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The mechanism of priming: Episodic retrieval or priming of pop-out?

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Abstract

Previous studies indicate that priming affects attentional processes, facilitating processes of target detection and selection on repetition trials. However, the results are so far compatible with two different attentional views that propose entirely different mechanisms to account for priming. The *priming of pop-out hypothesis* explains priming by feature weighting processes that lead to more frequent selections of nontarget items on switch trials. According to the *episodic retrieval account*, switch trials conversely lead to temporal delays in retrieving priority rules that specify the target. The results from two eye tracking experiments clearly favour the priming of pop-out hypothesis: Switching the target and nontarget features leads to more frequent selection of nontargets, without affecting the time-course of saccades to a great extent. The results from two more control experiments demonstrate that the same results can be obtained in a visual search task that allows only covert attention shifts. This indicates that eye movements can reliably indicate covert attention shifts in visual search.

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Keywords: Visual search; Attention; Eye movement; Pop-out; Priming

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1. Introduction

Visual attention selects specific items from a cluttered visual scene for further processing and discards irrelevant information. Given the importance of attention for conscious perception and action, researchers around the world have taken great efforts to find out what guides attention.

Selective attention has often been explored with the help of visual search paradigms, in which the task is to find a certain, pre-specified object among several nontarget items. The speed or efficiency of visual search is thereby known to be influenced by a number of different factors, like, for example, the number of nontargets: Searches in which response times (RTs) linearly increase with the number of nontargets are called ‘‘inefficient’’. Such a dependency of search times on the set size often occurs when the nontargets are highly dissimilar from each other, or else when the target shares one or more features with the nontargets (Duncan & Humphreys, 1989). On the other hand, when RTs are independent of the number of nontargets in the display, search is called ‘‘efficient’’. A corresponding result pattern can often be observed when the target constitutes a singleton, that is, when it differs in a single feature from nontarget items which are homogenous with respect to this feature (e.g., Treisman, 1982; Treisman & Souther, 1985). Phenomenally, singletons appear to ‘‘pop-out’’ from the display, which led to labelling the effect ‘‘*pop-out effect*’’.

Efficient search for such pop-out targets is usually taken as a diagnostic that the target can be detected pre-attentively, such that selective attention can immediately be guided to the respective location. Formerly, search efficiency has been thought to depend solely on the salience of the target, that is, on the feature difference between

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the target and the surrounding nontarget items (e.g., Theeuwes, 1991, 1992). Later, however, it has been shown that the pop-out effect of singleton targets also depends on the search history: Responses to a pop-out target are faster when the target feature is the same as in the previous trial, than when its features change, compared to the previous trial. This intertrial effect is also frequently referred to as "priming effect" or simply "priming" (Maljkovic & Nakayama, 1994, 1996, 2000).

1.1. Visual and response-selection views of priming

One of the first and foremost questions about the priming effect concerns the stage of processing at which priming affects search performance. Nowadays, researchers distinguish between *visual* and *response-selection views* of priming (cf. Olivers & Meeter, 2006). According to a *visual selection view*, repeating the target feature facilitates attentional processes of target detection and selection. Conversely, proponents of a *response-selection view* claim that priming does not affect attentional processes involved with search, but that it modulates later, post-selectional, processes. Such post-selectional processes might, for instance, concern perceptual identification processes or decisional processes that verify whether an already selected item is the target (Huang, Holcombe, & Pashler, 2004), or stimulus-to-response mappings (e.g., Cohen & Magen, 1999). Naturally, post-selectional priming effects might also contain any mixture of perceptual, decisional and response-related processes.

The available evidence on the feature priming effect favours a visual selection view: First of all, in compound search tasks, repetition facilitation effects can only be regularly observed with respect to the target-defining feature, but not for the response-related feature (Goolsby & Suzuki, 2001; Kristjansson, 2006; Maljkovic & Nakayama, 1994, 2000). Secondly, Goolsby and Suzuki (2001) showed that both pre-cueing of the target position and presenting the target alone in the search display reduces or even eliminates the effect of the previous, $n - 1$ trial. The absence of priming in conditions where the target does not have to be attentionally selected in turn indicates that priming usually affects attention shifts to the target position. Moreover, evidence for the attentional nature of feature priming also derives from eye tracking studies, which show that saccadic latencies to the target decrease as the number of repetition trials increases (Kowler, Martins, & Pawel, 1984; McPeek, Maljkovic, & Nakayama, 1999). More recently, it has also been shown that the duration needed to visually select a target ("target fixation latency") is shorter on repetition trials than on switch trials (Becker, submitted for publication).

1.2. Two different attentional views on priming

However, even if priming indeed operates on the attentional, and not post-selectional stage of search, it must be contended that the evidence is compatible with two different attentional hypotheses of priming, the *priming of pop-out hypothesis* and the *episodic retrieval view*. Although both hypotheses propose that repeating the target-defining feature facilitates processes of target detection and selection, the two accounts also differ in important respects. Most notably, two entirely different mechanisms have been proposed to account for the feature priming effect.

1.3. Priming of pop-out: A feature valencing account of priming

The priming of pop-out hypothesis centrally asserts that priming modulates the pop-out effect (or "attentional priority", or "attention-driving capacity") of the target-defining feature on a trial-by-trial basis: Upon successful detection of the target, the target-defining feature is encoded by a memory trace, which carries over to the next trial and facilitates attention shifts to this feature on subsequent trials. According to the "capacitor model" of Maljkovic and Nakayama (1996), the information that is transferred between trials can be conceived of as attention-driving "charges" or "valences" that are added to the activation signal of the target in case it is repeated, or to the nontarget feature in case target and nontarget features switch. In a pop-out search task, the activation signal guiding attention to the target is already high, because of its saliency, or feature contrast to the surrounding nontargets (e.g., Wolfe, 1994). Priming further modulates this activation signal, so that attentional guidance to the target will be speeded on repetition trials, in which the activation signal of the target feature is enhanced by added activation from the previous trial(s). In turn, target selection will be hampered on switch trials, in which enhanced activation of the nontarget feature favours selection of the nontargets, and-/-or produces additional noise. From this it follows that the target will be selected faster on repetition trials than on switch trials, in which attention is first misguided to the nontargets (Maljkovic & Nakayama, 1994, 1996).

1.4. Episodic retrieval: A time-course explanation of priming

On the second attentional account, the *episodic retrieval hypothesis*, attention is generally not guided by activation signals that are based on saliency. Instead, attention is ultimately guided by priority rules that specify the search target. These priority rules can either be retrieved from previous trials, or have to be created anew in a time-consuming process.

At the beginning of each trial, a feature map is created, independently from previous searches. Creation of this map then triggers retrieval of memory traces containing information about target and nontarget features in previous displays. If the retrieved memory trace can be matched to the current feature display, retrieval of the priority rule is complete and attention will be guided to the target. During retrieval, the visual system will simultaneously start to

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create a “new” priority rule to guide attention, because successful retrieval of memory traces that match the current display cannot be ensured. Both retrieval and creation of new priority rules are time-consuming processes, with the faster process winning the race.

The episodic retrieval account then explains intertrial facilitation effects with respect to the time-course with which the priority rule can be set up for attentional guidance: The speed with which an “old” priority rule can be retrieved from short term memory is a function of the recency of such a trace. Thus, if a given trial is similar to the previous one, as is the case when the target and nontarget features are repeated, retrieval of a memory trace matching the current display will be fast and allow immediate selection of the target. On the other hand, if a trial is dissimilar to the previous one, retrieval will be slowed, and selection of the target might even afford creation of new priority rules, which is even more time-consuming. Thus, according to the episodic retrieval hypothesis, speeded attentional selection of the target on repetition trials is due to fast retrieval of the correct priority rule. In turn, switch costs are due to the fact that such a rule is not immediately available, but still has to be retrieved, or must even be created anew in a more time-consuming process.

1.5. The role of saliency in priming

Despite the fact that priming of pop-out and episodic retrieval account propose entirely different mechanisms to account for the priming effect, it is at present unknown whether priming effects are based on a valencing or retrieval mechanism. The only evidence relating to this question is rather indirect: Hillstrom (2000) found that colour and orientation singleton targets produced priming effects of the same magnitude when they once constituted the target-defining feature. Assuming that colour singletons are more salient than orientation singletons, this result is incompatible with the hypothesis of the priming of pop-out view, that priming modulates the pop-out effect of the target. Accordingly, Hillstrom (2000) concluded that repeating the target feature does not change the activation signals of single features on a trial-by-trial basis, but instead modulates the time-course of target selection.

Although this line of reasoning seems to be entirely sound, the conclusion is somewhat uncertain: Because saliency was not directly measured, it is possible that the colour and orientation singletons accidentally had the same feature contrast. This would render the results again compatible with the priming of pop-out hypothesis.

In the present study, it should be investigated whether priming is indeed invariant to the saliency of the target, as was observed in the study of Hillstrom (2000). To that aim, the relative saliency of a size and colour singleton target was measured, by employing each of them in turn as target and irrelevant distractor (Huang & Pashler, 2005). This allows measuring the relative saliency of singletons, because more salient items show larger distraction costs than less salient items (Huang & Pashler, 2005; Theeuwes, 1992). In a second step, the magnitude of the priming effects of the two targets should be compared with each other, following the strategy of Hillstrom (2000).

