by bottom-up saliency and top-down guidance (Neisser, 1963; Sternberg, 1967; Treisman & Gelade, 1980; Wolfe, 1994; see recent historical review in Kristjánsson & Egeth, 2020). But it has become increasingly clear that the state of the nervous system at any given time also strongly affects attentional priorities (see e.g. Cicchini & Kristjánsson, 2015; Ramgir & Lamy, 2020 & Kristjánsson & Ásgeirsson, 2019 for recent reviews). This influence of priors from temporal context has, in the field of visual attention, mainly been studied with visual search tasks. Treisman (1992) studied the influence of what occurred on the last trial preceding visual searches where a single feature distinguished the target from distractors (a feature search) and searches where targets differed from distractors by a conjunction of features. Treisman found an intertrial priming benefit in response times of 10% to 15% when the same target appeared in the same location as on the last trial, and a smaller benefit when the same target appeared in a different location. Subsequently, in an influential study, Maljkovic and Nakayama (1994) instructed their observers to look for the oddly coloured diamond among distractors of a different colour and judge whether the target diamond had a notch at the right or left, a task originally introduced by Bravo and Nakayama (1992). Maljkovic and Nakayama (1994) found that observers were much faster when the same search was repeated across adjacent trials, calling this effect "priming of pop-out" (sometimes called PoP).

This terminology firmly placed this effect within the domain of speeded attentional capture by the target. Notably, this effect accumulated with more search repetitions, decreasing search times by 20-25% (Maljkovic & Nakayama, 1994, experiment 7). Additionally, Maljkovic and Nakayama (1996) found strong benefits if the target appeared in the same location as on the previous trial.

This influence of attentional history is important, especially in light of the large role history of attentional selection plays in recent theoretical accounts of visual attention (Awh, Belopolsky & Theeuwes, 2012; Chetverikov, Campana & Kristjánsson, 2017; Kristjánsson, 2022; Luck et al., in press; Theeuwes, 2013). Interestingly, this role of history is increasingly considered to be independent of the influences of top-down guidance and bottom-up feature contrasts, the traditional mainstays of theories of visual attention. Attentional

history plays, for example, a key role in the latest version of the well-known guided search model of attention (version 6.0, Wolfe, 2021).

In studies following up on the original findings of Maljkovic & Nakayama (1994, 1996) it became clear that such priming benefits are seen for a large number of visual search tasks and some argued that priming benefits could partly account for effects that are often attributed to top-down guidance (Ásgeirsson & Kristjánsson, 2019; Kristjánsson, Wang and Nakayama, 2002; see Theeuwes, 2013 for a strong version of such views and Lamy & Kristjánsson, 2013). Additionally, priming seemed to occur for a wide range of visual features, ranging from low-level features such as orientation and spatial frequency (Kristjánsson, 2006; 2009) to high-level features such as facial expression (Lamy et al. 2009, Amunts et al., 2014). Other authors claimed that priming reflected the facilitation of search episodes rather than of attention (Hillstrom, 2000; Huang and Pashler, 2004; see Thomson & Milliken, 2012, 2013, for more recent examples and Ramgir & Lamy, 2020 for a recent review).

Are all priming effects the same?

There is a tendency within the literature to equate all these history effects even though the paradigms used are very different, ranging from simple feature searches to far more difficult search where RT's are doubled or tripled relative to the feature tasks. Many studies involving diverse paradigms have claimed to reveal *the* mechanisms behind priming of attentional selection in a general sense. But there is simply no reason to believe that facilitation from repetition, in general, reflects the same mechanism (as is often assumed either implicitly or explicitly), and that "priming of pop-out (PoP)" reflects a unitary phenomenon. It is important that priming occurs not only for targets that pop out from among distractors, but also more difficult searches so the term "priming of pop-out" is undesirable, although it was certainly appropriate in Maljkovic & Nakayama (1994). It may therefore be preferable to refer to this as priming of attentional selection. An example is the debate over whether "PoP" is episodic, featural or even response related, since it is not clear that the tasks in these studies involve pop-out.

A key question revolves around what is actually primed. Kristjánsson & Campana (2010) and more recently Kristjánsson & Ásgeirsson (2019) have emphasized that priming is simply a characteristic of various forms of processing at different levels within the visual

system and that the nature of the task is not the critical variable. Kristjánsson & Ásgeirsson (2019) concluded in a recent review that priming effects "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. (p. 71)" It seems that individual features can prime independently (Kristjánsson, 2006; Kristjánsson, Ingvarsdóttir & Teitsdóttir, 2008) but also whole search episodes (Thomson & Milliken, 2012,2013; Hillstrom, 2000; Huang, Holcombe & Pashler, 2004) and such different priming effects can even be seen within similar overlapping paradigms that differ only in difficulty, through minor tweaks to the stimulus parameters (Ásgeirsson & Kristjánsson, 2011).

