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Oculomotor capture by colour singletons depends on intertrial priming

Stefanie I. Becker

School of Psychology, The University of Queensland, McElwain Building, St. Lucia, Brisbane, QLD 4072, Australia

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ABSTRACT

In visual search, an irrelevant colour singleton captures attention when the colour of the distractor changes across trials (e.g., from red to green), but not when the colour remains constant (Becker, 2007). The present study shows that intertrial changes of the distractor colour also modulate oculomotor capture: an irrelevant colour singleton distractor was only selected more frequently than the inconspicuous nontargets (1) when its features had switched (compared to the previous trial), or (2) when the distractor had been presented at the same position as the target on the previous trial. These results throw doubt on the notion that colour distractors capture attention and the eyes because of their high feature contrast, which is available at an earlier point in time than information about specific feature values. Instead, attention and eye movements are apparently controlled by a system that operates on feature-specific information, and gauges the informativity of nominally irrelevant features.

1. Introduction

At any moment in time, our visual environment contains much irrelevant information that is not immediately important to our goals. 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 and controls eye movements.

Current theories of visual attention assume that attention can be guided by two attentional systems: first, salient items can capture attention and the eyes in a stimulus-driven manner to regions in the visual field that have a high feature contrast (e.g., Theeuwes, 1991; Theeuwes, 1992). Secondly, capture by salient stimuli can be modulated by the intentions and goals of the observers. For instance, when observers know that the target is red, the attention-driving capacity of all red objects is enhanced, compared with the non-red objects in the visual field (e.g., Duncan & Humphreys, 1989; Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Johnston, 1993; Wolfe, 1994).

Knowledge about the exact features of an irrelevant distractor can also attenuate the attention-driving capacity of irrelevant salient distractors. For instance, Theeuwes and Burger (1998) showed that an irrelevant distractor with a unique colour can be successfully ignored when both the features of the target and of the distractor are known and remain constant throughout a block, whereas the salient distractor interferes with selection of the target when either the features of the target or of the distractor vary (e.g., between red and green). Similar results were also obtained with respect to eye movements: Theeuwes, de Vries, and Godijn (2003) found that, in search for a shape target, a salient colour distractor did not produce oculomotor capture when both the exact target shape and the colour of the distractor were known and remained constant, whereas the distractor was selected on 38% of all trials when the features of the target and the distractor randomly varied. These results were taken to show that salient items have an inherent attention-driving capacity, which in turn can be modulated and even overridden by top-down attentional control settings. The effectiveness of such top-down control settings in turn critically depends on the observers' knowledge about the specific features of the target and distractor (e.g., Theeuwes & Burger, 1998; Theeuwes et al., 2003).

Recent studies investigating *intertrial priming effects* however called this view into question. To note, in previous studies, top-down knowledge about the features of the target was prevented by switching the features of the target and the remaining items across trials. Similarly, knowledge about the distractor feature was prevented by switching the features of the distractor and the remaining items across trials, so that the distractor feature could either be repeated or switched, compared to the previous trial. However, repeating versus switching features can modulate search performance on a trial-by-trial basis (Maljkovic & Nakayama, 1994). In particular, switching the features of the target with the nontarget features can slow response times (RT) by 50–100 ms, compared to repetition trials (e.g., Becker, 2008a; Becker, 2008b; Maljkovic & Nakayama, 1994). Moreover, eye movement studies showed that the target could be selected faster and with higher accuracy on repetition trials than on switch trials, where the eyes frequently selected one of the nontargets before moving over to

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E-mail address: s.becker@psy.uq.edu.au

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the target: For example, in colour search, 12% of first eye movements went to a nontarget on switch trials, compared to 4% on repetition trials; in size search, 44% of first eye movements went to a nontarget on switch trials, compared to 23% on repetition trials (Becker, 2008a).

These findings have been taken to show that there is a third attentional system that modulates the attention-driving capacity of the target when the features of target and nontargets vary randomly. According to the *priming of pop-out hypothesis*, selection of a pop-out target on a given trial activates the particular feature value of the target (e.g., red), which carries over to the next trial and primes attention shifts to items which possess this feature value. There is still a debate about whether these priming effects should be attributed to a top-down or a bottom-up controlled mechanism (for a review, see Kristjansson & Campana, 2010). However, what seems to be clear is that these carry-over effects are automatic and occur without active support from top-down controlled processes.

Note that these automatic intertrial carry-over effects are also very powerful: Studies on attention and eye movements have shown that priming effects can override the effects of the other two known attentional systems in the guidance of attention and the programming of eye movements. First, priming modulates attention shifts and eye movements even when observers know the target feature that will be presented on the upcoming trial, indicating that priming effects persist despite perfect top-down knowledge (e.g., Becker, 2008a; Hillstrom, 2000; Maljkovic & Nakayama, 1994). Second, switching the target and nontarget features misguides attention and eye movements to the nontargets even in pop-out search, where the nontargets are all non-salient and the target is the only salient item in the display (e.g., Becker, 2008a, 2008b, 2008c, 2010). This indicates that feature-based intertrial effects modulate the attention-driving capacity of items to such an extent that they can override the bottom-up saliency-based guidance system. The latter fact was also noted by Maljkovic and Nakayama (1994), who concluded that pop-out items with a unique feature do not pop out solely in virtue of their feature contrast, but need to be "primed" by the previous target feature in order to pop out (cf. Maljkovic & Nakayama, 1994).

In sum, the finding that intertrial carry-over effects can strongly modulate the attention-driving capacity of very salient pop-out targets calls into question the importance of feature contrasts and top-down knowledge in the guidance of attention. More importantly, priming effects could also already be sufficient to explain differences in search performance that were previously attributed to a lack of top-down knowledge about the target feature. Since previous studies regularly introduced target feature uncertainty by varying the features of the target, it is possible that performance decrements in this condition reflect switch costs, so that it is possible that effects which were previously attributed to a top-down, feature-specific attentional system are entirely due to intertrial carry-over effects (cf. Kristjansson, Wang, & Nakayama, 2002; Pinto, Olivers, & Theeuwes, 2005; but see Becker, Ansorge, & Horstmann, 2009; Folk & Remington, 2008).

Intertrial priming effects could also be responsible for effects that were previously attributed to the bottom-up, saliency-based attentional system. The prime evidence for the view that feature contrasts can guide attention and eye movements is presumably the demonstration that salient items can capture attention even when they are irrelevant to the task (e.g., Theeuwes, 1991; Theeuwes, 1992). However, the interpretation of these findings is less clear when we consider that intertrial priming effects can also modulate capture by irrelevant salient distractors. A study by Becker (2007) showed that, in search for a size target, an irrelevant colour singleton distractor only captured attention when its features switched, compared to the previous trial (e.g., from red distractor among green items, to green distractor among red items). By contrast, when the colours of the distractor and the remaining items were repeated, the distractor did not capture (Becker, 2007), indicating that attentional capture by an irrelevant salient distractor, too, is mediated by intertrial priming effects. Presumably, the feature of the distractor (e.g., red) is usually inhibited on each trial, and this inhibition automatically carries over to the next trial. Thus, if the distractor feature is repeated, the inhibited feature of the distractor cannot compete for attention with the target and thus, does not capture. By contrast, when the features of the distractor and the remaining items switch, all other items inherit the inhibited feature, so that the distractor has a relative advantage in the competition for attention and thus can capture attention on a portion of trials (e.g., Becker, 2007; see also Olivers & Humphreys, 2003; Pinto et al., 2005).