If it can be replicated that the magnitude of the priming effect does not vary with the saliency of different targets, then this would certainly be incompatible with the priming of pop-out hypothesis. On the priming of pop-out hypothesis, one would expect priming effects to vary with targets of different saliency, because saliency determines the magnitude of the initial activation signal. Consequently, the magnitude of the priming effect should vary with the saliency of the target, with less salient targets showing greater priming effects than more salient targets, whose activation signals are already very high. This in turn should result in greater priming effects for less salient targets and *vice versa*. On the other hand, according to the episodic retrieval view, employing targets of different saliency should not modulate the magnitude of the priming effect, because priming modulates only the speed of retrieval of a priority rule.

1.6. How the priming mechanism affects eye movements

The central aim of the present study is to investigate whether priming modulates the pop-out effect of the target, as proposed by priming of pop-out, or whether it only affects the time-course of target selection, as proposed by episodic retrieval. To that aim, eye movement behaviour during a visual search task was measured.

Previous studies using eye movement measurements cannot decide the question whether a valencing or retrieval mechanism accounts for priming, mainly for two reasons: First, the principal dependent measure in previous studies is saccade latency, that is, the time needed to initiate a saccade to the target (Kowler et al., 1984; McPeek et al., 1999). However, saccade latencies are uninformative with respect to the question whether facilitation on repetition trials is due to faster retrieval of priority rules, or to an enhanced pop-out effect of the target. A second problem is that previous studies used a saccade-task, in which participants have to visually select the target. In such a task, priority settings favouring selection of one of the nontargets however would not necessarily result in erroneous saccades. This is because, in a saccade-task, observers may use strategies to prevent erroneous selections when they are uncertain about which item to select, and these strategies might prompt longer saccade latencies instead of erroneous selections, similar to a speed-accuracy trade-off (Findlay, 1997). Therefore it must be contended that it is still an open question whether priming indeed modulates the activation signals of the target on a trial-by-trial basis, or whether it merely modulates the time-course of retrieving corresponding priority rules.

In order to circumvent the problems enumerated above, the present study did not use a saccade-task, but measured eye movements in a standard visual search task. To ensure

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that the priming effect indeed operates on the attentional stage, as proposed by both episodic retrieval and priming of pop-out accounts, the *target fixation latencies* were measured, that is, the time needed to visually select the target. Since both priming of pop-out and episodic retrieval hypothesis maintain that priming operates on the attentional stage, the two hypotheses conjointly predict that intertrial contingencies should modulate the time needed to find the target in the search array, with shorter target fixation latencies on repetition trials than on switch trials.

Additional measurements were then included to further investigate the mechanism of priming: If priming changes the activation signals of target and nontarget features on a trial-by-trial basis, then repeating the target should yield more efficient and precise visual selection of the target. On the other hand, switch trials should result in more frequent erroneous selections of nontarget items, because in this case, the activation signal of the nontarget feature is enhanced. Thus, on the priming of pop-out hypothesis, intertrial contingencies should affect the *number of nontarget selections* before target selection.

Conversely, on the episodic retrieval hypothesis, repeating the target speeds up retrieval of priority rules and thus, priming should only modulate the time-course with which an item is selected. Thus, repeating the target should primarily speed up the initiation of the search process, whereas switches should lead to delays in initiating saccades to an object. According to the episodic retrieval hypothesis, intertrial contingencies should thus modulate the *initial fixation latencies*, that is, the duration that the eyes remain fixated at the centre of the display at the beginning of a trial. On repetition trials, the initial fixation latencies should be shorter than on switch trials, in which the eyes remain longer in the fixation area. This holds because on switch trials, retrieval of priority rules that specify the saccade target must be awaited before any item can be selected.

In sum, the hypotheses of the priming of pop-out and episodic retrieval account about the mechanism of priming were tested by measuring the number of nontarget fixations until target selection, and the initial fixation latencies at the beginning of each trial.

1.7. Possible objections against eye movement measures

However, the proposed method to investigate the mechanism of priming might also be subject to criticism. It might, for example, be doubted that eye movement measures constitute a reliable guide to covert attention shifts. Although the majority of studies shows that there is a close connection between covert attention shifts and eye movements (Deubel & Schneider, 1996; Hoffman & Subramian, 1995; Peterson, Kramer, & Irwin, 2004; Shepherd, Findlay, & Hockey, 1986; Theeuwes, de Vries, & Godijn, 2004; Van Zoest, Donk, & Theeuwes, 2004), there is also some evidence to the contrary (Murthy, Thompson, & Schall, 2001; Wu & Remington, 2003). More importantly, such a close correspondence between covert attention shifts and eye movements has not yet been established for the realm of priming effects.

To eliminate this uncertainty, priming effects were measured in two more experiments, which allowed only covert attention shifts. Otherwise, the covert attention experiments were designed to closely resemble the eye tracking studies. The results from the eye tracking experiments were then compared with these experiments, to ensure that conclusions drawn from eye tracking studies can be generalised to account for priming effects in covert attention studies.

1.8. Overview of experiments

In sum, the first two experiments investigated priming of colour and size singleton targets in a typical visual search task. Eye movement measures were included for two reasons: First, the time needed to focus on the target (“target fixation latency”) was measured to ensure that the priming indeed affects attentional processes of target detection and selection – as conjointly predicted by both priming of pop-out and episodic retrieval hypothesis. Secondly, the initial target fixation latencies (i.e. the time until the eyes leave the fixation area) and number of nontarget fixations before selection of the target were measured. This allows evaluating whether intertrial contingencies change the attention-driving capacity of target and nontarget items on a trial-by-trial basis – as proposed by the priming of pop-out hypothesis – or whether they merely affect the time-course of target selection, as maintained by the episodic retrieval hypothesis.

For an assessment of target saliency, all experiments included a distractor present condition, in which colour and size singletons were interchangeably used as target and distractor.

Finally, two control experiments ensured that priming effects in eye tracking experiments are identical to priming effects observed in more typical RT-tasks. To that aim, the last two experiments were designed to match the eye tracking experiments as closely as possible, while simultaneously using short display durations, of 200 ms, that only allow covert shifts of attention and render eye movements useless.

2. Experiment 1

The first experiment was conducted to replicate and extend previous results of priming in a visual search task: Participants in Experiment 1 had to search for a target square that could be either larger or smaller than the remaining items, and to indicate the direction of a stimulus located inside these squares with a keypress. In half of all trials, an irrelevant colour singleton distractor was presented, by replacing one of the black nontargets with a white square. The irrelevant distractor was included to permit an assessment of the relative saliency value of a size vs.

colour singleton (Huang & Pashler, 2005), which becomes important later, in Experiment 2.

To ensure that the repetition facilitation effect found in the present study affects attentional processes of target selection, the target fixation latencies of all participants were measured. Furthermore, to find out whether priming is based on a valencing or a retrieval mechanism, the number of nontarget selections before target selection and the initial fixation latencies, that is, the time needed to initiate the first saccade in each trial, were measured. This allows comparing the magnitude of the priming effect in the number of nontarget selections and initial saccade latencies to the priming effect in the manual RTs.

To account for the possibility that priming of the response might interfere with priming of the target-defining feature, feature priming and response-priming effects were continuously assessed separately from each other.

2.1. Method

Participants. Twelve students from the University of Bielefeld, Germany, took part in the experiment for small monetary exchange. Four of them were female and eight male; their mean age was 25.7. All subjects had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Materials. In all eye tracking experiments, an Intel Pentium(R) 4CPU 3.00 GHz-Computer (tico) with a 19 in. SVGA colour monitor (AOC) controlled the timing of events and generated the stimuli. Stimuli were presented with a resolution of 1024 × 768 pixels and a refresh rate of 99.9 Hz. For recording of eye movements, a video-based infrared eye tracking system (iViewX, SMI, Teltow) with a spatial resolution of 0.1° and a temporal resolution of 240 Hz was used. Participants were seated in a dimly lit room, with their head fixated by the eye trackers chin rest and forehead support, and viewed the screen from a distance of 92 cm. For registration of manual responses, a standard USB optical mouse was used. Event scheduling and RT measurement were performed by Presentation software (*Neurobehavioral Systems*).

Stimuli. The response-related stimuli consisted of five red (20 cd/m^2) arrows pointing to the right or left side. The arrows measured 0.1° × 0.5° and were centrally located against the background of five white (92 cd/m^2) or black (0 cd/m^2) coloured squares. The squares could either be small (1.5° × 1.5°) or large (3° × 3°), and were located on the outlines of an imaginary circle with a diameter of 12°. All stimuli were equally spaced from each other and presented on a constantly grey background (46 cd/m^2; MAVOLUX digital photometer). Fig. 1 depicts an example of the displays in Experiment 1.

Design. The experiment consisted of the 2 × 2 × 2 within-subjects conditions "distractor presence", "intertrial contingency of the target-defining feature" and "intertrial contingency of the response-related feature". The distraction variable was blocked and the order of blocks balanced across participants. In the distractor absent condition, participants searched for a black size singleton square among homogeneously coloured black squares of a different size. The target could be of two different sizes, with the remaining nontarget squares assuming the opposite size. In the distractor present condition, one of the nontarget squares was coloured white, constituting an irrelevant colour singleton.