While Maljkovic & Nakayama (1994) originally argued that what was primed was the attended feature and therefore called this "priming of pop-out", others argued against this conclusion. Huang, Holcombe and Pashler (2004) and Hillstrom (2000) argued that the primed entity was selection episodes, while Yashar & Lamy (2010) claimed that priming occurred after attentional selection (see also Ramgir & Lamy, 2020 for an overview). But these conclusions were reached with highly diverse paradigms and there is no certainty that they reflect the same kind of process. A telling example comes from Ásgeirsson & Kristjánsson (2011). They tested a number of variations of a task that Huang, Holcombe and Pashler (2004) had used to argue that what was primed were search episodes rather than features. Ásgeirsson & Kristjánsson (2011) found that priming operated very differently with only slight changes to the signal strength of target against distractors. For difficult search with low signal-to-noise ratios of target against distractors, priming patterns accorded with episodic priming: Priming from the repetition of different features of a target in a visual search task resulted in significant response time (RT) reductions when both target brightness and size were repeated, but when only one feature was repeated and the other changed, RTs were longer than when neither feature was repeated. But when Ásgeirsson & Kristjánsson increased the feature contrasts between target and distractors in an otherwise identical paradigm as the one that Huang et al. used, priming of different features was independent and additive. So, two very similar search tasks resulted in very different forms of priming with only minor tweaks of the task. This makes the idea that priming effects are either featural or episodic suspect as both patterns can occur within virtually identical paradigms. A related issue is that different entities (e.g., individual objects or independent

features) can be primed depending on the nature of the stimuli involved in the search task in each case (Kristjánsson, Ingvarsdóttir & Teitsdóttir, 2008). This general point was also made, for example in Lamy, Yashar & Ruderman (2010), Rangelov, Müller & Zeheleitner (2013) and Zeheleitner, Rangelov & Müller (2012).

The time course of priming

Recent research has revealed that priming of attentional selection has particular temporal characteristics. For example, colour priming effects in pop-out tasks are long lasting (Brinkhuis et al., 2015; 2020; Kruijne et al., 2015), consistent with Maljkovic and Nakayama's (1994, experiment 5) original findings, that stimuli from up to six trials in the past could influence the current one. Additionally, Brinkhuis et al. (2020) found that this long-lasting temporal effect was reflected in the BOLD signal in frontoparietal attention-related areas. Martini (2010) argued that two temporal processes are revealed in priming patterns, a high-gain, fast-decay component and a low-gain, slow-decay component which is consistent with the idea that priming occurs at more than one level. Brascamp et al., (2011) similarly suggested that priming effects contain both rapid and more sustained components.

But similar analyses of temporal patterns have not been performed for higher-level features (such as facial expression) and an important issue is whether priming effects for different features show similar temporal profiles. Unless they do, equating the two is highly suspect. Also, particular markers of priming can be similar while the underlying mechanisms are different (although this is not an issue that is directly addressed here). Generally, it is a problem in research on priming how its time course is often ignored and only repeats or non-repeats are contrasted.

So called memory kernel analyses provide a way of assessing the priming contribution of a single trial (n), i trials in the past (where i can take any value), independently of any effects of the trials in between n and $n-i$. This involves categorizing a target on a given trial (n) as being the same or different as the target on a particular trial, 1-trial, 2-trials, 3-trials (or i trials) in the past (see description in Chetverikov et al., 2019; McPeck et al, 1999). Over a large number of trials, RT's for different targets between n and

$n-i$ should even out (Maljkovic and Nakayama, 1994). To evaluate the influence of a particular trial i trials back, performance on trial n can therefore be compared as a function of whether the target identity on trial $n-i$ was the same or different as on trial n , holding all other trials constant. Notably, similar analyses can be made for any "influence" of *future* trials ($n+i$) on trial n , that cannot, by definition, have any effect on trial n . This analysis of "future" influences can therefore be a useful sanity check and provides an estimate of the noise levels that can be expected in the data (see Marmarelis & Berger, 2005; Martini, 2010 for mathematical explications of kernel analyses).

Current experiments

The experiments introduced here were aimed at investigating similarities and differences between two attentional priming effects. As the discussion above makes clear, priming of a particular property is often used to draw conclusions about another one. Specifically, colour priming (Maljkovic and Nakayama, 1994; Goolsby & Suzuki, 2001; Kristjánsson, 2006) and priming of facial expression (Lamy et al., 2008; Amunts, Yashar & Lamy, 2014) were contrasted within a single, otherwise identical, paradigm. The aim was to contrast priming of very different features, within paradigms that are otherwise highly similar. Images of happy and angry faces from the Radboud database of different facial expressions (Langner et al., 2010) were manipulated in photoshop and tinted red and green with custom filters. This enabled the use of the same stimuli for a colour-based odd-one-out search and an expression-based odd-one-out search where the task was to report the gender of the person in the target image. So, in experiments 1A and 1B the exact same paradigm was used, except that the feature that defined the target (colour in experiment 1A and facial expression in experiment 1B) and which one was the irrelevant one differed. If priming is based on the same mechanisms and can be compared across different tasks, we should firstly expect the two priming effects to be of similar size and secondly, to see similar temporal profiles for the priming effects. To assess the size of the priming effects we used three measures, the percentage change, effect size estimates (partial eta squared, η_p^2) and finally, the influence of a single trial n trials in the past upon the current search was assessed through Kernel analysis (Chetverikov et al., 2019; McPeck, Maljkovic & Nakayama, 1999; Maljkovic & Nakayama, 1994).

In experiments 2A and 2B the task was to judge whether an odd-one-out stimulus (on colour in experiment 2A and facial expression in experiment 2B) was present or not in an array of four visual search items. Again, the aim was to assess the size of the priming effects. Note that this present/absent paradigm is not well suited to reliably assess temporal profiles of priming since there are not enough adjacent target present trials, but instead allows the assessment of the unique priming effect from repeating distractors (Kristjánsson & Driver, 2008).