Previous studies have shown that the strength of distractor inhibition can vary. For instance, it has been found that infrequent or rare distractors can capture attention, whereas capture is usually much reduced or even eliminated when the distractor is presented frequently during a block of trials (e.g., Geyer, Müller, & Krummenacher, 2008). This has been taken to show that inhibition of the irrelevant distractor depends on the observers' expectancies, and whether they have a good incentive to inhibit the distractor feature – whereby there is more incentive to inhibit frequent distractors than infrequent ones.

In addition, it has been found that inhibition of the distractor varies with differences in the way the distractor is mapped to the target and nontarget features. Distractor effects are commonly assessed in two different visual search paradigms; (a) in the *Irrelevant Singleton Paradigm* (henceforth: ISP), where the distractor is presented at chance level at the target location (e.g., Yantis & Egeth, 1999), and (b) in the *Additional Singleton Paradigm* (henceforth: ASP), where the distractor is never presented at the target location (e.g., Theeuwes, 1991; Theeuwes, 1992). Note that the singleton distractor is consistently mapped to the nontargets in the ASP, whereas this mapping is inconsistent in the ISP, where distractor and target can be presented at the same location. Previous studies showed a trend for more interference by the irrelevant distractor in the ISP than in the ASP (Becker, 2007). This indicates that the distractor feature was less strongly inhibited in the ISP, possibly because strong inhibition of the distractor feature would have impaired search on valid trials, where the distractor is presented at the same location as the target.

Taken together, the available evidence suggests that attentional capture by an irrelevant colour singleton distractor does not depend so much on knowledge about the features of the distractor, or on its saliency, but on automatic intertrial carry-over effects, which dynamically change the attention-driving capacity of the distractor on a trial-by-trial basis (cf. Becker, 2007).

1.1. Aim of the present study

The aim of the present study was to investigate whether switching the colours of the distractor and the remaining items would affect eye movements in visual search, and lead to more oculomotor capture by the salient distractor. To that aim, the eye movements of the observers were tracked in four different conditions of a size search task with an additional or irrelevant colour singleton (ASP vs. ISP), while the colour of the distractor either remained constant across a block of trials, or randomly switched across trials. Assessing oculomotor capture also allows a more decisive test of whether switch trials indeed lead to stronger attentional capture: Previous research shows that eye movements are preceded by attention shifts to a location (e.g., Deubel & Schneider, 1996). Thus, monitoring the eye movements of the observers during search can provide detailed information about the location that was attended.

To date, the question of whether switch trials will initiate more frequent visual selection of the irrelevant distractor has not been examined. However, this is an important question, because switch trials could amplify the distractor effect without directly modulating the attention-driving capacity of the distractor. First, it should be noted that previous studies assessed capture by assessing baseline RTs and response-compatibility effects (Becker, 2007). This evidence may be regarded as being still somewhat indirect, because response-compatibility effects may not be due to attentional capture by the irrelevant distractor, but could reflect parallel processing of target and distractor (e.g., Becker, 2007; Folk, Remington, & Wu, 2009). According to this view, the distractor may not have captured attention fully, but diverted only a small portion of the attentional resources, so that processing of the target was delayed, and processing of the response-relevant item at the distractor location could interfere with processing of the response-related item of the target. However, if it can be shown that switch trials produce oculomotor capture by the irrelevant distractor, this would indicate that, in previous studies, stronger distractor effects on switch trials were indeed due to the fact that the distractor captured attention (because eye movements presumably indicate that at least the majority of attentional resources was allocated to this location).

A second complication of previous studies is that they cannot exclude that switching the colours of all items in the display amplified the distractor effect by interfering primarily with detection of the target. The presence of a salient distractor could add noise to the display, thus making it harder to find the target without necessarily instigating a shift of attention to its location. In line with this idea, Theeuwes et al. (2003) found that, in search for a shape target, the presence of an irrelevant colour distractor significantly reduced the proportion of first eye movements to the target, compared with a distractor absent control condition. However, this reduction was due to the fact that observers frequently selected one of the inconspicuous nontargets (on 31% of all trials), whereas the irrelevant distractor was selected on only 1.5% of all trials. This indicates that the presence of an irrelevant distractor can interfere with target selection without directly summoning attention or eye movements to its location. Analogously, it is conceivable that switching the colours of the distractor and the remaining items interferes with target selection, without directly modulating the attention-driving capacity of the distractor. In particular, it is possible that switch trials impair target selection such that *all* irrelevant items – that is, the nontargets and the distractor – are selected more frequently than on repetition trials. This hypothesis is consistent with the observation that compatibility effects were amplified on switch trials (e.g., Becker, 2007), but it would offer an alternative explanation for that. Hence, it would be wrong to claim that switching features increases the attention-driving capacity of the distractor, because switch trials would primarily modulate the attention-driving capacity of the target and not of the distractor.

The present study addressed this problem by assessing oculomotor capture by comparing the proportion of first fixations on the *distractor* with the proportion of first fixations on the *nontargets*. This allows to determine whether the distractor was selected because the distractor's attention-driving capacity was enhanced, or because target's attention-driving capacity was impaired: If changing the distractor colour across trials primarily modulates the attention-driving capacity of the target, then we should observe an increase in first fixations on the distractor but also an increase of fixations on the inconspicuous nontargets. If, on the other hand, switch trials selectively increase the attention-driving capacity of the distractor, then this should lead to an increase in the fixations on the irrelevant distractor without a concomitant increase in the proportion of nontarget fixations.

In addition to the proportion of eye movements, the latencies of fixations on the target, the distractor and the nontargets were also analysed, to ensure that differences in the proportion of first fixations were not due to a speed-accuracy trade-off. To note, eye movements that are initiated at an earlier point in time are more prone to saccade errors, and the proportion of erroneous saccades decreases with increasing saccade latencies (e.g., Findlay, 1997). Hence, it is important to monitor the fixation latencies, to ensure that a particular condition (e.g., switch trial) does not produce more erroneous fixations by such speed-accuracy trade-offs.

The fixation latencies, or in short: *VRTs* (visual response times), were measured as the duration from the onset of the trial until selection of an item, whereby a fixation was counted as a fixation on a target or nontarget when the gaze was within 1° of the centre of the stimulus. Thus, the VRTs reported here do not reflect only the saccade initiation times, but also the time needed to execute the saccade.