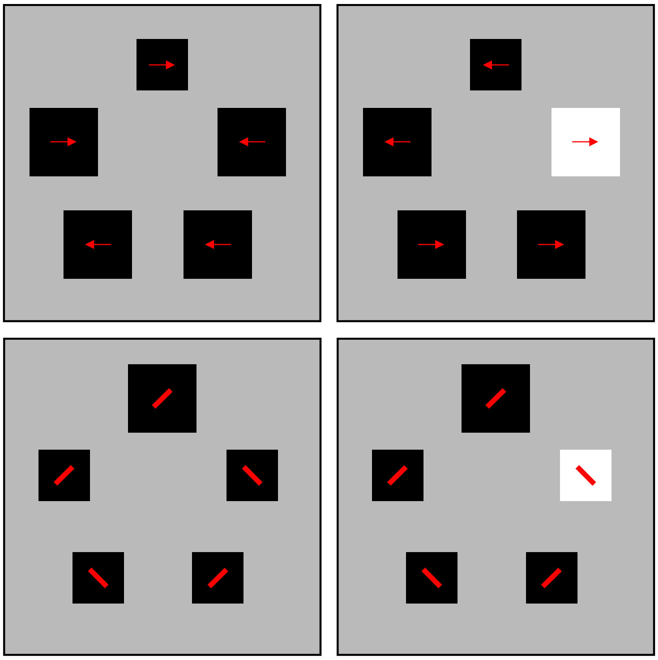

Fig. 1. Example of the displays used in the eye tracking experiments are depicted in the top row of Fig. 1; the displays used in the RT-tasks are displayed in the bottom row. In Experiments 1 and 3, the size of the squares constituted the target-defining feature, and a colour singleton had to be ignored, whereas these relations were reversed in Experiments 2 and 4. The response-related feature was constituted by the orientation of arrows or bars, located inside the target square.

Intertrial contingency was manipulated within blocks, in the following way: In both distractor present and absent conditions, the target on trial n could either be the same as in the previous, $n-1$ trial which constitutes a "same target trial", or it could inherit the size previously associated with the nontargets, which represents a "different target trial" or "switch trial". In addition, the response-related feature inside the target square could be repeated, constituting a "same response trial", or it could differ from the previous, $n-1$ trial, constituting a "different response trial".

The positions of target and distractor as well as the combinations of each target-type with each response-related item were controlled such that each response-related item appeared together with each target-type (small vs. large) on each of the five possible locations equally. Moreover, the number of response-related items on the display was controlled such that it always included an equal number of arrows pointing to the left and right (exempting the target). This resulted in 2 (right/left response) × 2 (small/

large) × 5 (target positions) × 4 (distractor positions) × 2 (right/left response-related item inside the distractor), that is, 160 trials in the distractor present condition. The same number of trials was completed in the distractor absent control condition, yielding 320 trials per subject.

Procedure. Each trial started with the presentation of a small black fixation cross. Participants were instructed to fixate on the centre of the cross. At the beginning of each trial, a fixation control was implemented: The stimulus display was only presented if the tracking was stable (no blinks) and the gaze was within 50 pixels (1°) of the centre of the fixation cross, for at least 350 ms (within a time-window of 3000 ms). Otherwise, participants were calibrated anew (5-point calibration) and the next trial started again with the fixation control.

Before each block, participants were calibrated with a 5-point calibration and were afterwards given written instruction about the following block. With respect to the distractor present condition, they were fully informed that the distractor would never coincide with the target position, and were accordingly instructed to ignore the colour singleton. Moreover, participants were instructed to respond to the target as fast as possible without making mistakes. On average, it took 45 min to complete the experiment.

2.2. Results

Data. Trial data were excluded from all analyses when RTs were longer than 2000 ms or if the target had not been fixated during the trial. The eyes were counted as fixating the target if the gaze was within a distance of 50 pixels (1°) from the centre of the response-related stimulus, and no saccade occurred (velocity smaller than 30°/s). Removing the outliers and errors from the data resulted in a loss of 10.10% of all trials.

Before analyses of the eye position data, a drift correction was included: At the onset of the search display, the gaze was assumed to have rested in the centre, with the deviation being subtracted from all subsequent eye position data of this trial. Since Experiment 1 also included a fixation control which only started the trial when the eyes had rested in the centre of the display (within 1° of the centre of the fixation point), the maximum deviation subtracted in this subsequent drift correction was 1°.

For an analysis of the manual responses, a 2 × 2 × 2 ANOVA comprising the variables "distractor presence" (present vs. absent), "$n-1$ target-defining feature" (same target vs. different target), and "$n-1$ response-related feature" (same response vs. different response) was calculated over the mean RTs and error scores. The mean RTs in each of the conditions of Experiment 1 are depicted in Fig. 2. Table 1 summarises the mean percentage of errors in all experiments.

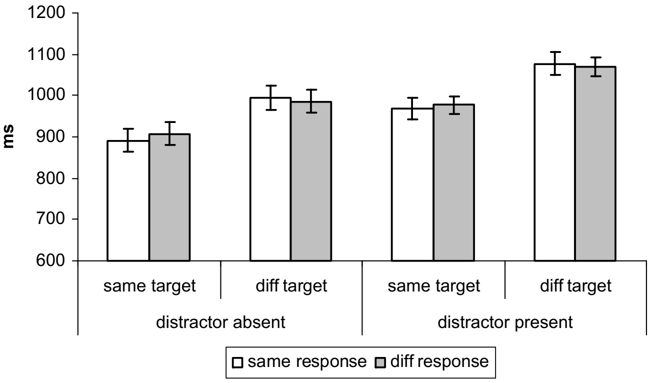

Fig. 2. Mean RTs of Experiment 1, depicted separately for distractor absent and present trials, as a function of intertrial contingencies of the target-defining feature size ("same target" vs. "diff targ"), and the response-related feature ("same response" vs. "diff response"). Error bars represent the SEM.

Table 1
Mean error scores in Experiments 1 to 4

	Same target		Diff target	
	Same resp	Diff resp	Same resp	Diff resp
Experiment 1				
Absent	3.1 [1.1]	2.8 [0.6]	2.5 [1.0]	3.8 [1.2]
Present	6.0 [1.4]	2.8 [0.8]	4.8 [2.1]	5.1 [2.1]
Experiment 2				
Absent	3.1 [1.5]	1.8 [0.8]	1.8 [0.5]	2.4 [0.7]
Present	1.6 [0.8]	1.3 [0.9]	2.2 [0.6]	3.6 [1.0]
Experiment 3				
Absent	10.2 [2.3]	12.0 [3.2]	14.5 [2.5]	13.2 [3.2]
Present	14.6 [3.0]	14.6 [3.1]	20.2 [3.4]	16.1 [2.5]
Experiment 4				
Absent	3.2 [1.1]	2.7 [0.6]	4.1 [1.2]	2.5 [1.0]
Present	3.8 [1.1]	3.2 [0.9]	6.4 [1.2]	4.7 [1.0]

Note. Mean error scores as a function of intertrial contingencies in the distractor absent and present condition of Experiments 1–4. Numbers in brackets represent the standard error of means.

RTs. The ANOVA yielded a significant main effect of distractor presence ($F(1,11) = 5.47$; $MS_e = 26{,}813.43$; $p = .039$), indicating that responses were on average 78 ms slower on distractor present trials ($M = 1023$) than on distractor absent trials ($M = 945$ ms). Moreover, repeating the target size had a significant effect ($F(1,11) = 61.75$; $MS_e = 3{,}551.73$; $p < .001$), reflecting that responses were 95 ms faster on repetition trials ($M = 937$ ms) than on switch trials ($M = 1032$ ms). Conversely, repeating the response-related item did not significantly affect mean RTs ($F < 1$), and similarly, none of the interactions approached significance (all ps > .26).

Errors. The same analysis calculated over the mean error scores did not yield any significant effects (all ps > .06). Collectively, the errors showed the same non-significant trends as the RTs, indicating that the results are not due to a speed-accuracy trade-off (see Table 1).

Eye movement data. Eye position data were committed to the same analysis as the manual RTs, comprising the $n-1$ contingencies of target and response as well as distractor presence as variables. In order to find out whether

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priming effects in the manual RTs were due to processes operating on the attentional stage, a first analysis was undertaken to see whether priming modulates the target fixation latencies, that is, the time needed to find the target in the search array. Secondly, target fixation latencies were analysed into the duration until the eyes left the fixation area (“initial fixation duration”) and the number of nontarget fixations until selection of the target, to assess whether priming affects the kind of selected items, or the time-course of target selection.

Eye movements were classified as saccades when their velocity exceeded 30°/s. Furthermore, eye movements were classified as fixations on an object, if the gaze had been within 1° of the centre of a possible object position (or the fixation cross), for at least 50 ms, and no saccade occurred. Fig. 3 depicts the mean target fixation latencies (Fig. 3a), initial fixation latencies (Fig. 3b), and the mean number of nontarget selections (Fig. 3c) in each of the conditions of Experiment 1.