The main research question was whether the sizes and temporal profiles of priming for the two different features (colour or facial expression) would be similar or not.

Figure 1. The experimental paradigms used in experiments 1A and 1B. In both experiments the task on each trial (N) was to find the odd one out target and judge it's gender. In experiment 1A the odd face image was tinted in a different colour than the other items while in experiment 1B the odd image had a different facial expression than the other items. The 4 faces on each trial each showed a different person (2 male and 2 female). Kernel analyses were used to assess the independent influence of a single trial N , i trials in the past (see methods for details).

General methods

Hardware and Software Used for Designing and Running the Experiments

Custom software written in Python within PsychoPy (Peirce 2007, 2009) was used to control stimulus presentation, measure response times and record whether observers responded correctly. The experiment was run on a CoolerMaster Elite 342 m/500W computer with 8 GB RAM with a GeForce GT 610 graphics card. The stimuli were presented on a 27-inch Asus PG279Q LCD monitor with a 60Hz refresh rate.

Stimuli

Each trial started with the presentation of a white (56.6 cdm^{-2}) fixation cross for 750 to 1250 ms on a dark grey background (37.2 cdm^{-2}), followed by a search display containing four face images (each sized 2.8° by 3.8° at 4.5° from screen centre, assuming 60 cm viewing distance) on the same background. Viewing distance was set to be as close to 60 cm as possible. The 4 items were always equidistant from one another either at the N, S, E, W or the NE, NW, SW, SE locations (randomly determined on each trial, see figure 1). Four faces from the Radboud database were used on each trial (2 male and 2 female, each of the 4 faces always involved a different person). They were colour-filtered in photoshop with red tinted (mean 21.3 cdm^{-2}) and green tinted (mean 23.5 cdm^{-2}) uniform filters. In experiment 1A the target was the oddly coloured item where 3 items were red and 1 (the target) was green, or vice versa. In this case expression was not unique to any item since 2 had a happy expression and 2 an angry expression. In experiment 1B the target was the one with the odd expression (3 had a happy expression and 1, the target, had an angry expression, or vice versa) where 2 items were red and 2 were green so that colour never distinguished the target. The identity of the faces on each trial was randomly determined except that there were always 2 male and 2 female faces and each face within a trial had a different identity so only the critical feature in each case (colour or expression) determined target identity.

Procedure

Figure 1 shows the paradigms in experiments 1A, where the task was to find the odd target in terms of colour and report it's gender and experiment 1B where observers had to find the target with the odd expression (happy or angry) and again report it's gender. A target was

therefore present on all trials. Observers responded by pressing the left arrow key if the target was male and the right arrow key if it was female.

Participants

In experiment 1A, 13 observers participated in 468 trials in 3 blocks of 156 trials and in experiment 1B 13 participants participated in 468 trials in 3 blocks (2 observers did not finish experiment 1B and were therefore excluded). The participants (7 female, mean age 22.5 years) were the same and the order of the experiments was counterbalanced across experiments, which allows considerable comparison of the data from experiments 1A and 1B.

Sample size selection

To calculate the required sample size, the Superpower toolbox was used (Lakens & Caldwell, 2019). Estimates of effect sizes in priming studies were extracted from a number of different studies from the priming literature, including the most relevant ones for this particular study (Maljkovic and Nakayama, 1994; Goolsby & Suzuki, 2001; Kristjánsson, 2006; Lamy et al., 2008; Amunts, Yashar & Lamy, 2014). The estimates for the sample size for reliably detecting differences at $p < .05$ ranged from 6 to 11 observers depending on study. The results were compared with sample size estimates from G*Power (Faul, Erdfelder, Buchner, & Lang, 2009) which yielded very similar results. Thirteen participants were therefore recruited for each experiment in an attempt to ensure enough statistical power for reliable assessment of the size and time course of the priming effects.

Results and discussion - Experiments 1A and 1B

In experiments 1A and 1B priming of colour and facial expression was contrasted in otherwise identical paradigms. In experiment 1A the odd-one-out feature was colour, while it was facial expression in experiment 1B. In both experiments, observers had to report the gender of the person in the odd-one-out image. As figure 2 shows, there was a strong colour priming effect in experiment 1A, $F(4,48)=19.101$; $p = 1.89 \times 10^{-9}$; $\eta_p^2=0.614$. Additionally, the

effect of priming of facial expression in experiment 1B was also strong, $F(4,40)=12.15$; $p = 1.2 \times 10^{-6}$; $\eta_p^2=0.556$.

Figure 2. The results from experiments 1A and 1B. The upper panel shows the response times for experiment 1A (in green) and from experiment 1B (in red). The error bars show the 99% confidence intervals. The lower panel shows the error rates in the same colour scheme.

The first notable observation is that priming occurs for repetition of both facial expression and for colour. But there are also highly notable differences between the priming effects for the two tasks. Firstly, there is a dramatic difference in the difficulty of the two search types. Finding the odd expression takes about 1500 ms longer (recall that the same participants took part in both tasks, so comparisons can be made rather straightforwardly). At first glance the priming profiles appear to be very similar – since the downward slope as a

function of repetition is rather similar. But this tells only half the story. In terms of percentages, the priming effect for colour is far larger (21.1% versus 11.5%; see further analyses of the size of priming effects in the kernel analyses below). Since the RT's are far longer for expression search, one might actually expect the priming to have a larger effect in that condition, but the opposite is actually true, arguing that the colour priming effects are, in fact, considerably stronger. The percentage differences between the two priming effect were compared with a t-test ($t_{(10)} = -2.643261$; $p = .0246$) confirming that the difference between the two was significant.