Other studies have occasionally used the point in time where the eyes left a (randomly) defined area around the fixation point as a measure for VRTs (or *SRTs*: saccadic response times), or a combined speed-/space-based criterion (e.g., the point in time where an eye movement directed at a particular item exceeded the speed of 30°/s, or exceeded a particular acceleration; e.g., Theeuwes et al., 2003). Computing the VRTs in this way seemed less ideal for the purpose of the present study, because the endpoint of a saccade can deviate from its initial direction. Thus, computations of mean VRTs and computations of the mean proportion of first saccades that terminate on an item will usually be based on different pools of trials. This however complicates assessing the possibility of a speed-accuracy trade-off. By contrast, applying the same endpoint-criterion to measurements of VRTs and the proportion of first fixations on an item ensures that the data are based on the same pool of trials, which allows assessing speed-accuracy trade-offs in a more straightforward manner. Secondly, the present method of computing VRTs seemed more appropriate, because the presence of an irrelevant distractor can also affect eye movements while a saccade is executed: For instance, saccades are usually curved away from an irrelevant colour singleton (e.g., Becker et al., 2009; Ludwig & Gilchrist, 2002; Ludwig & Gilchrist, 2003; Van der Stigchel, Meeter, & Theeuwes, 2006; Wu & Remington, 2003), and saccades initially directed at a distractor can change direction in mid-flight (e.g., Godijn & Theeuwes, 2002; Godijn & Theeuwes, 2003). Hence, including the time needed to execute a saccade is a potentially more sensitive measure – this at least holds with regard to the present question, whether and to what extent a distractor can affect the first eye movement on a trial.

2. Experiment

In the present study, observers had to search for a target bar that was consistently thicker and larger than the nontarget bars, and to respond to its orientation (see Becker, 2007). To assess whether the differences between the target and nontarget bars were sufficient to produce a pop-out effect, the number of items (set size) was varied between 5 and 7. Efficient search or pop-out is usually inferred if search times are below 10 ms/item (e.g., Wolfe, 1998). As in the study of Becker (2007), search performance was assessed in four conditions: (1) In the *ASP constant* ($\text{ASP}_{\text{const}}$) condition, the colour singleton distractor always had the same colour (e.g., red) and was never presented at the target location. (2) In the *ASP mixed* ($\text{ASP}_{\text{mixed}}$) condition, the colour of the distractor and the remaining items randomly changed across trials, so that the distractor was unforeseeably either red or green (whereas the remaining items were presented in the other colour). (3) In the *ISP constant* ($\text{ISP}_{\text{const}}$) condition, the distractor always had the same colour across all trials (and this was the same colour as in the $\text{ASP}_{\text{const}}$ condition), but the distractor was presented at the same location as the target at chance level (i.e., on 1/6 of all trials). (4) In the *ISP mixed* ($\text{ISP}_{\text{mixed}}$) condition, the distractor colour randomly varied across all trials, and the distractor was presented at the target location at chance level (see Fig. 1 for an example of the displays).

In the ISP conditions, the distractor could be presented at the target location, constituting a *valid* distractor trial, or it could be presented away from the target, constituting an *invalid* distractor trial (e.g., Yantis, 1993; Yantis & Egeth, 1999). In the ASP conditions, the distractor was always invalid. In the ASP and ISP mixed conditions, the colour of the distractor and the remaining items were chosen randomly on each trial. In a sequence of trials, the colour of the distractor and the target from the previous trial could thus either be repeated, constituting a "repetition trial", or the colours could switch, constituting a "switch trial". Moreover, in the ISP conditions, trials could be preceded by invalid trials ($n - 1$ *invalid* trial) or by valid trials ($n - 1$ *valid trial*). Switch trials in the $\text{ASP}_{\text{mixed}}$ condition and $n - 1$ valid trials in the $\text{ISP}_{\text{const}}$ condition have similar yet slightly different characteristics: on both switch trials and $n - 1$ valid trials, the colour of the target changes, compared to the previous trial. However, on switch trials, the colour of the distractor, too, changes, whereas on $n - 1$ valid trials, the distractor colour remains the same and only the target feature changes (because it was previously presented at the same position as the distractor. In the $\text{ISP}_{\text{mixed}}$ condition, it is also possible that only the distractor colour changes on $n - 1$ valid trials, whereas the target colour remains the same). One aim of the present study was to examine whether valid trials have a stronger impact on subsequent (invalid) trials; for instance, because the distractor is then correlated with the target location, which may produce stronger activation of the target colour or stronger inhibition of the colour of all nontargets (than on invalid trials, where the nontargets are always mixed red and green; see Becker, 2007).

To assess the effect of changing the target and/or distractor colours across trials, capture by the irrelevant distractor was assessed within each experimental condition and between conditions. If a condition (e.g., switching the features of the distractor and the remaining items) increases the capacity of the irrelevant distractor to capture, then we should observe more frequent selection of the distractor, but not of the nontargets in this condition, resulting in a statistically significant interaction between condition (e.g., switch vs. repetition trial) and the selected item (i.e., distractor vs. nontarget). In contrast, if switch trials interfere mainly with target selection, we should observe similar increases in the number of selection of the nontargets and the irrelevant distractor (leading to a main effect of switch trials).

2.1. Method

2.1.1. Participants

Twelve paid volunteers ($10/h) from the University of Queensland, Australia, took part in the experiment. The participants were half male and half female, and had a mean age of 22.5. All subjects had normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

2.1.2. Materials

An Intel Duo 2 CPU 2.4 GHz computer with a 17″ flat screen colour monitor (FP92E) was used to generate and display the stimuli and to control the experiment. Stimuli were presented with a resolution of

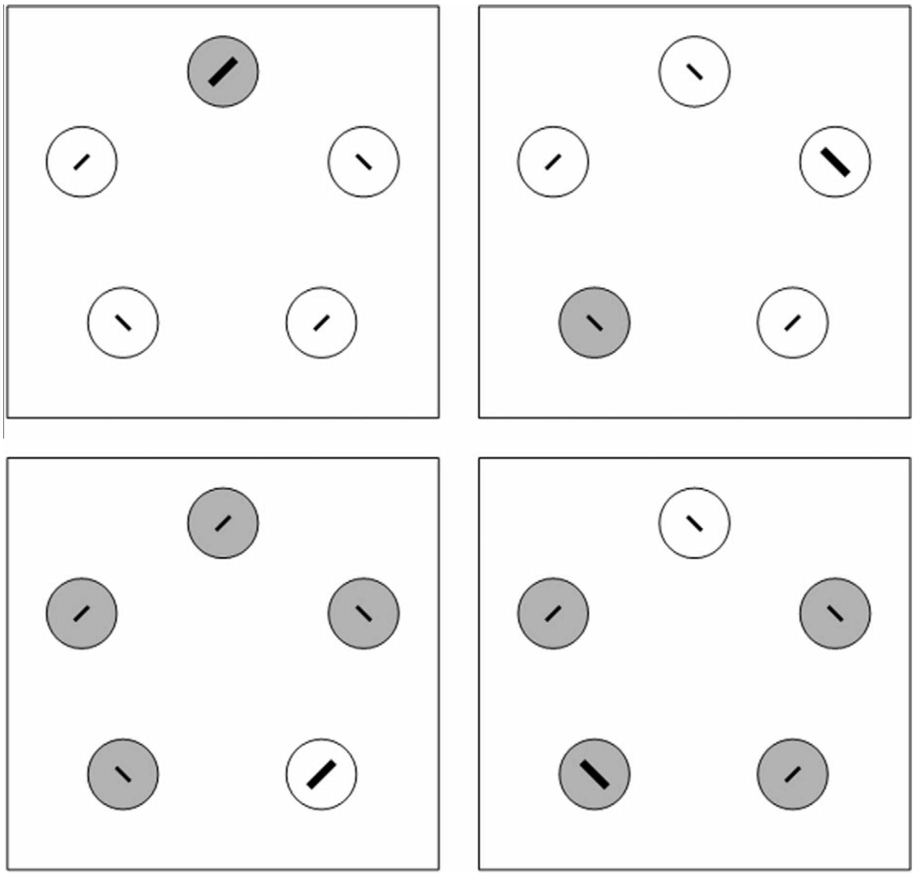

Fig. 1. Example displays: observers had to respond to the orientation of a large bar (left/right), while ignoring the odd coloured distractor (red or green). Panels on the left depict examples of valid trials, where the colour singleton distractor was at the same position as the target; displays on the right depict examples of invalid trials. The set size 7 condition is not displayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1280 × 1024 pixels and a refresh rate of 75 Hz. A video-based infra-red eye-tracking system was used (Eyelink 1000, SR Research, Ontario, Canada) with a spatial resolution of 0.1° and a temporal resolution of 500 Hz. Participants were seated in a normally lit room, with their head fixated by the eyetracker's chin rest and forehead support, and viewed the screen from a distance of 62 cm.