First of all, mean target fixation latencies were statistically analysed, in order to see whether the effects in the RTs were already present at the time the eyes were first focused on the target. Mean target fixation latencies were significantly affected by distractor presence ($F(1,11) = 16.79$; $\mathrm{MS_e} = 11{,}207.04$; $p = .002$), indicating that it took 71 ms longer to focus on the target in the presence of an irrelevant distractor ($M = 524$ ms) than in its absence ($M = 453$ ms). Additionally, the target fixation latencies were significantly modulated by repeating the size of the target $F(1,11) = 55.8$; $\mathrm{MS_e} = 3{,}080.02$; $p < .001$, indicating that they were on average 85 ms longer on switch trials ($M = 522$ ms) than on repetition trials ($M = 437$ ms) (all other $ps > .14$).

Next, the same analysis was conducted over the initial fixation latencies, in order to assess whether the effects observed in the target fixation latencies are due to inflated retrieval durations on switch trials and/or distractor present trials. Analysis of the latencies of the first saccade that left the fixation point, however, show that the presence of an irrelevant distractor did not modulate initial saccade latencies ($F < 1$), as these were equal in the presence ($M = 241$ ms) and absence of a distractor ($M = 245$ ms). Switching the target-defining feature had a small but significant effect on initial latencies ($F(1,11) = 5.63$; $\mathrm{MS_e} = 311.72$; $p = .037$), reflecting that the eyes left the fixation point 9 ms earlier on feature repetition trials ($M = 238$ ms) than on switch trials ($M = 247$ ms). Repeating the response-related item similarly produced slightly lower initial fixation latencies ($M = 240$ ms) than changing it ($M = 246$; $F(1,11) = 10.45$; $\mathrm{MS_e} = 78.12$; $p = .008$), but this was qualified by a significant interaction between distractor presence and response repetition ($F(1,11) = 8.42$; $MS_e = 149.45$; $p = .014$), reflecting that the response repetition effect was confined to the distractor absent condition (*mean difference* = 13 ms), and did not occur in the presence of a distractor (*mean difference* = 1 ms) (all other $ps > .13$).

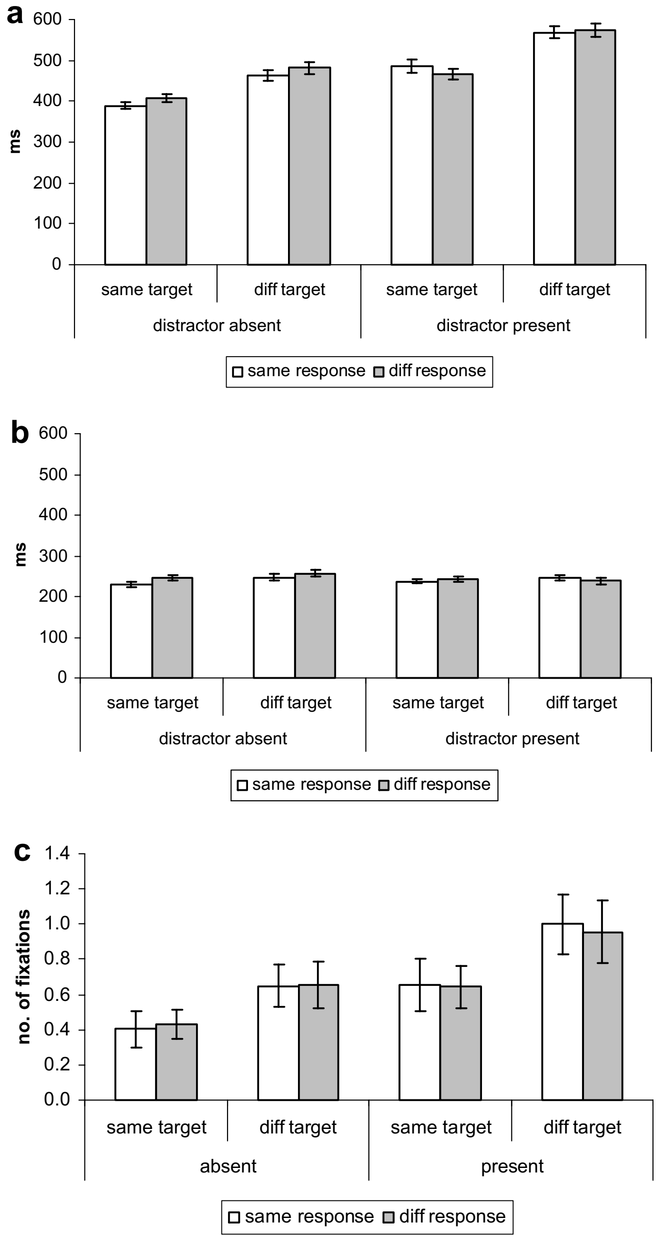

Fig. 3. Mean eye movement data of Experiment 1, depicted separately for the respective distractor conditions and as a function of intertrial contingencies of the target-defining and response-related feature: (a) mean target fixation latencies, (b) mean initial fixation latencies; (c) mean number of nontarget fixations before selection of the target. Error bars represent the SEM.

Furthermore, the mean number of nontarget and distractor fixations (before the eyes fixated on the target) was analysed, in order to see whether intertrial and distractor effects could be attributed to prioritisation of the nontarget feature. The results show significantly more nontarget fixations in the presence of a distractor ($M = 0.81$) than on distractor absent trials ($M = 0.53$; $F(1,11) = 24.27$; $\mathrm{MS_e} = 0.08$; $p < .001$). Similarly, more fixations on nontargets occurred on switch ($M = 0.86$) than on target repetition trials ($M = 0.57$; $F(1,11) = 73.21$; $\mathrm{MS_e} = 0.03$; $p < .001$) (all other $ps > .09$).

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2.3. Discussion

The results of the first experiment show that feature priming affects attentional processes of target detection and selection: The time needed to visually select the target is shorter on repetition than on switch trials. The fact that this difference equals the differences observed in the manual RTs moreover indicates that post-selectional processes do not further contribute to the priming effect. Since it is thus ensured that the observed priming effect is attentional, both priming of pop-out hypothesis and episodic retrieval can in principle account for it.

Further analyses of the initial fixation latencies and number of nontarget selections show significant priming effects in both measures. This indicates that both initial fixation latencies and efficiency of selection can contribute to priming. However, the results appear to be more in line with the priming of pop-out hypothesis, that priming modulates the activation signals of target and nontarget features: Although significant target repetition effects could be found both in the initial saccade latencies and in the number of nontarget selections alike, the effect in the initial fixation latencies is too small, measuring only 9 ms, to account for the overall switch costs observed in the target fixation latencies (85 ms) and RTs (95 ms).

This indicates that the increase in erroneous nontarget selections on switch trials must be responsible for the intertrial effect. At first, the increase in the number of nontarget and distractor selections on switch trials might seem quite small, too, resulting only in 0.3 and 0.1 more erroneous selections of nontarget and distractor items. However, it should be observed that the mean *durations* the eyes remained on these erroneously selected items amounted to 243 ms and 196 ms, respectively. Hence, the increase in erroneous selections on switch trials led to a net increase of approximately 93 ms on switch trials, and thus can fully account for the costs of 90 ms observed in the target fixation latencies and RTs. With this, the present results are more in support of the priming of pop-out hypothesis, which asserts that priming modulates the saliency of the target-defining feature on a trial-by-trial basis.

3. Experiment 2

In Experiment 2, participants had to search for an odd-coloured target that could be either white or black, while the nontargets were presented in the opposite colour. In half of all trials, an irrelevant distractor on the size dimension was present. With this, Experiment 2 reinstates the reverse conditions of the previous experiment, in which participants had to search for a size singleton whereas an irrelevant colour singleton should be ignored.

As stated in the Introduction, employing the size and colour singleton alternately as target and distractor allows an estimate of the relative saliency of the respective singleton targets: If, for example, the colour singleton distractor in Experiment 1 produces larger distraction costs than the size singleton distractor used in the present experiment, then it can be inferred that the colour singleton is more salient than the size singleton (e.g., Huang & Pashler, 2005; Theeuwes, 1992). Comparing the priming effects of the respective singleton targets with each other then allows evaluating whether priming effects are insensitive to the saliency of the target, as proposed by episodic retrieval, or whether priming effects vary with the target saliency, as predicted by the priming of pop-out hypothesis.

3.1. Method

Participants. Twelve students from the University of Bielefeld, Germany, took part in the experiment for small monetary exchange. Half of them were female and half male; their mean age was 26.4. All subjects had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Materials. These were the same as in the first experiment.

Stimuli, Design and Procedure. These were the same as in the previous experiment, with the exception that in Experiment 2, the roles of target-defining and irrelevant features were reversed. Thus, the search display either consisted of a black target square, while the nontargets were presented in white colour, or *vice versa*. In the distractor present trials of Experiment 2, the irrelevant distractor was constituted by an item that was consistently larger than the remaining items. Experiment 2 also included a control condition; however, the results will not be reported here because they are unrelated to the main research question.

3.2. Results

Data. Excluding all trials with manual RTs exceeding 2000 ms and trials in which the eyes had not been fixating on the target, resulted in a loss of 5.01% of all data.