Do the irrelevant features prime?

When colour was the target defining feature, the facial expression of the target could either repeat or the target expression could change between trials. The priming effects from the repetition of these task irrelevant features can therefore be assessed. For experiment 1A a 3 by 3 ANOVA (no repetition, 1 repetition and 2 repetitions of colour and expression; 3 and more repetitions resulted in empty cells for many conditions) revealed a strong effect of colour repetition $F(2,24) = 60.272$; $p < .001$, ($\eta_p^2 = .417$) while the effect of expression repetition was not significant, $F(2,24) = 2.163$; $p = .137$ ($\eta_p^2 = .076$). The two effects did not interact $F(4,48) = 1.17$, $p = .334$ ($\eta_p^2 = .022$), showing that priming of colour did not differ by any priming of facial expression, nor vice versa. Bayes factors were calculated for the findings of no difference (see Dienes, 2014), for expression repetition the BF was 0.19, constituting moderate evidence for the null hypothesis and for the interaction the BF was 0.14 constituting strong evidence for the null hypothesis.

In experiment 1B there was a strong effect of repeating facial expression $F(2,20) = 19.518$, $p < .00001$ ($\eta_p^2 = .31$) while there was no significant effect of target colour repetition $F(2,20) = .775$, $p = .474$ ($\eta_p^2 = .03$); BF = 0.17. Again, the interaction between the two effects was not significant, $F(4,40) = .882$; $p = .484$ ($\eta_p^2 = .034$); BF = 0.12. Kristjánsson (2006, 2009) observed considerable limits on whether irrelevant visual search features led to priming or not and speculated that this might reflect the differences and to some extent the overlap in the neural mechanisms involved in the processing of the different features (see General Discussion). Here, there were no significant priming effects from irrelevant features.

Kernel analyses – Experiments 1A and 1B

Kernel analyses allow the assessment of the influence of trial $n-i$, i trials in the past (where i can be any number) upon the current trial n , independently of any influence of the trials between $n-i$ and n . Figure 3 shows the results from kernel analyses of Experiments 1A and 1B. The results reveal marked differences between the two forms of priming. The priming influence is much longer lasting for colour, significant priming at $p .01$ (indicated by the shaded regions in figures 3A and 3B) lasting for at least 5 trials as previously observed by Maljkovic & Nakayama (1994), whereas only the last two trials before the current one lead to expression priming.

Figure 3. The results of kernel analyses for experiments 1A and 1B. Shaded areas in panels A and B show where the differences between when the same target feature (colour or expression) were significant (at $p < .01$). Letters denote the evidence for the hypothesis of a difference between feature repetition and feature change according to Bayes Factors (N denotes no evidence for the hypothesis of a difference between the two means, similarly M denotes moderate evidence, S strong evidence and VS very strong evidence for the hypothesis of a difference between the means).

Overall, experiments 1A and 1B clearly show how the size and duration of the colour priming effect dwarfs the size of the facial expression priming effect. This is consistent with the effect size estimates from the ANOVA analyses above. What this indicates is that priming influences from these two different features should only be compared with great caution. The large difference in the modulatory effects of priming makes it quite suspect to use results from one form of priming to draw any strong conclusions about the nature of another priming effect nor to conclude that priming effects of different features reflect modulations of the same mechanism.

EXPERIMENTS 2A and 2B

To further investigate the priming patterns for the repetition of colour and expression, in experiments 2A and 2B, priming was assessed with a different visual search paradigm involving judgement of whether an odd-one-out target was present or not in each display. Such paradigms have previously been shown to induce priming effects (see e.g. Kristjánsson, Wang & Nakayama, 2002; Wang, Kristjánsson & Nakayama, 2005). Among other things, this enables assessment of effects of priming from distractor sets independently of priming effects from target repetition. Maljkovic and Nakayama (1994, experiment 8) and later Kristjánsson, Wang and Nakayama (2002), and Wang Kristjánsson & Nakayama (2005, experiment 6) showed how distractor repetition can exert its' own priming influence, a finding further developed by Kristjánsson & Driver (2005; 2008; see also Lamy et al. 2008; Saevarsson et al. 2008).

Methods

Methods were similar to experiments 1A and 1B except that a target was only present on 2/3 of the trials and instead of judging the gender of the odd-one-out target, observers responded whether an odd-one-out target was present or absent (odd colour in experiment 2A and odd expression in experiment 2B). Other task-irrelevant features were constant within trials. As in experiments 1A and 1B there were four items on the screen, but now, on 1/3 of trials no target was present, so that all the stimuli were distractors, all having the

same colour in experiment 2A and the same expression in experiment 2B. This asymmetry in target present/target absent ratios was applied to provide enough target present trials to enable reliable assessment of any effects from repetition of target features. In both experiments 2A and 2B there were 13 observers (8 females, mean age 22.5 in experiment 2A; 7 females, mean age 26.6 in experiment 2B). Each observer participated in 234 trials in 2 blocks (total 468 trials). One observer in each experiment (2A and 2B) did not finish the data collection, leaving 12 observers in each experiment. Observers were told to find an odd-one-out target and press the right arrow key if they found one and press the left arrow key if no odd-one-out target was present on the screen. They were asked to respond as quickly as possible while also performing as accurately as they could. There was little overlap in the participant groups in these two experiments.