2.1.3. Stimuli

Fig. 1 shows an example of the stimuli. The search displays consisted of 5 or 7 red or green disks (2.9° diameter) presented against a white background. Red and green were matched for luminance with a digital photometer (red: 32.90 cd/m^2; green: 32.74 cd/m^2). The task-relevant items were black bars tilted 45° to the left or right and presented centrally on each disk. The target was a bar that was larger (1.75° × 0.28°) than the other bars (all 0.74° × 0.09°). All stimuli were equally spaced on the outlines of an imaginary circle with a diameter of 12.5°, starting at the 12 o'clock position.

2.1.4. Design

In the experiment, participants had to search for a large bar and to report its orientation by a keypress. In all search displays, one of the coloured disks was presented in a different colour than the remaining disks, constituting a colour singleton distractor. The experiment comprised four blocked conditions which differed in the featural certainty of the distractor (same vs. mixed colours) and the way the distractor was mapped to the nontarget and target positions across trials (ASP vs. ISP; see above). The order of blocks was counterbalanced across participants using a Latin square procedure.

Within each block, the set size (5 or 7 items) was controlled so that each block consisted of roughly equal numbers of set size 5 and 7 trials. Moreover, the target position, distractor position and response were controlled such that the target occurred with each response-defining item (left vs. right) once in each position combined with the distractor position. In the mixed conditions, the colour of the distractor was varied randomly, so that repetition trials and switch trials had the same probability. In the ASP constant and ASP mixed conditions, participants completed 164 trials each (5 target positions × 4 distractor positions × 2 response alternatives × 2 repetitions + 7 target positions × 6 distractor positions × 2 response alternatives = 80 + 84 = 164 trials), in the ISP constant and ISP mixed condition, participants completed 198 trials (5 target positions × 5 distractor positions × 2 response alternatives × 2 repetitions + 7 target positions × 7 distractor positions × 2 response alternatives = 100 + 98 = 198 trials).

Before the first block, participants completed 25 practice trials without any colour singleton distractors, which were not included in the analyses. Between blocks, participants were encouraged to take a rest. On average, it took 50 min to complete the experiment.

2.1.5. Procedure

Each trial started with the presentation of a small black fixation cross (0.28° × 0.28°) that served as a fixation control: The stimulus display was only presented if the tracking was stable (no blinks) and the gaze was within 50 pixels (1.3°) of the centre of the fixation cross, for at least 500 ms (within a time-window of 2000 ms). Otherwise, participants were calibrated anew (9-point calibration) and the next trial started again with the fixation control.

Upon presentation of the stimulus display, participants were required to search the display for the large bar and to press the right mouse button when it was tilted to the right, and the left button when it was tilted to the left. The stimulus display remained on screen until response, and was immediately succeeded by a feedback display. The feedback display consisted in the black printed words "right" or "wrong" (Arial Black, 13 pt.) that were presented centrally and remained on screen for 500 ms. After an intertrial interval of 250 ms, in which a blank white screen was presented, the next trial started with the presentation of the fixation cross.

Before each block, participants were calibrated with a 9-point calibration and were given written instruction about the next block. In particular, they were given full information about the colour singleton distractor (e.g., whether the items could change colour; and whether the distractor coincided with the target at chance level or not). Participants were instructed to ignore the distractor and to respond as fast as possible without making any mistakes.

2.2. Results

2.2.1. Data

Data were excluded from all analyses when the manual response times (RTs) exceeded 2000 ms, or when the eyes had not been fixating on the target within 2000 ms. The eyes were counted as fixating on the target if the gaze had been within 1° of the centre of the response-related stimulus, and no saccade occurred (velocity < 30°/s). One subject was excluded because the eye movement data indicated that he had not moved his eyes away from the fixation point on a sufficient number of trials. Of the remaining trials, 5.44% had to be excluded (0.1% because of RT outliers, 5.34% because of the failure to select the target within 2000 ms). Moreover, trials on which a manual response error occurred were excluded from the analyses of RTs and eye movements (1.58%). In the statistical analyses, where appropriate, the Greenhouse-Geisser corrected *p*-values were reported, together with the uncorrected degrees of freedom.

2.2.2. Set size effects

Search efficiency was assessed by computing a 4 × 2 ANOVA over the mean RTs of each distractor condition ($\text{ASP}_{\text{const}}$, $\text{ASP}_{\text{mixed}}$, $\text{ISP}_{\text{const}}$, $\text{ISP}_{\text{mixed}}$), and set size condition (5 vs. 7). The results showed only a significant main effect of set size ($F(1, 10) = 16.7$; $p = .002$), reflecting that, on average, RTs were 14 ms shorter in the set size 5 condition than in the set size 7 condition (all other Fs < 1). The slope (7 ms/item) was thus within the range of efficient or *pop-out* search (e.g., Wolfe, 1998). For the subsequent analyses, data were pooled over the different set size conditions.

2.2.3. Capture by the irrelevant distractor

The mean proportion of first fixations on the target, the distractor and the nontargets in each of the conditions are depicted in Table 1. Capture by the irrelevant distractor was assessed by comparing the proportion of trials where the irrelevant distractor was selected first with the proportion of trials where one of the inconspicuous nontargets was selected first. Moreover, to ensure that the results were not due to a speed-accuracy trade-off, the visual response time (VRT), that is, the time from the onset of the trial to the point in time where the eyes were located at a stimulus location. In the ISP conditions, only invalid trials were included in this analysis, to render the ISP comparable to the ASP conditions, which consisted of invalid trials only.

The results of a 4 × 2 ANOVA comparing the proportion of nontarget and distractor fixations across the four conditions showed that the salient distractor (27.2%) was selected more often than any of the nontargets (13.8%; $F(1, 10) = 9.7$; $p = .011$). However, this effect was qualified by a significant interaction between the selected item (nontarget vs. distractor) and the search condition ($F(3, 30) = 6.3$; $p = .013$).

Pairwise comparisons revealed that the distractor was selected more frequently than the nontargets in three of the four blocked conditions; the $\text{ASP}_{\text{mixed}}$ condition, where the colour of the distractor randomly varied (*mean difference* = 12.2%; $t(10) = 3.6$; $p = .005$),

Table 1

Mean proportion of first fixations on the target, distractor and nontargets (Prop), and latencies of these fixations (VRTs).