RTs. The mean RTs of Experiment 2 are depicted in Fig. 4. A 2 × 2 × 2 ANOVA comprising the variables "distractor presence" (present vs. absent), "$n-1$ target-defin-

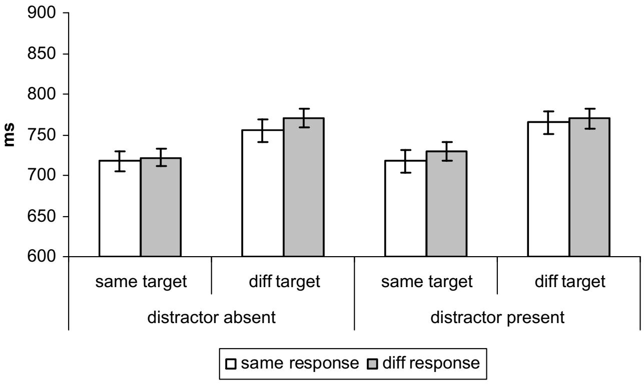

Fig. 4. Mean RTs of Experiment 2, depicted as a function of intertrial contingencies of the target-defining feature colour ("same target" vs. "diff targ"), and the response-related feature ("same response" vs. "diff response"). Error bars represent the SEM.

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ing feature" (same target vs. different target), and "$n-1$ response-related feature" (same response vs. different response) calculated over the mean RTs of Experiment 2 showed that distractor presence did not significantly affect RTs ($F < 1$), as the distraction costs only amounted to 4 ms. However, the main effect of repeating the target colour reached significance ($F(1,11) = 42.70$, $\mathrm{MS_e} = 1.067,69$; $p < .001$), reflecting that mean RTs were 43 ms shorter on colour repetition trials ($M = 722$ ms) than when the target colour switched ($M = 765$ ms). None of the remaining effects approached significance (all $ps > .3$).

Errors. The same ANOVA calculated over the mean percentage of errors only yielded a significant interaction between repeating the target and the response-related feature ($F(1,11) = 7.91$; $\mathrm{MS_e} = 2.23$; $p = .017$), reflecting that repeating the response increased mean errors by 0.7% when the target feature was also repeated, but decreased mean errors by 0.9%, when the target feature switched (all other $ps > .1$; see Table 1).

Eye movement data. Fig. 5 depicts the mean target fixation latencies (Fig. 5a), initial fixation latencies (Fig. 5b), and mean number of nontarget selections (Fig. 5c). For statistical analyses, the same ANOVA as in Experiment 1 was calculated over the eye position data.

Concerning the mean target fixation latencies, the analysis yielded a significant main effect of repeating the target colour ($F(1,11) = 34.43$; $\mathrm{MS_e} = 1{,}074.05$; $p < .001$), reflecting that target fixation latencies were 40 ms shorter on colour repetition trials ($M = 277$ ms) than on switch trials ($M = 317$ ms). None of the remaining effects or interactions approached significance (all $ps > .12$).

The same analysis calculated over the initial fixation latencies similarly yielded only a significant main effect of repeating the target-defining feature ($F(1,11) = 10.62$; $\mathrm{MS_e} = 123.35$; $p = .008$), indicating slightly shorter initial latencies when colour was repeated ($M = 207$ ms) than when it switched ($M = 214$ ms; all other $ps > .16$).

Concerning the mean number of nontarget selections, there were more erroneous fixations when the target colour switched ($M = 0.36$) than when it remained constant ($M = 0.20$; $F(1,11) = 25.58$; $\mathrm{MS_e} = 0.02$; $p < .001$). Moreover, the number of nontarget fixations was also slightly increased in the presence of an irrelevant distractor ($M = 0.30$) when compared with the distractor absent condition ($M = 0.26$), but this effect just failed to reach significance ($F(1,11) = 3.53$; $\mathrm{MS_e} = 0.02$; $p = .087$; all other $ps > .26$).

3.3. Discussion

The results from Experiment 2 in part replicate and in part deviate from the results of Experiment 1. First, they replicate the results of the last experiment insofar as switching the colour of the target also resulted in significant costs, which cannot be attributed to processes located at a post-selectional stage: Priming effects in the manual RTs and the target fixation latencies were of approximately the same magnitude, indicating that attentional processes can fully account for priming effects in the manual responses.

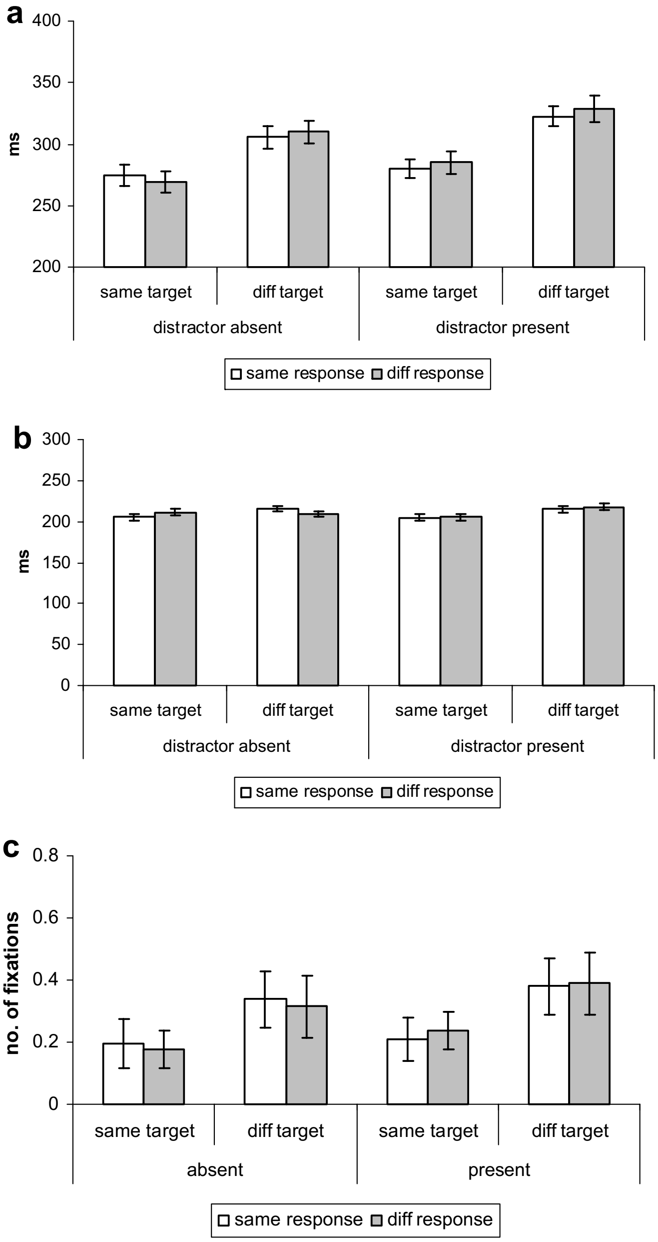

Fig. 5. Mean (a) target fixation latencies; (b) initial fixation latencies, and (c), mean number of nontarget selections in Experiment 2, depicted separately for the respective distractor conditions and as a function of intertrial contingency of the target-defining and response-related feature. Error bars represent the SEM.

Secondly and more importantly, Experiment 2 also replicates the finding that priming affects the priority settings, and not only the time to retrieve priority rules: As in Experiment 1, repetition facilitation effects in the initial saccade latencies were too small (7 ms) to account for a larger part of priming effects in the target fixation latencies (40 ms) or manual RTs (43 ms). Instead, switch costs again have to be attributed to the fact that erroneous selections of nontarget items were more frequent on switch trials than on

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repetition trials. This corroborates the hypothesis that priming modulates the priorities or attention-driving capacity of certain features instead of modulating only the time-course of retrieving the priority rule.

Interestingly, the irrelevant size singleton distractor failed to produce significant distraction costs. This markedly differs from the distraction costs found in the first experiment, and will be assessed in greater detail below.

3.4. Comparisons between Experiments 1 and 2

The most ostensible difference between Experiments 1 and 2 probably concerns the distraction effect: Whereas the irrelevant colour singleton distractor in Experiment 1 resulted in costs of 76 ms, the size singleton distractor in Experiment 2 only yielded non-significant costs of small magnitude. The distraction costs in Experiments 1 and 2 also differed significantly from each other, as assessed by between-subjects comparisons (*RTs*: $F(1,22) = 4.63$; $\mathrm{MS_e} = 14{,}172.75$; $p = .043$; *target fixation latencies*: $F(1,22) = 10.34$; $\mathrm{MS_e} = 6446.25$; $p = .004$; *mean number of nontarget fixations*: $F(1,22) = 13.92$; $\mathrm{MS_e} = 0.05$; $p = .001$). This indicates that the colour singleton is more salient than the size singleton (see, e.g., Huang & Pashler, 2005; Theeuwes, 1991).