Results and discussion – Experiments 2A and 2B

Figure 4 shows the results for experiments 2A (search for an odd-one-out target on colour) and 2B (odd-one-out on expression) as a function of consecutive search repetitions (0, 1 or 2 or more repetitions). Again, we see that there is a large difference between the two search types in response times, where observers respond much faster during the odd-colour search than the odd-expression search, indicating that the colour condition was much easier for observers. In experiment 2A a 3 by 3 repeated measures ANOVA (with the factors repetition of target colour and repetition of target expression) showed a strong main effect of the repetition of target colour $F(2,22) = 86.205$; $p = 3.9 \times 10^{-11}$, $\eta_p^2 = .443$ while the effect of repetition of facial expression (in this case irrelevant feature) was not significant $F(2,22) = 1.387$, $p = .271$, $\eta_p^2 = .056$. In addition, the interaction between these two factors was not significant $F(2,22) = .708$, $p = .59$, $\eta_p^2 = .03$. There was, in other words no evidence of any priming from the irrelevant feature in experiment 2A.

In experiment 2B where facial expression was the task relevant feature there was a significant effect of the repetition of target identity, although it was smaller than in 2A. A 3 by 3 repeated measures ANOVA showed a main effect of the repetition of target expression $F(2,22) = 6.71$; $p = .0053$, $\eta_p^2 = .309$ while the effect of colour repetition (in this case the irrelevant feature) was not significant $F(2,22) = .503$, $p = .271$, $\eta_p^2 = .032$. The interaction between these two factors was not significant $F(2,22) = .396$, $p = .59$, $\eta_p^2 = .026$. In other

words, as in experiment 2A, the effect from repeating the irrelevant feature was not significant.

The size of the priming effects

The difference in the size of the two effects was considerably larger than in experiments 1A and 1B, for colour in experiment 2A it ranged from 17% to 24% for the different observers, but only from 1-3% in experiment 2B. This corresponds with what the effect size estimates for the two repetition effects also revealed ($\eta_p^2 = .443$ for colour repetition in experiment 2A and $\eta_p^2 = .309$ for expression repetition in experiment 2B). It is important to note that there was little overlap in the participant groups in the two experiments, which makes direct comparisons not as straightforward as for experiments 1A and 1B. Nevertheless, a one-way ANOVA was performed to compare the size of the effects, revealing a large difference between the two effects $F(2,22) = 5.5, p < .001$. Again, this difference in the size of the priming effects argues for important differences between the two forms of priming.

Figure 4. The response times from experiments 2A (colour search) and 2B (expression search) as a function of the repetition of the task-relevant and task-irrelevant features. The error bars show 99% confidence intervals.

Effects from repetition of distractor sets

Since no targets were presented on 1/3 of the trials in experiments 2A and 2B, this allows the measurement of priming effects from repeated distractor sets (see e.g., Wang et al., 2005; Saevarsson et al., 2008). Figure 5 shows the effect of repeating distractor identity both when the target is present and when it is absent. Figure 5 clearly shows that repeating distractor identity also causes priming, that leads to benefits both on trials where the target is present and when it is absent. For colour search, a 2 by 2 ANOVA (with the factors target presence and repetition) showed a significant effect of distractor repetition ($F_{(1,11)} = 17.3$; $p < .01$) while neither the effect of target presence nor the interaction were significant (p 's $> .3$). For expression search there was again a significant effect of distractor repetition ($F_{(1,11)} = 11.16$; $p < .05$) and a significant effect of target presence ($F_{(1,11)} = 5.11$; $p < .05$) but no interaction ($p > .5$). In terms of percentages, this priming effect was once again much larger for colour than for expression (10% versus 3% respectively).

Figure 5. The effects of repeating distractor sets in experiments 2A and 2B, shown separately for target present (purple) and target absent trials (blue). The error bars show 99% confidence intervals.

Error rates

Error rates were, overall, very low in experiments 2A and 2B (see table 1) and do not provide much information because of this. But the most notable finding is that the target present error rates were higher than the target absent rates in experiment 2A while this was reversed in experiment 2B (repetition did not significantly affect error rates, all p 's > .3). This suggests that observers had a slight bias towards false alarms in 2A and misses in 2B, which falls in line with the fact that finding the target was much harder in experiment 2B than in experiment 2A.

Table 1: Percentage error rates in experiments 2A and 2B

		Repetition			Target absent
		1	2	3	
Experiment 2A	Colour	1.93	1.17	0.87	4.58
Experiment 2B	Expression	6.02	7.89	7.33	5.27

GENERAL DISCUSSION

Attentional priming, often called 'selection history', plays an increasingly large role in theoretical accounts of attention (Awh, Belopolsky & Theeuwes, 2012; Chetverikov, Campana & Kristjánsson, 2017; Kristjánsson, 2022; Luck et al., in press; Theeuwes, 2013) including the latest version of the well-known guided search model (version 6.0, Wolfe, 2020; see Kristjánsson & Ásgeirsson, 2022; Ramgir & Lamy, 2020 for recent overviews). This highlights the need for a thorough understanding of these history-based processes. The main motivation behind the research presented here was to address a tendency within the literature on attentional priming to place seemingly diverse priming effects under the single hat of "priming of pop-out", even effects in paradigms that cannot be said to involve a situation where a target pops out among distractors. So the current aim was to assess to what degree priming effects from very different features are comparable, or more specifically, whether the sizes and temporal profiles of priming for the two features are similar or not. This was addressed here by contrasting attentional priming from colour (a

basic lower-level feature) on the one hand and facial expression (a higher-level feature) on the other, but crucially within otherwise identical paradigms.