Selected item		$\text{ASP}_{\text{const}}$	$\text{ASP}_{\text{mixed}}$		$\text{ISP}_{\text{const}}$		$\text{ISP}_{\text{mixed}}$		*$\text{ISP}_{\text{mixed}}$, only invalid & n-1 invalid*[b]	
		invalid	*invalid*		*valid*	*invalid*	*valid*	*invalid*	*Switch*	*Rep.*
Target	*Prop*	62.7%	59.4%		87.8%	57.6	82.6%	57.5%	54.6%	60.9%
	VRT	282	286		260	282	265	283	288	281
Distr.	*Prop*	19.8%	26.2%		–	33.4%	–	28.7%	35.2%	23.9%
	VRT	258	271		–	255	–	267	268	270
Nont.	*Prop*	17.5%	14.4%		12.2%	9.0%	17.4%	13.8%	11.8%	15.9%
	VRT	242	242		324	252	252	240	240	239
			$\text{ASP}_{\text{mixed}}$		*$\text{ISP}_{\text{const}}$, only invalid trials*		*$\text{ISP}_{\text{mixed}}$, only invalid trials*[a]		*$\text{ISP}_{\text{mixed}}$, only Rep.*[c]	
			Switch	*Rep.*	*$n-1$ valid*	*$n-1$ invalid*	*$n-1$ valid*	*$n-1$ invalid*	*$n-1$ valid*	*$n-1$ invalid*
Target	*Prop*		56.7%	62.1%	43.1%	60.6%	54.8	57.9%	39.1%	61.0%
	VRT		292	281	292	281	283	284	286	281
Distr.	*Prop*		30.1%	22.3%	50.6%	29.8%	31.6%	28.2%	50.5%	23.2%
	VRT		277	266	251	257	260	269	253	270
Nont.	*Prop*		13.2%	15.6%	6.3%	9.5%	13.6%	13.9%	10.4%	15.8%
	VRT		244	240	227	255	235	241	236	239

[a,b,c] Data from analyses 1, 2, and 3 of the $\text{ISP}_{\text{mixed}}$ condition, respectively.

and in both ISP conditions, where the distractor coincided with the target at chance level ($\text{ISP}_{\text{const}}$: *mean difference* = 24.3%; $t(10) = 3.6$; $p = .005$; $\text{ISP}_{\text{mixed}}$: *mean difference* = 14.9%; $t(10) = 4.3$; $p = .001$). However, the nontargets and the distractor were equally often selected in the $\text{ASP}_{\text{const}}$ condition, where the distractor colour was constant (*mean difference* = 2.2%; $t < 1$).

Capture by the irrelevant distractor (i.e., proportion of distractor fixations minus proportion of nontarget fixations) was also significantly or marginally significantly stronger in the $\text{ISP}_{\text{const}}$ condition than in the $\text{ASP}_{\text{const}}$ condition ($t(10) = 5.6$; $p < .001$) and the $\text{ASP}_{\text{mixed}}$ condition ($t(10) = 2.1$; $p = .059$). Moreover, capture was marginally significantly stronger in the $\text{ISP}_{\text{mixed}}$ condition than in the $\text{ASP}_{\text{const}}$ condition ($t(10) = 2.2$; $p = .052$).

Taken together, the results indicate that the distractor captured more strongly in the ISP than in the ASP, and in the ASP, capture was stronger when the distractor varied ($\text{ASP}_{\text{mixed}}$) than when it remained constant across trials ($\text{ASP}_{\text{const}}$). To ensure that these differences were not due to a speed-accuracy trade-off, the mean VRTs of fixations on the target, the nontargets and the irrelevant distractor were compared across the four search conditions. The 4 × 3 ANOVA showed no significant differences in VRT between the different conditions, indicating that the differences in the distractor effect were not due to a speed-accuracy trade-off. The analysis showed a significant main effect of the selected item only ($F(2, 10) = 23.9$; $p < .001$), reflecting that, in all conditions, VRTs to the nontargets were shortest and VRTs to the target were longest, with VRT to the distractor being intermediate. Across all conditions, saccades to the nontargets were reliably initiated earlier than saccades to the target (all $ps < .001$). Saccades to the distractor were initiated significantly earlier than saccades to the target only in the $\text{ASP}_{\text{const}}$ and $\text{ISP}_{\text{const}}$ conditions (both $ps = .004$). Moreover, saccades to a nontarget were initiated significantly earlier than saccades to the distractor in all search conditions, with the only exception of the $\text{ISP}_{\text{const}}$ condition (all other $ps < .05$).

2.2.4. Oculomotor capture on switch trials and after valid trials

To assess whether the irrelevant distractor would capture attention more strongly when its features changed ($\text{ASP}_{\text{mixed}}$) or when the distractor had been presented at the target location ($\text{ISP}_{\text{const}}$), or both ($\text{ISP}_{\text{mixed}}$), the proportion of trials where the distractor had been selected first was assessed separately for repetition trials and switch trials (or for trials following valid versus invalid trials, respectively).

A 2 × 2 ANOVA comparing the mean proportion of distractor selections and nontarget selections on repetition versus switch trials in the $\text{ASP}_{\text{mixed}}$ condition showed a significant main effect of the selected item ($F(1, 10) = 12.4$; $p = .006$) and a significant effect of switch ($F(1, 10) = 5.2$; $p = .046$). The interaction between the two variables was also significant ($F(1, 10) = 8.4$; $p = .016$), indicating that capture by the irrelevant distractor was significantly stronger on switch trials than on repetition trials. Pairwise comparisons showed that the distractor was selected significantly more often than the nontargets on switch trials ($t(10) = 3.9$; $p = .003$), and marginally significantly more often than the nontargets on repetition trials ($t(10) = 2.2$; $p = .053$). Critically, switching the features of the distractor led to significantly more frequent selection of the distractor ($t(10) = 2.9$; $p = .014$), but not of the nontargets.

The same analyses computed over the mean VRTs revealed that saccades to the target were significantly delayed by switching the features of the distractor ($t(10) = 2.5$; $p = .031$). Switch trials also delayed eye movements to the distractor and the nontargets, but these differences were far from significant (both $ps > .26$). This indicates that switch trials do not prompt more erroneous selection of the distractor by prompting saccades to be initiated earlier.

In the $\text{ISP}_{\text{const}}$ condition, capture on invalid trials was compared between trials where the distractor on the previous trial had been presented at the target position ($n-1$ valid trials) and trials where the distractor on the previous trial had been presented away from the target position ($n-1$ invalid trials). A corresponding 2 × 2 ANOVA comparing the proportions of distractor versus nontarget selections on $n-1$ valid trials versus $n-1$ invalid trials showed a significant main effect of the selected item ($F(1, 10) = 18.2$; $p = .002$), of $n-1$ validity ($F(1, 10) = 21.9$; $p = .001$), and a significant interaction between the two variables ($F(1, 10) = 13.0$; $p = .005$). The interaction reflects that the distractor (but not the nontargets) captured stronger after a valid trial than after an invalid trial. However, the distractor was selected more frequently than the nontargets both after valid trials ($t(10) = 4.5$; $p = .001$) and after invalid trials ($t(10) = 3.1$; $p = .011$).