More importantly, colour and size singleton also differed in their respective priming effects when they constituted the target-defining feature: In Experiment 1 with the less salient size singleton target, priming effects were quite large, reaching 95 ms. Conversely, the priming effect of the more salient colour singleton target in Experiment 2 amounted to less than half this size, reaching only 43 ms, and this difference between the experiments also proved to be reliable (RTs: $F(1,22) = 14.06$; $\mathrm{MS_e} = 2{,}309.71$; $p = .001$; *target fixation latencies*: $F(1,22) = 11.89$; $\mathrm{MS_e} = 2{,}077.03$; $p = .002$; *mean number of nontarget fixations*: $F(1,22) = 8.52$; $\mathrm{MS_e} = 0.02$; $p = .008$).

Thus, the present experiments fail to replicate Hillstrom's observation that priming is independent of the saliency of the target (Hillstrom, 2000). Instead, the experiments indicate that priming varies with the saliency of the employed target, with stronger priming effects for less salient targets, or *vice versa.* With this, the findings support the priming of pop-out hypothesis, that priming modulates the activation signals of the target, which in turn are based on the saliency or feature contrast of the target.

It is also interesting to note that the small repetition facilitation effect in the initial fixation latencies is obviously not modulated by saliency: The eyes left the fixation area around 7 ms earlier on repetition trials, in both Experiments 1 and 2, notwithstanding the large differences regarding the saliency of the two targets. This result might suggest that two independent processes contribute to the priming effect, with only one of these processes being sensitive to the saliency of the target. Further research is necessary to explore this possibility in better controlled experimental settings.

4. Experiment 3

The method of investigating the mechanism of priming with eye movement measurements might also be criticised, for the following reasons: First, it is unclear whether the mechanism of priming is the same in experiments that require covert shifts of attention vs. overt eye movements. Second, eye tracking experiments necessarily slightly differ in their experimental settings from more typical RT studies. Hence, it might be doubted whether the priming effect in Experiments 1 and 2 is identical to priming measured in covert attention experiments.

Such concerns might, for example, be based on the following considerations: First, the mean RTs in Experiments 1 and 2 were quite long, especially in Experiment 1, where they amounted to 1000 ms and more. This is probably due to the fact that participants have to make a saccade to the target, before a response can be given. However, this might have reduced or even eliminated some short-lived effects, like response-related effects.

Secondly, RTs of such a magnitude are also compatible with the conjecture that the target could not be found by performing an efficient search, but required attentional scanning of the whole display (e.g., Treisman, 1982). This criticism might seem especially plausible, because the set size was not varied in Experiment 1 and 2. Thus, the previous experiments cannot guarantee that the size and colour singleton targets were indeed pop-out targets than can be found by efficient search.

Experiments 3 and 4 were designed to overcome these shortcomings. They were both designed along the lines of Experiments 1 and 2, but the experimental design was optimised for measuring covert attention shifts. Thus, the display duration was shortened to 200 ms, which renders eye movements ineffective. Moreover, Experiments 3 and 4 also included two different set size conditions (5 and 7), to investigate whether the target could be found by performing an efficient search. Finally, the response-related items were created differently. First, the size of the response-related items was enlarged in order to permit discrimination of the items in the periphery. Secondly, the complexity of the response-related items was reduced, and the response-related feature was also construed such as to be highly response-compatible. Taken together, the changes in the design of the response-related feature should allow optimal conditions for short-lived response-priming effects to occur.

If the results of the covert attention do not deviate from the results observed in the eye tracking studies, it may be safely concluded that the priming mechanism discovered in Experiments 1 and 2 also accounts for priming in covert attention experiments.

4.1. Method

Participants. Sixteen students from the University of Bielefeld, Germany, took part in the experiment for small monetary exchange. Half of them were female and half male; their mean age was 28.0. All subjects had normal or corrected-to-normal vision and were naive as to the purpose of the experiment. Four subjects had to be excluded because they committed too many errors (>28%).

Materials. All covert attention experiments reported in this article used a standard keyboard, a microcomputer with an Intel 80486/100 MHz CPU and a 17 in. Belinea computer monitor for stimulus presentation and response registration. Stimuli were presented with a resolution of 640 × 480 pixels and a refresh rate of 60.1 Hz. The arrow down and arrow left keys of the computer keyboard were used as right and left response keys, respectively. For event scheduling and RT measurement the experimental runtime system ERTS (BeriSoft Cooperation) was used.

Stimuli. The response-related stimuli consisted of red bars (25 cd/m^2), which were tilted to the right or left by an angle of 45°. The bars measured $0.2° \times 0.8°$ and were presented centrally on the background of black (0 cd/m^2) coloured squares. The squares were placed on the outline of an imaginary circle with a diameter of 12°. At a viewing distance of 57 cm, the small squares measured $1.1° \times 1.1°$ and the big square $2.2° \times 2.2°$. All stimuli were equally spaced from each other and presented on a constantly grey background (50 cd/m^2), together with a small black fixation cross ($0.6° \times 0.1°$). Displays consisted either of one big target square and several small squares, or of one small target square while the remaining squares were all big. Displays contained either 5 or 7 items, in order to ensure that the target could be found by performing an efficient search. As in Experiment 1, subjects had to search for the differently sized square and respond to the orientation of the bar located inside.

Design. The experiment consisted of the $2 \times 2 \times 2 \times 2$ within-subjects conditions "set size" (5 vs. 7), "distractor presence" (present vs. absent), "$n - 1$ target-defining feature" and "$n - 1$ response-related feature". The factors "set size" and "distractor" were both blocked, while the two $n - 1$ conditions of the target-defining and response-related features were varied within each block. As in Experiment 1, the target position, target distractor distance and combination with type of response-related item (tilt right vs. left) was controlled. Participants completed 160 trials each in the distractor present and absent block of the set size 5 condition, and 168 trials in the respective blocks of the set size 7 condition, yielding 656 trials per subject. The order of blocks was controlled by balancing different sequence conditions across participants according to a latin square procedure. Each block was preceded by an instruction about the next block and 10 practice trials chosen randomly from the following block. Performance in the practice trials was not recorded. On average, it took half an hour to complete the experiment.

Procedure. Each trial started with the presentation of a small black fixation cross. After 500 ms, the stimulus display consisting of the coloured squares and the tilted bars appeared. Participants were required to search the display for the odd-sized square and to press a right key when the bar inside was tilted to the right and a left key when it was oriented to the left. The stimulus display remained on screen for 200 ms. This stimulus duration was chosen in order to render eye movements ineffective. After presentation of the search display, a blank grey screen was presented for 2,800 ms, or until response. RTs longer than 3,000 ms were counted as errors. A feedback was provided on every trial and consisted in the written words "correct" or "wrong" (in German), which were presented for 1,000 ms. After an intertrial period of 750 ms, the next trial started with the presentation of the fixation cross.

All participants were instructed to maintain fixation on the fixation cross throughout the presentation of the stimulus display and to prevent eye movements. As in Experiment 1, participants were also fully informed that the distractor never coincided with the target, and were instructed to ignore the irrelevant item. Moreover, they were asked to respond as fast as possible without making mistakes.

4.2. Results

Data. Excluding RTs above 2000 ms resulted in a loss of 0.55% of all data. In order to ensure comparability between the statistical analysis of Experiments 3 and 1, mean RTs and errors were first analysed for possible set size effects, and afterwards subjected to the same ANOVA as employed in the previous experiments.

RTs. First of all, the data were probed for a set size effect, in order to check whether search was efficient or inefficient. Comparing the set size 5 condition with the set size 7 condition however did not yield any significant differences in performance ($F < 1$).

Next, data were pooled over the different set size conditions and subjected to a $2 \times 2 \times 2$ ANOVA comprising the variables "distractor presence" (present vs. absent), "$n - 1$ target-defining feature" (same target vs. different target), and "$n - 1$ response-related feature" (same response vs. different response). The results showed a significant main effect of distractor ($F(1,11) = 5.56$; $MS_e = 7{,}665.2$; $p = .038$), indicating that mean RTs were increased by 42 ms in the presence of an irrelevant distractor ($M = 773$ ms) compared with the distractor absent control condition ($M = 731$ ms). Secondly, switching the target-defining size had a significant main effect ($F(1,11) = 24.48$; $MS_e = 5580.54$; $p < .001$), indicating that RTs were reduced by 75 ms when the target size was repeated ($M = 715$ ms) compared with switch trials ($M = 790$ ms). In contrast, repeating the response did not affect performance, as mean RTs were very similar in response repetition ($M = 751$ ms) and switch trials ($M = 753$ ms; $F < 1$). However, the interaction between repeating the target-defining and response-related item was significant ($F(1,11) = 8.86$; $MS_e = 441.26$; $p = .013$). The interaction was due to the fact that repeating the response led to a reduction of RTs by 15 ms, when the target size was also repeated, but that repeating the response

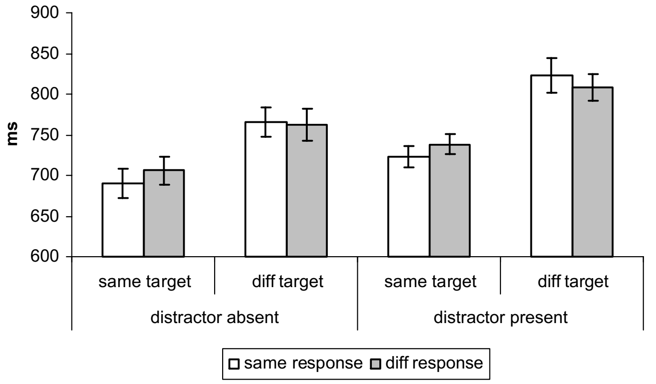

Fig. 6. Mean RTs in the covert attention Experiment 3, depicted, as a function of intertrial contingencies of the target-defining feature size ("same target" vs. "diff targ"), and the response-related feature ("same response" vs. "diff response"). Error bars represent the SEM.

increased RTs by 10 ms when the target size switched. None of the remaining effects approached significance (all $p > .22$).