The results draw up clear distinctions in terms of the time course and the size of priming effects of colour and facial expression. The priming effects from colour in experiments 1A and 2A were much larger than for expression in experiments 1B and 2B. This was especially notable when the priming for the two features was contrasted in a present/absent visual search task in experiments 2A and 2B. Secondly, the Kernel analyses in experiments 1A and 1B revealed that the time courses of the two priming effects differ markedly, where for colour, a priming influence was notable from at least 5 trials in the past, while effects from only 2 trials in the past were seen for expression. This makes the case that the two priming effects have differing effects upon behaviour, and the most likely reason is that the priming in these paradigms reflects history modulations of different perceptual mechanisms at all levels of the hierarchy of perceptual processing (Kristjánsson & Ásgeirsson, 2019). In a review of the priming literature Kristjánsson and Campana (2010) made this point strongly and concluded that "priming occurs at many different levels of the perceptual hierarchy, reflecting activity modulations ranging from lower to higher levels, depending on the stimulus, task, and context" (p. 5). This point was echoed in a more recent review (Kristjánsson & Ásgeirsson, 2019) who argued that "priming effects [...] occur on many levels of perceptual processing, and [...] these effects cannot and should not be thought of as reflecting the operation of any single type of mechanism" (p. 71). And later they claimed: "the mistake we make is when we try use one repetition benefit to account for another" (p. 74). The research here was inspired by this issue. A second key question (that partially overlaps with the first one) involved whether priming is similar for tasks involving pop-out and more difficult tasks.

Neurology, physiology and neuropsychology of priming

With regard to the question of whether priming is a general feature of perceptual mechanisms and whether priming effects reflect the characteristics of the differing neural mechanisms involved in the processing in each case, it is useful to look at what is known about the neural mechanisms behind the priming effects. It is important to note, however,

that I am not claiming that the evidence presented here has direct bearing upon what the neural mechanisms of priming are. While the neurophysiology of priming has received less attention than the behavioural characteristics, a number of studies are available (see Westerberg & Schall, 2020 and Kristjánsson, 2022 for recent reviews). The first important observation, regarding neurophysiological and neurological evidence, is that priming effects show great variability and diversity in the neural mechanisms involved. With regard to the current findings, it is firstly important to note that the two stimulus types tested here involve processing within very different neural mechanisms. Facial expression is processed in areas such as the fusiform face area and the amygdala (Vuilleumier & Pourtois, 2007; Kanwisher et al., 1998) while the primary colour processing area of the cortex is V4 in the ventral stream (see e.g. Bartels and Zeki 2000).

Neuroimaging. The idea that priming is a general mechanism of different modules in the brain that serve differing functions, is consistent with findings from neuroimaging that show that priming of colour, for example, causes BOLD activity modulations in areas related to the processing of colour, areas such as V4 while location priming is connected with processing in, for example, the intraparietal sulcus (Brinkhuis et al., 2020; Kristjánsson et al., 2007; Rorden et al., 2011). It seems unreasonable to expect that these two very different features lead to similar priming effects and that the temporal profiles will be similar, especially if the neural mechanisms behind the priming are so different as seems likely from the fMRI findings. The fMRI results for colour and location priming also show that attentional networks such as the frontal eye fields and the intraparietal sulcus (sometimes referred to as the frontoparietal attention network) are modulated with priming (Becker, Grubert & Dux, 2014; Brinkhuis et al., 2020; Geng et al., 2006; Kristjánsson et al., 2007).

It is also important to note an important finding regarding the temporal characteristics of priming reported by Brinkhuis et al., 2020 who found that the BOLD signal modulation matched the measured temporal profiles of the priming as seen in Brascamp, Pels & Kristjánsson (2011; see also Geyer & Müller, 2009; Goolsby & Suzuki, 2001; Kruijne et al., 2015; Maljkovic & Nakayama, 1994) as well as the findings here. This is consistent with the idea of multiple loci for the priming, since there is also behavioural evidence of different temporal profiles during priming (Martini, 2010; Brascamp et al. 2011) and importantly these findings demonstrate two different temporal priming profiles for the same task.

Brinkhuis et al. (2020) reported BOLD signal modulations supporting this account of different temporal profiles. The fact that two simultaneous but distinguishable components seem to be involved in the priming effects again argues against unidimensional accounts of priming.