An analysis of the VRT showed a trend for saccades being delayed when the previous trial was a valid trial ($t(10) = 2.0$; $p = .07$), and the opposite trend for saccades to the distractor and nontargets, which were elicited earlier ($t(10) = 1.1$; $p = .28$, and $t(8) = 2.0$; $p = .08$). (Note that the analysis of the nontarget VRT included only nine subjects, because two subjects had not selected any of the nontargets in the $\text{ISP}_{\text{const.}}$)

The data from the $\text{ISP}_{\text{mixed}}$ condition were analysed in three different ways:

1. First, the data were analysed analogously to the data from the $\text{ISP}_{\text{const}}$ condition, to test whether the priming-induced distractor effect is driven by the spatial co-occurrence of a salient colour distractor and the target (Lamy, Bar-Anan, Egeth, & Carmel, 2006). To that aim, changes in the colour of the distractor across trials were ignored (repetition and switch trials were pooled together), and the effect of distractor validity from the previous trial was assessed by comparing the effects of $n - 1$ valid trials to $n - 1$ invalid trials on distractor and nontarget selection. A corresponding 2×2 ANOVA showed only a significant main effect of the selected item, with more frequent selection of the salient distractor than the nontargets ($F(1, 10) = 19.3$; $p = .001$), but selection was not influenced by the validity of the distractor on the previous trial. This contrasts with the results from the $\text{ISP}_{\text{const}}$ condition and indicates that increased capture after valid distractor trials critically depends on the feature value of the distractor, not merely on its singleton status. Analoguously, the mean VRTs to the target, distractor or a nontarget did not differ between $n - 1$ valid and $n - 1$ invalid trials (all $ps > .17$).
2. Secondly, data from the $\text{ISP}_{\text{mixed}}$ were analysed for possible effects of colour changes on capture, analogous to the results of $\text{ASP}_{\text{mixed}}$ condition. As in the ASP, only invalid trials that were preceded by invalid trials were included in the analysis, and capture was compared between repetition trials versus switch trials. A corresponding 2×2 ANOVA comparing the effect of repetition versus switch trials on the proportion of nontarget and distractor fixations showed a significant main effect of the selected item ($F(1, 10) = 17.7$; $p = .001$), the previous trial ($F(1, 10) = 6.4$; $p = .030$), and a significant interaction between the two variables ($F(1, 10) = 13.8$; $p = .004$). Pairwise comparisons showed that the distractor was significantly more often selected than the nontargets on switch trials ($t(10) = 4.9$; $p = .001$), whereas these differences were only marginally significant on repetition trials ($t(10) = 2.2$; $p = .055$). However, both the distractor and the nontargets were more frequently selected on switch trials than on repetition trials (distractor: $t(10) = 3.7$; $p = .004$; nontargets: $t(11) = 2.4$; $p = .037$). In sum, the results from the $\text{ISP}_{\text{mixed}}$ condition replicate the results from the $\text{ASP}_{\text{mixed}}$ condition. Analysis of the VRTs showed no differences between repetition and switch trials on the speed of eye movements to the target, distractor or the nontargets (all $ps > .14$), indicating that the results are not complicated by a speed-accuracy trade-off.
3. The third analysis evaluated possible effects of distractor validity on capture, analogous to the analysis of the $\text{ISP}_{\text{const}}$ data. In this analysis, only trials where the distractor feature had remained the same across trials were included (i.e., repetition trials), and capture was compared between trials following valid versus invalid trials (i.e., $n - 1$ valid vs. $n - 1$ invalid trials; see Fig. 2 for a comparison of the effects). Comparing capture between $n - 1$ valid and $n - 1$ invalid trials showed a significant main effect of the selected item ($F(1, 10) = 20.2$; $p = .001$), of the validity of the distractor on the previous trial ($F(1, 10) = 18.8$; $p = .001$), and also a significant interaction between the variables ($F(1, 10) = 17.8$; $p = .002$). The distractor was significantly more often selected than the nontargets on trials following valid trials ($t(10) = 4.7$; $p = .001$), whereas these differences were only marginally significant often selected on trials following invalid trials ($t(10) = 2.2$; $p = .052$). Both the distractor and the nontargets were selected significantly more frequently after a valid than after an invalid trial (distractor: $t(10) = 4.4$; $p = .001$; nontargets: $t(10) = 2.2$; $p = .021$).

   In addition, the VRTs to the distractor were also 17 ms shorter on same-colour $n - 1$ valid trials ($t(10) = 2.1$; $p = .06$), whereas the VRTs to the target or the nontargets did not show any differences between $n - 1$ valid and $n - 1$ invalid trials (all $ps > .52$). Taken together, in the $\text{ISP}_{\text{mixed}}$ condition, the distractor captured more strongly on trials preceded by same-colour valid trials than on same-colour invalid trials, replicating the result pattern in the $\text{ISP}_{\text{const}}$ condition. This indicates that capture by the distractor does not depend only on whether it has the same feature as the target on the previous trial. In addition, the informativity of the distractor feature on the previous trial apparently plays an important role, since capture was stronger when the singleton feature had been presented at the target position ($n - 1$ valid trial).

To further evaluate this hypothesis, it was tested whether the validity of the distractor on the previous trial (analysis (3)) exerts a stronger effect on capture than repeating vs. changing the distractor feature (analysis (2); see Fig. 2). A 2×2 ANOVA comparing the two effects in the $\text{ISP}_{\text{mixed}}$ condition showed a significant main effect of condition ($F(1, 10) = 9.2$; $p = .013$) and of the previous trial ($F(1, 10) = 22.8$; $p = .001$). Moreover, the interaction between the two variables was significant ($F(1, 10) = 9.2$; $p = .013$), reflecting that presenting the distractor at the same location as the target enhanced capture by the distractor more than changing the distractor colour across invalid trials. The same results were obtained when the difference scores between distractor selection and nontarget selection were taken as an indicator for capture. The corresponding analysis of the VRTs did not show any significant differences. Thus, analysis of the $\text{ISP}_{\text{mixed}}$ condition reveals that the distractor is selected much more frequently when it was valid on the previous trial than when it merely changes the feature.

2.3. Cumulative repetition effects in $\text{ASP}_{\text{mixed}}$ and $\text{ISP}_{\text{const}}$

A previous study showed that attentional capture by the distractor was not only stronger, but also longer-lasting in the ISP than the ASP condition: Whereas capture was mostly eliminated after just one repetition trial in the ASP, capture gradually decreased with an increasing number of repetition trials in the ISP and ceased to exist only after two or more repetitions (Becker, 2007). To test whether this result pattern can also be obtained with the present, oculomotor capture paradigm, the effect of consecutively repeating the distractor feature for 1, 2 or 3 times on invalid trials was compared between the $\text{ASP}_{\text{mixed}}$ and the $\text{ISP}_{\text{const}}$ condition (see Fig. 3A and B).

A 2×3 ANOVA comparing distractor and nontarget selections in each of the three repetition conditions in the $\text{ASP}_{\text{mixed}}$ condition showed only a marginally significant effect of the selected item ($F(1, 10) = 4.7$; $p = .055$), but no significant interaction between repetition and distractor selection ($F < 1$). Selection of the distractor was only more frequent than selection of the nontargets on switch trials ($t(10) = 3.8$; $p = .003$), but not on any of the repetition trials (all $ts < 1.9$; all $ps > .09$). Thus, in the $\text{ASP}_{\text{mixed}}$ condition, the distractor apparently loses the ability to capture after the first repetition.