Errors. The mean error scores did not differ between the set size 5 condition and set size 7 condition ($F < 1$), indicating that the target could be found by performing an efficient search. The ANOVA calculated over the pooled data of the set size 5 and 7 conditions yielded a significant main effect of distractor presence, indicating higher error scores in the distractor present condition ($M = 16.4\%$) than in the distractor absent condition ($M = 12.5\%$; $F(1,11) = 9.04$; $MS_e = 41.29$; $p = .012$). Additionally, the main effect of switching the target-defining feature was significant ($F(1,11) = 13.54$; $MS_e = 17.38$; $p = .004$), with less errors on repetition trials ($M = 12.9\%$) than on switch trials ($M = 16.0\%$). None of the remaining effects approached significance (all ps $> .13$). Thus, interpretation of the results is not complicated by a speed-accuracy trade-off (see Table 1).

4.3. Discussion

Fig. 6 depicts the mean RTs of Experiment 3. As can be seen in the figure, the results from Experiment 3 closely resemble the result pattern of Experiment 1 (see Fig. 2). Accordingly, a between-subjects ANOVA calculated over the mean RTs of Experiments 1 and 3 did not yield any significant differences between the experiments (see Appendix A).

Although mean RTs were thus visibly higher in Experiment 1 than in Experiment 3, and the mean errors showed the inverse trend, the distractor and priming effects did not show any important differences between Experiments 1 and 3. Consequently, the results do not support the conjecture that the priming effects in eye tracking experiments differ in any way from priming effects in covert attention experiments.

5. Experiment 4

Experiment 4 was also designed as a covert attention experiment, and its purpose was to exclude that the priming effect in Experiment 2 was unduly influenced by the implemented eye tracking method. As in Experiment 2, the task in Experiment 4 was to search for an odd-coloured square that could be black or white, while the irrelevant distractor was a size singleton.

5.1. Method

Participants. Six male and 6 female students from the University of Bielefeld, Germany, took part in the experiment (mean age: 25.4), for small monetary exchange.

Stimuli, Design and Procedure. These were exactly the same as in the previous experiment, with the exception that the target-defining feature was now constituted by a colour singleton that randomly switched colours between black and white. The task-irrelevant distractor was constituted by a square that was consistently larger than the remaining items. The task in Experiment 4 was thus the same as in Experiment 2.

5.2. Results

Excluding RTs above 2,000 ms resulted in a loss of 0.06% of the data.

RTs. First, performance in the colour search task was not affected by varying the set size ($F < 1$). Secondly, the $2 \times 2 \times 2$ ANOVA computed over the mean RTs yielded a significant main effect of distractor ($F(1,11) = 12.4$; $MS_e = 776.17$; $p = .005$). On average, RTs were 20 ms shorter in the absence of an irrelevant distractor ($M = 586$ ms) than when it was present ($M = 606$ ms). The main effect of $n - 1$ target colour also proved to be reliable ($F\ (1,11) = 55.11$; $MS_e = 827.63$; $p < .001$), reflecting that search was 43 ms faster when the target colour was repeated ($M = 574$ ms) than when it switched ($M = 617$ ms). Conversely, repeating the response did not affect performance ($F < 1$). Of the interactions, the distractor × $n - 1$ target colour interaction proved to be reliable ($F(1,11) = 8.0$; $MS_e = 221.60$; $p = .016$), indicating that on switch trials, distraction costs amounted to 29 ms ($F(1,11) = 19.99$; $MS_e = 491.63$; $p = .001$), whereas on repetition trials, distraction costs of only 11 ms occurred, where they also did not reach significance ($F(1,11) = 3.1$; $MS_e = 506.15$; $p = .11$). Additionally, in the distractor absent trials, response repetition effects significantly interacted with repetitions of the target colour ($F(1,11) = 12.24$; $MS_e = 112.58$; $p = .005$), indicating that, on average, mean RTs of response repetition trials were speeded by 10 ms when the target-defining feature was repeated, but slowed by 12 ms when the target colour switched. However, the same interaction in the distractor present trials was far from significant ($F < 1$).

Errors. The mean error scores were equally not affected by varying the set size ($F < 1$). The $2 \times 2 \times 2$ ANOVA computed over the mean errors only yielded a significant main effects of repeating the target colour ($F(1,11) = 8.77$; $MS_e = 9.15$; $p = .013$), as participants committed more errors when the target colour switched ($M = 4.3\%$) than when it was repeated ($M = 2.5\%$). Moreover, the analysis showed a marginally significant main effect of distractor presence ($F(1,11) = 4.44$; $\mathrm{MS_e} = 3.64$; $p = .059$), with higher error rates in the presence of a salient distractor ($M = 3.8\%$) than in its absence ($M = 3.0\%$). The response repetition effect also approached significance ($F(1,11) = 4.75$; $\mathrm{MS_e} = 11.67$; $p = .052$), with lower error scores on response repetition trials ($M = 2.7\%$) than when the response changed ($M = 4.2\%$). None of the interactions approached significance (all ps $> .11$). Since the results correspond to the effects found in the RTs, the results are not due to a speed-accuracy trade-off (see Table 1).

5.3. Discussion

The mean RTs of Experiment 4 are depicted in Fig. 7. As can be seen in the figure, the result pattern of Experiment 4 parallels the results obtained in the eye tracking version of this experiment, Experiment 2 (see Fig. 4).

Deviating from the results of Experiment 2, the present results indicate that the irrelevant size singleton distractor can produce costs of small magnitude. However, the distractor effect only reached significance on switch trials and remained non-significant on repetition trials, which again dwarfs the differences between the experiments.

Correspondingly, a between-subjects ANOVA calculated over the RTs shows that Experiments 2 and 4 do not differ from each other in any of the main effects or interactions (see Appendix A).

Taken together, the results of Experiments 3 and 4 do not support concerns such that eye tracking experiments and experiments designed to measure covert shifts of attention differ in important respects. The absence of a set size effect in Experiments 3 and 4 indicates that both colour and size singleton targets were available pre-attentively and could be used to guide attention to the position of the target. Moreover, the fact that the response-priming effects in Experiments 1 and 2 did not differ from response-priming effects in Experiments 3 and 4 (See Appendix A) rules out that response-priming effects failed to occur in the first two experiments because mean RTs were too long to allow short-lived response-priming effects to have an effect, or because the response-related feature was too complex to guide attention.

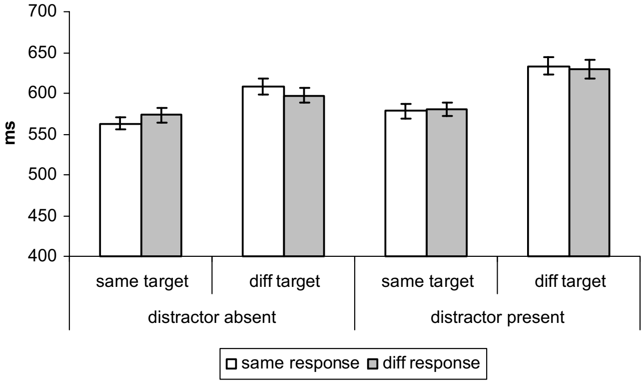

Fig. 7. Mean RTs in the covert attention Experiment 4, depicted, as a function of intertrial contingencies of the target-defining feature colour (“same target” vs. “diff targ”), and the response-related feature (“same response” vs. “diff response”). Error bars represent the SEM.

Instead, the results support the contention that the eye tracking experiments measure the same priming effect usually observed in covert attention experiments. This indicates that the same priming mechanism that is operative in eye movements also produces the priming effect in covert attention shifts. Methodologically, this demonstrates that eye movements are a reliable indicator for covert attention shifts.

6. General discussion

The present study yielded several interesting findings. First, the results provide converging evidence for the hypothesis that feature priming operates on the attentional stage: Repetition facilitation effects of equal magnitude can be found in the manual RTs and the time needed to visually select the target (“target fixation latency”). This indicates that processes at the stage of target detection and selection can fully account for priming effects of the target-defining feature. In contrast, post-selectional processes located at the decisional or response-related stage apparently do not further contribute to priming effects.

Experiments 3 and 4 moreover show that feature priming effects of a comparable magnitude can be obtained in a visual search task that only allows covert shifts of attention. This invalidates concerns such that the priming effect measured in eye tracking experiments differs from the one typically found in a typical RT task. Instead, the absence of any differences between priming in eye tracking studies and covert attention experiments indicates that in priming, eye movement measures may be used to draw reliable inferences about covert attention shifts.