Single-cell neurophysiology. Findings from single-cell neurophysiology show that diverse areas are connected with the priming effects. In an influential study, Bichot, Schall & Thompson (1996) showed that neurons in the frontal eye fields start to show feature selectivity (for colour) as observers (macaque monkeys) learn to perform a visual search task. Bichot and Schall (2002) then showed that this can occur in the short-term as well, using a standard priming paradigm similar to the ones we use here and introduced by Maljkovic and Nakayama (1994). During a visual search task that required the monkeys to make saccades to oddly coloured targets, frontal eye field neurons discriminated target properties more quickly and more accurately when the same features distinguished the target as on the last trial. More recently, Westerberg, Maier & Schall (2020) showed that target selection in area V4 (more specifically, the time when responses to targets diverge from distractor responses) are speeded (as seen previously for the frontal eye field, Bichot & Schall, 1999, 2002). Westerberg et al. (2020) also found evidence of enhancement from repetition of targets and suppression from repetition of distractors. The distinguishable distractor repetition effects are important, since they are very notable in behavioural priming patterns and can be separated from target effects (see Kristjánsson & Driver, 2008; Lamy et al., 2008 and discussion above).

Neuropsychology, ablation and TMS. Notable insights have also been gained into the nature of attentional priming from studying people with neurological problems, studies of lesioning of animals, or temporary artificial "lesioning" of human observers with TMS. Kristjánsson et al., (2005) studied priming of location and colour in patients with hemispatial neglect from lesions in the right parietal cortex. They found that search performance was speeded when either the location or colour of a singleton target was repeated over successive trials both from and to targets in the patients' contralesional visual field. But they also observed a notable dissociation in that location priming only arose from preceding left hemifield targets that were consciously detected, but colour priming did not depend on awareness of the

preceding target. This is likely to reflect that the colour priming arises from within intact mechanisms related to colour processing in the ventral stream. This colour priming effect for neglect patients was replicated by Saevarsson, Jóelsdóttir, Hjaltason & Kristjánsson (2008) who also studied the performance of patients with neglect in a paradigm aimed at specifically testing priming from distractor sets. They found that repetition of distractor sets (or context) in visual search was mostly intact for patients suffering from hemispatial neglect and they went as far as claiming that context repetition can temporarily ameliorate neglect symptoms by facilitating visual search. So the mechanisms for location priming seem to differ from those involved in distractor priming, once again highlighting the varied nature of the priming effects.

Campana et al. (2007) and Campana, Cowey, & Walsh (2006) then revealed a double dissociation of priming effects, reporting that disruption of area V5/MT with transcranial magnetic stimulation (TMS) abolished priming of motion direction while priming of spatial position was intact. Conversely, they found that TMS applied to the left frontal eye field strongly reduced priming of spatial position, but did not affect priming of motion direction (see O'Shea, Muggleton, Cowey, & Walsh, 2007, for related results). Moreover, whereas area V5/MT in humans has been shown not to be involved in colour priming (Campana, Cowey, & Walsh, 2002), the ablation of areas V4 and TEO in monkeys has been found to eliminate colour priming even though colour discrimination was normal (Walsh, Le Mare, Blaimire, & Cowey, 2000). These studies suggest that the particular neural mechanisms involved in the processing of a given perceptual attribute (a particular feature or spatial position) also show activity modulations that can explain the priming effects seen for that particular attribute, indicating that the priming effects are distributed throughout the brain at diverse sites involved in the processing in question.

EEG evidence. Eimer, Kiss & Cheung (2010; see also Becker et al., 2014) reported that the so-called N2pc component of the EEG signal is temporally affected by priming. The N2pc is thought to reflect the operation of attention so this finding is overall consistent with the idea that the priming effects are related to attentional function and is part of the reasons behind the terminology of *attentional* priming. But research on EEG has also revealed other components related to priming. Westerberg, Maier et al (2020) found EEG evidence that

performance monitoring signals are modulated with priming. This finding is consistent with fMRI evidence for modulations of the anterior cingulate cortex (Brinkhuis et al, 2020) that are likely to reflect performance monitoring.

To summarize, the findings from various neurophysiological measures clearly indicate that attentional priming reflects activity modulations of many different neural mechanisms operating at various stages throughout the visual system. In many cases, the neural mechanisms concerned with the processing of particular features of the stimuli are modulated when priming occurs, according to the primed features in each case. Kristjánsson & Campana (2010) argued that the neurophysiological findings were consistent with the proposal that priming of perceptual attributes depends on a general memory system, called the *perceptual representation system*, proposed by Tulving and Schacter (1990) and Magnussen & Greenlee (1999). This memory system is considered to be largely unconscious and involves a number of different subsystems that each are dedicated to the retention of a certain feature of the primed object, that reside at different levels of the perceptual hierarchy at the feature appropriate sites.

What can different forms of priming tell us?

Other evidence for something that might be called a multifactor view of priming comes from behavioural studies involving response time or accuracy measurements. Some authors have argued that "priming of pop-out" reflects priming of episodic representations of past search trials, instead of feature-specific facilitation. For example, Huang, Holcombe and Pashler (2004) found that during visual search when a target of the same size was repeated, search was faster if the brightness of the target was also repeated. On the other hand, when target size differed between trials, repetition of target brightness harmed performance. Huang et al. argued that when single features are repeated, the pattern was consistent with feature facilitation but such interactions in the priming occur when different features are independently repeated. They proposed that priming does not affect features but reflects episodic memory traces of the foregoing trial, a view previously proposed by Hillstrom (2000).