By contrast, the same ANOVA computed over repetitions of invalid trials in the $\text{ISP}_{\text{const}}$ showed a significant main effect of the selected item ($F(1, 10) = 14.3$; $p = .004$) and a marginally significant main effect of repetition ($F(1, 10) = 3.6$; $p = .059$). More important, the interaction between the two variables was significant

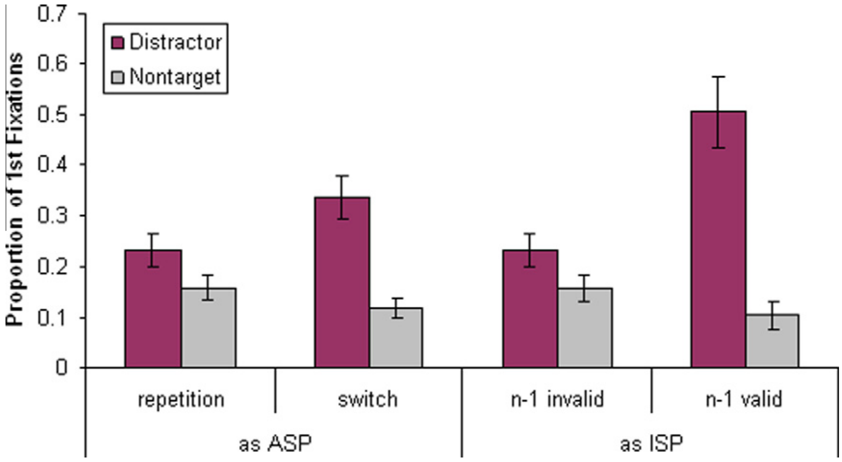

Fig. 2. Mean proportion of first fixations on the irrelevant distractor and the nontargets in the ISP_{mixed} condition. Histograms on the left ("as ASP") show differences in capture on trials where the previous distractor colour was same versus different from the distractor on the current trial (repetition and switch, respectively). Histograms on the right ("as ISP") show differences in capture according to whether the distractor on the previous trial had been valid versus invalid ($n-1$ valid and $n-1$ invalid, respectively). Error bars represent ±1 SEM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

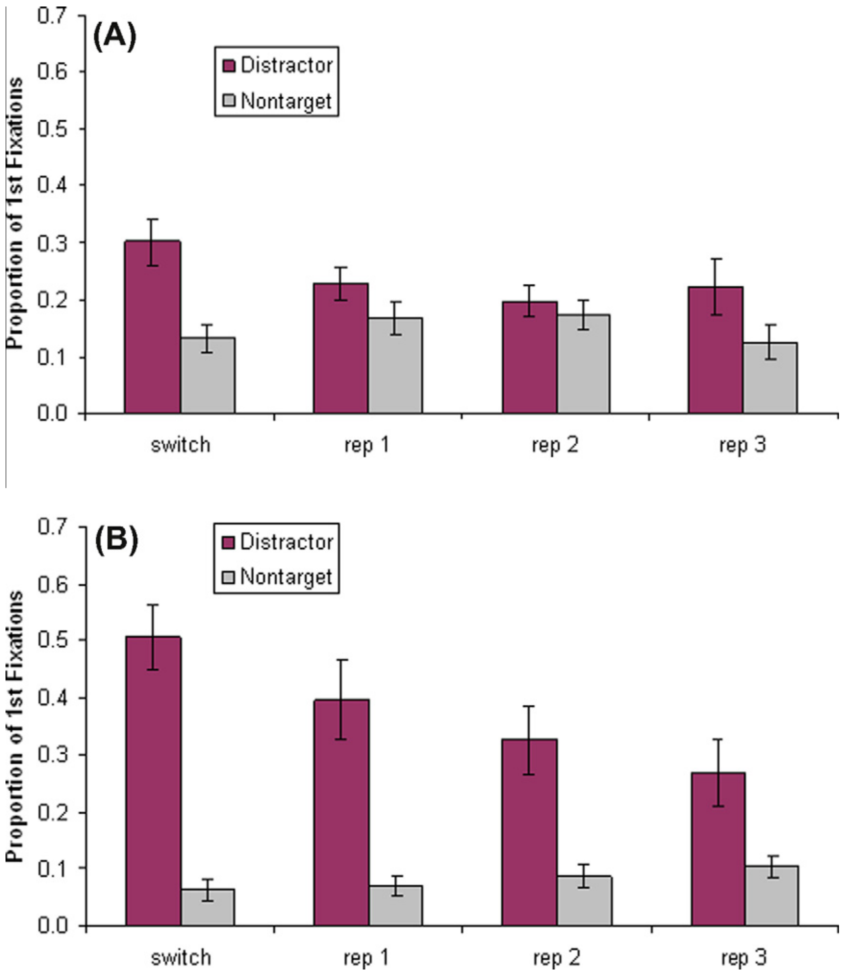

Fig. 3. Effects of repeating the distractor colour on successive trials, depicted separately for the ASP_{mixed} condition (3A) and the ISP_{const} condition (3B). The VRTs for selection of the distractor and nontarget were not depicted, because the amount of data was insufficient: In the ASP, there were 77, 38, 19, and 22 trials, and in the ISP there were 51, 40, 36 and 170 trials in each repetition condition, respectively. Error bars represent ±1 SEM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

($F(1, 10) = 7.6$; $p = .005$), reflecting that repeating invalid trials over consecutive trials significantly reduced the proportion of distractor selection ($F(1, 10) = 6.8$; $p = .007$), whereas it did not affect selection of the nontargets ($F < 1$). However, pairwise comparisons revealed that the distractor was more frequently selected than the nontargets across all repetition conditions (all $ts > 2.4$; all $ps < .04$), indicating that the distractor had generally stronger and longer lasting effects in the ISP than in the ASP.

This interpretation could be confirmed by a 2 × 2 × 3 ANOVA computed over the repetition trials in the $\text{ASP}_{\text{mixed}}$ and $\text{ISP}_{\text{const}}$ condition. The analysis showed a significant main effect of the selected item ($F(1, 10) = 14.7$; $p = .003$), a marginally significant main effect of the previous trial ($F(1, 10) = 3.8$; $p = .058$), a significant two-way interaction between the search condition and the selected item ($F(1, 10) = 11.5$; $p = .007$) as well a significant 3-way interaction between all variables ($F(1, 10) = 5.4$; $p = .017$). Separate ANOVAs computed over selection of the distractor versus the nontargets showed that consecutive repetitions reduced distractor selection significantly more in the $\text{ISP}_{\text{const}}$ than in the $\text{ASP}_{\text{mixed}}$ condition ($F(2, 20) = 4.3$; $p = .039$; selection of the nontargets did not differ between the $\text{ISP}_{\text{const}}$ and the $\text{ASP}_{\text{mixed}}$ condition). This indicates that valid trials (in the ISP) affected capture on subsequent invalid trials much stronger than mere changes of the colour of the irrelevant distractor on invalid trials (in the ASP; compare Fig. 3A and B).