Regarding the question whether priming accords to a feature valencing mechanism, as proposed by the priming of pop-out hypothesis, or to a retrieval mechanism, as proposed by the episodic retrieval view, the results from the first experiments clearly favour the priming of pop-out hypothesis: The results from Experiments 1 and 2 show that switch costs must be attributed to more frequent selections of nontarget items. This indicates that priming modulates the attentional priorities or activation signals of the target and nontarget features on a trial-by-trial basis, which biases attention shifts to the target on repetition trials and to nontargets on switch trials.

In contrast, the results appear to be incompatible with the episodic retrieval view, which proposes that priming modulates the time-course of target selection by affecting the retrieval time of a priority rule. On this account, switch costs should have been due to delayed shifts of attention to the target on switch trials. Contrary to this assumption, differences in the initial fixation latencies between repetition and switch trials were much too small to account for the priming effect found in the target fixation latencies or manual RTs.

At a first glance, this negative finding might seem to be at odds with previous studies showing that saccade latencies become successively shorter as the number of repetitions increases (e.g., McPeek et al., 1999). However, it should be noted that previous studies employed a saccade task, in contrast to the standard visual search task of the present study. The finding that, under standard conditions of visual search, switch costs are not due to longer saccade latencies (or initial fixation latencies), but to more frequent erroneous selections of nontargets, reinforces previous concerns that, in a saccade-task, participants trade speed for accuracy (e.g., Findlay, 1997): To prevent erroneous selections, participants apparently suppress all eye movements until they have safely located the target. This in turn produces delays in the saccade latencies on switch trials, in which covert attention shifts are often initially directed to a nontarget. In contrast, when participants are not required to visually select the target with the first saccade, switch trials do not produce comparable delays in the initial saccade latencies. Instead, saccades seem to follow covert attention shifts more readily, resulting in more frequent erroneous selections of nontargets on switch trials.

If this explanation is correct, then saccades would be a more reliable indicator for covert attention shifts in a standard visual search task, in which participants are not given any instructions regarding their eye movements.

6.1. *Evidence for a Saliency-based account of priming*

A second important finding of the present study is that priming effects vary with the saliency of the target: Priming effects are larger when the target is constituted by a less salient feature singleton than when the target is more salient. This finding is at odds with the episodic retrieval view, which claims that priming effects should not vary as a function of the saliency or feature contrast of the target-defining feature. Presumably, Hillstrom (2000) did not detect any differences in the priming effect between orientation and colour singleton targets because, accidentally, targets of comparable saliency were chosen. This possibility was ruled out in the present study, in which the relative saliency of size and colour singleton targets was measured by presenting each of them as irrelevant distractor on half of all trials.

In contrast, the finding that the magnitude of the priming effect depends on saliency is in line with the priming of pop-out hypothesis: On this account, intertrial contingencies modulate the pop-out effect of the target, which in turn originates from its feature contrast or saliency (e.g., Maljkovic & Nakayama, 1994; Wolfe, 1994).

At first, one might be tempted to explain these findings by claiming that valence settings, or the amount of activation transferred across trials, can be flexibly adapted to the saliency of the target-defining feature (Pinto, Olivers, & Theeuwes, 2005; see also Meeter & Olivers, 2005). According to this view, priming would be both sensitive to the initial saliency values of the target and nontarget features, and also modulates them, to such an extent as to ensure efficient selection of the target on repetition trials (Pinto et al., 2005).

However, it should be observed that it seems to be quite unnecessary to propose both, that priming *modulates* the activation signal of the target, and is also *sensitive* to it. Instead, the first of these hypotheses is already sufficient to account for the results. At least if we conceive of priming as distributing a fixed amount of charge to the activation signal of the target, it automatically follows that less salient items will be greater affected by priming than more salient items. This holds because identical amounts of activation will modulate detectability of less salient items to a much larger extent than detectability of more salient items.

Hence, if we assume that priming already modulates the activation signal of the target, there is no need to assume different valence settings for targets of different saliency. Thus, the present findings only require the original proposal of the priming of pop-out account, that priming modulates the pop-out effect of the target (Maljkovic & Nakayama, 1996).

6.2. *Objection against a saliency-based view*

From a different point of view, the results of the present study might also be viewed as conflicting with a saliency-based view of priming: It might, for instance, be argued that, if priming modulates the activation signals of the target, we would have expected priming to modulate the amount of attention deployed to the irrelevant distractor as well. In particular, distraction costs should be higher on switch trials, because the target suffers a competitive disadvantage relative to the distractor. This in turn should lead to an interaction between distractor presence and feature priming.

A corresponding result pattern of larger distraction costs on switch trials than on repetition trials could already be observed in previous studies (e.g., Becker, submitted for publication; Pinto et al., 2005). However, in the present study, priming failed to modulate distraction costs, with the sole exception of Experiment 4. This negative result might in turn be taken to indicate that priming obviously does not modulate the activation signals of target and nontarget features, contrary to the interpretation advanced above.

This apparent conflict can probably be resolved when we acknowledge that adding or subtracting valences from the activation signal of the target will only affect the amount of attention deployed to the irrelevant distractor, when target and distractor are of equal or comparable saliency. In contrast, if the distractor is much less salient, or much more salient than the target, then the amount of activation conferred by priming might not be sufficient to bridge the difference, and to decide the competition between target and distractor on a trial-by-trial basis. This

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at least holds if we assume that the amount of activation transferred by priming is limited.

Now, the results from the present experiments do not indicate that colour and size singleton targets were of equal or comparable saliency. Conversely, the large distractor effect of the colour singleton and the small or absent distractor effect of the size singleton distractor indicate that the colour singleton was much more salient. Although further research is required to explore the interaction between distractor effects and priming more thoroughly, the large saliency difference between the colour and size singleton target may serve as an explanation for the failure of priming to affect the distraction costs (see also Becker, 2007).

Despite the interpretation advanced above, a caveat regarding the saliency-based view also seems to be in order. It should be noted that the evidence for the role of saliency in priming is still quite indirect because in Experiments 1 and 2, the saliency of different targets was varied by involving targets of different feature dimensions. Although unlikely, it is therefore possible that the magnitude of the priming effect depends more on the stimulus characteristics than on the saliency of the varied feature.

Thus, the present experiments do not provide an ideal test for the hypothesis that repeating the target feature enhances the activation signal or pop-out effect of the target. For the future, more direct tests of the role of saliency in priming would be desirable, in which the saliency of the target-defining feature is more systematically and gradually varied.

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Appendix A

The main aim of Experiments 3 and 4 was to check whether search performance differs between experiments optimised for measuring eye movements and covert attention shifts. Clearly, conclusions about the comparability of these two paradigms should better be based on statistical comparisons, and not just appearances. Therefore, the results of Experiments 1 and 2 were statistically compared with those of Experiments 3 and 4, respectively. Naturally, given the nature of the task, only the manual responses could be subjected to these analyses. The present analyses do not include comparisons of the mean error scores across the experiments, because the predictions exclusively concern the temporal dynamics, and previous analyses already exclude that the RT data are contaminated by speed-accuracy trade-offs. For the present analyses, the RT data of the last two experiments additionally had to be pooled across the different set sizes.

A.1. Results of comparing Experiments 1 and 3

Mean RTs were subjected to a $2 \times 2 \times 2 \times 2$ ANOVA comprising the between-subjects variable “experiment”, and the within-subject variables “distractor presence” (present vs. absent), “$n-1$ target-defining feature” (same target vs. different target), and “$n-1$ response-related feature” (same response vs. different response).

The results show that mean RTs were significantly higher in the eye tracking Experiment 1 ($M = 984$ ms) than in Experiment 3 ($M = 752$ ms; $F(1,22) = 15.82$; $\text{MS}_\text{e} =$ 163,398.85; $p = .001$). Moreover, the main effects of distractor presence ($F(1,22) = 10.08$; $\text{MS}_\text{e} = 156{,}618.21$; $p = .004$), repeating the target-defining feature ($F(1,22) = 76.89$, $\text{MS}_\text{e} = 4{,}872.21$; $p < .001$), and the interaction between this variable and repeating the response reached significance ($F(1,22) = 5.52$; $\text{MS}_\text{e} = 1{,}166.25$; $p = .028$). More importantly, however, there were no differences in these effects between the two experiments, as indicated by the non-existent interactions with the variable experiment (all ps > .31).

A.2. Results of comparing Experiments 2 and 4

The same ANOVA computed over the mean RTs of Experiments 2 and 4 showed that mean RTs were significantly higher in Experiment 2 with the eye tracker ($M = 743$ ms), than in Experiment 4 ($M = 596$ ms; $F(1,22) = 24.36$; $\text{MS}_\text{e} = 42{,}037.55$; $p < .001$). Moreover, there was a main effect of distractor presence ($F(1,22) = 6.13$; $\text{MS}_\text{e} = 1{,}154.12$; $p = .021$), reflecting slightly higher RTs in the presence of an irrelevant distractor ($M = 675$ ms) than in its absence ($M = 663$ ms). Repeating the target-defining colour also significantly affected performance ($F(1,22) = 96.23$; $\text{MS}_\text{e} = 947.66$; $p < .001$), with shorter RTs on repetition ($M = 648$ ms) than on switch trials ($M = 691$ ms). However, this effect did not differ between the two experiments ($F < 1$), and none of the other main effects or interactions approached significance (all ps > .12).

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