It seems clear that such episodic representations may prime between trials, but evidence in the field also indicates that different single features can prime depending on the context. In fact, there is nothing that precludes that the two effects could occur either simultaneously or separately depending on context. A good example comes from Ásgeirsson & Kristjánsson (2011) who investigated what might be called the boundary conditions of episodic priming. They used the task that Huang, Holcombe & Pashler (2004) had used to argue that the original findings of Maljkovic and Nakayama (1994) reflected episodic priming rather than priming of features. Ásgeirsson and Kristjánsson found that episodic priming only occurred when target-distractor discrimination was difficult. When they increased the feature contrasts (making the search easier) the priming pattern clearly reflected the priming of independent features. Their findings therefore showed how two forms of priming can co-exist within virtually identical paradigms. Findings relevant to this were also reported in Kristjánsson (2006, 2009) where different features could prime independently even though they belonged to the same object. So, for example, attended features of a Gabor patch can prime, but unattended features within the same object did not lead to priming which is clear evidence of feature-based priming.

Further evidence for what could be called episodic priming comes from Thomson & Milliken (2012) who reported that rare search trial types (such as a red target among green distractors) presented within a sequence of more frequent trial types (e.g. blue and yellow items) caused priming effects even when up to 16 trials of the more frequent search type intervened. They argued that the priming could not reflect feature priming, but that the search episode was retained. Note that while this may argue against a pure feature facilitation view of priming it is quite consistent with the view proposed here that various perceptual mechanisms can be primed. And notably, there is no a priori reason why feature facilitation could not be long lasting. Thomson & Milliken (2013) also showed that such long-term priming can depend on whether the rare trials differed from frequent trials in location or configuration – the priming can in other words depend on context. Furthermore, Cochrane, Xhu & Milliken (2020) showed that given enough preparation time, an imagined target colour different from the primed one, can interfere with priming. Both these results were used to argue for episodic over feature-based priming. But these interesting findings

merely appear to be consistent with the proposal that priming occurs on many levels and should not be considered to reflect a single mechanism.

Another account is the so-called relational encoding account of priming (Becker, 2008; 2013) where the entity that is assumed to be primed is the relation between the target and distractor features. While this account has merit and is supported by data, it is once again important to note that priming most likely occurs at many different levels. This question may in fact be highly related to recent discussions of how attentional templates may be biased through selection history (see e.g. Carlisle & Kristjánsson, 2018; Chetverikov, Campana & Kristjánsson, 2020; Geng, DiQuattro & Helm, 2019; Hansmann-Roth et al., 2001; Navalpakkam & Itti, 2007; see Geng, Won & Carlisle, 2019 and Kristjánsson, 2022 for reviews) where target-distractor relations play an important role in biasing templates.

Temporal characteristics of priming.

An often overlooked characteristic of priming was a major part of the original investigations of Maljkovic and Nakayama. They used kernel analyses to assess the temporal course of priming effects, that have the notable feature that they allow the assessment of a single trial 1, 2, 3 or more (or n) trials preceding the current one, independently of any influences of intervening trials (see e.g. Chetverikov et al., 2019). For colour, they observed that the influence of a single trial during colour repetition could be observed from up to 5 trials in the past. This result is replicated here. Even more interestingly, in the current study, the temporal pattern was quite different for priming from colour versus expression since significant expression effects only lasted up to 2 trials into the past. This difference makes it unlikely that the same mechanism is involved in the two priming effects. It seems quite clear that temporal profiles are highly important characteristics of attentional priming, and it is therefore regrettable that many studies in the literature have only looked at repeats versus non-repeats, presumably pooling the data for different repetition numbers (see e.g. Cochrane et al. 2018; Milliken & Thomson, 2011; Olivers & Meeter, 2006; Peremen, Hilo & Lamy, 2013; Pinto, Olivers & Theeuwes, 2005; Theeuwes, Riemann & Mortier, 2006). What our data indicate is that there may be a lot of information hidden in temporal profile data from published studies.

Finally, the caveat should be noted that of course a situation can be envisioned where the exact same mechanisms can explain the priming patterns, and that differential activation of this single mechanism explains priming in a general sense. The problem is that such an explanation seems neither likely, nor particularly parsimonious especially in light of the neural evidence showing how distributed the priming effects are. And it is not clear which single mechanism would then explain the varied priming patterns.

Conclusions

The results here make the case that we should use findings from one particular paradigm to explain priming in a general sense only with great caution. The findings most likely reflect that priming occurs on many levels and its manifestations can vary depending on stimulus or context because various different mechanisms are primed. This is in fact the most parsimonious explanation for diverse findings in the literature. Many accounts of priming have been proposed, feature facilitation (Maljkovic & Nakayama, 1994; Kristjánsson, 2006) episodic retrieval (Hillstrom, 2000; Huang et al., 2004; Thomson & Milliken) response facilitation (Burnham, 2018) and relational coding accounts (Becker, 2008) that all have their merit, and can explain parts of the large amounts of data available. But, in the end, this scenario seems merely best suited to support the claim that priming is multifaceted.

So, is it useful think of priming of attention shifts as a single phenomenon? The answer is clearly no. But is it useful to think of priming as a general principle of neural mechanisms involved in visual processing? The answer to this question is yes, as long as we are open to the different manifestations of the effects, such as their different sizes and time courses. Kristjánsson (2022) has recently made the case that templates for attentional selection and rejection are dynamic and modulated by the temporal, spatial and featural context, and that priming of attentional selection can help us to achieve this by keeping us on track in our interactions with the environment. For this to work well, it should be able to operate at various levels of perceptual processing.

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