2.4. Discussion

The results of the present study yield some important new insights into the factors that guide attention and the eyes in visual search. First, the results showed that oculomotor capture by a colour singleton is mediated to a large extent by intertrial effects, as the distractor foremost captured when its features switched, compared to the previous trial. These findings are in line with earlier studies using a covert attention task.[1] For instance, Olivers and Humphreys (2003) found that an irrelevant distractor interfered most with search when the distractor had been presented at the target position on the previous trial ($n-1$ valid trial). Similarly, Pinto and colleagues (2005) found that an irrelevant colour singleton distractor produced more interference when the target shape switched across trials. Finally, Becker (2007) showed that switching the features of the distractors led to stronger distractor effects, as measured by compatibility effects. These earlier findings already undermine the view that attentional capture by an irrelevant salient distractor depends on (1) the feature contrasts of target and distractor and (2) knowledge about the exact features of the target and distractor (e.g., Theeuwes et al., 2003).

However, the present study is the first study to demonstrate that oculomotor capture by an irrelevant colour singleton distractor is mediated by intertrial priming effects. This helps resolving some difficulties of earlier studies that provided only indirect evidence for the view that intertrial changes selectively enhance the attention-driving capacity of the distractor. In advance to earlier studies, the present study assessed capture by comparing the proportion of distractor fixations with the proportion of fixations on the inconspicuous nontargets. This allows assessing whether switch trials indeed modulate the attention-driving capacity of the distractor, as was commonly assumed (e.g., Becker, 2007) – or whether switch trials affect distractor selection more indirectly, either by promoting parallel had processing of the distractor and target, or by interfering primarily with target selection, which leads to more frequent selection of the distractor because all nontargets are selected more frequently.[2] The results showed that switching the distractor colour led to selectively more frequent fixations of the distractor, without increasing the proportion of fixations on the inconspicuous nontargets. This shows that switching the colour of the distractor directly modulated the attention-driving capacity of the distractor, and legitimates earlier claims that the distractor effect is largely based on feature-specific intertrial effects (e.g., Becker, 2007; Olivers & Humphreys, 2003): Presumably, irrelevant distractors are usually filtered out by inhibiting the particular feature value of the distractor on a given trial (e.g., red). This inhibition then carries over to the next trial, allowing immediate selection of the target when the distractor has the same feature as on the previous trial. By contrast, when the features of the distractor switch, the inhibited feature is transferred to the remaining items, whereas the distractor has a high attention-driving capacity on switch trials. The finding that capture by the irrelevant salient distractor is mediated by such feature-based intertrial effects emphasises the importance of feature-based intertrial effects over feature contrast computations in the guidance of attention and eye movements.

2.5. Implications for priming

A second important finding was that intertrial priming effects affected eye movements differently according to the informativity or $n-1$ validity of the distractor. This shows that information about the informativity or correlatedness of the distractor colour with the target feature is transferred across trials along with information about the colour itself. The programming of saccades is then influenced both by information about the distractor feature and by the correlatedness of this feature with the target position. This indicates that intertrial priming effects are more sophisticated than originally thought, because they vary with the predictivity or the "correlated-ness" of a feature with the target position (e.g., Maljkovic & Nakayama, 1994).

On the other hand, the conjecture that more complex information can be transferred across trials is in accord with some recent studies that show, for instance, that priming can consist in intertrial transfers of holistic information (e.g., Hillstrom, 2000; Huang, Holcombe, & Pashler, 2004), and object-specific information (Kristjansson, Ingvarsdottir, & Teitsdottir, 2008). In addition, Becker (2008c, 2010), showed that priming can consist of intertrial transfers of relational or contextual information about the target, that

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[1] Deviating from the covert attention study, the present study showed that, in the $\text{ISP}_{\text{mixed}}$ condition, capture was stronger on invalid trials following valid trials than invalid trials – but only if the feature of the distractor had remained the same across trials. In the covert twin attention study, the $\text{ISP}_{\text{mixed}}$ condition did not show any systematic pattern of intertrial changes (Becker, 2007). However, this may be due to the fact that trials were pooled and analysed differently in the earlier study (see Becker, 2007).

[2] It could be argued that inferences from eye movements about attention are not legitimate, because it is possible that attention shifts to the distractor are not followed by an eye movement. For instance, Theeuwes et al. (2003) found in their $\text{ASP}_{\text{const}}$ condition that the distractor was selected on only 1.5% of all trials and did not elongate VRT to the target, but that RT were nevertheless longer in the distractor present condition than in the distractor absent condition. From these results, they concluded that the distractor had captured attention without capturing the eyes. However, this interpretation is not without problems: Assuming that covert attention shifts to the distractor cost time and that such attention shifts occur prior to target selection, it follows that mean VRTs to the target should have been elongated in the distractor present condition, if the distractor had indeed captured attention covertly. This was not the case, indicating that longer RT in the distractor present condition was not related to attentional capture by the distractor. Analogously, in the present study, there is no reason to assume that – contrary to the eye movement data – attention was captured more in the $\text{ASP}_{\text{const}}$ condition than in the $\text{ASP}_{\text{mixed}}$ condition, or more on repetition trials than on switch trials, because the VRT to the target were very similar across the conditions, leaving no room for covert attention shifts. Secondly, the observation that attention can shift without moving the eyes does not necessarily invalidate the method of investigating attention with eye movements. Note that all interpretations are restricted to cases where an eye movement was observed, whereas the absence of eye movements is not interpreted. There is a large consensus that attention shifts precede eye movements, so that an attention shift to the distractor can be inferred from a corresponding eye movement (e.g., Deubel & Schneider, 1996).

specifies how the target differs from the nontargets (e.g., larger, redder, or darker).

Although these results suggest that more complex information or a different kind of information than feature-specific information can be transferred across trials, most of the studies left open whether this information indeed influenced selection, or whether it affected processes located at later stages (e.g., decisional processes, or response selection; see, e.g., Becker, 2008c). Specifically with regard to more complex information, it has been proposed that it may affect post-selectional processes rather than early processes that guide attention (e.g., Huang et al., 2004). In contrast to this, the present study suggests that, in priming, feature-specific information can combine with a different kind of information (e.g., about the correlatedness of the target) and influence the guidance of attention and eye movements on subsequent trials.

2.6. Implications for theories of attention and eye movements

The present study found that the mean times needed to select the distractor (VRT) were consistently shorter than the VRTs for target selection. This is in line with earlier studies (e.g., Ludwig & Gilchrist, 2003; Theeuwes et al., 2003), and shows that saccades to the distractor were initiated earlier than saccades to the target.[3] In previous studies, corresponding findings have been taken to show that information about feature contrasts is available at an earlier point in time than feature-specific information. Thus, salient items with a high feature contrast are thought to affect the guidance of attention and eye movements at an earlier point in time than top-down, feature-specific information, which feeds later into the stream and can influence eye movements only at a later stage (e.g., competitive integration model of eye movements; Godijn & Theeuwes, 2002; Van Zoest & Donk, 2004; Van Zoest & Donk, 2005; Van Zoest & Donk, 2006; Van Zoest, Donk, & Theeuwes, 2004).

However, the results of the present study are not in line with such models of attention and eye movement control. First, the present study also showed that the VRTs of saccades to the distractor were shorter than VRTs of saccades to the target. However, shorter VRTs of saccades to the distractor were probably not due to the fact that feature contrast information was available at an earlier point in time. Rather, capture by the salient distractor was mediated by feature-specific intertrial effects, indicating that shorter VRTs of saccades to the distractor than to the target were similarly due to feature-specific intertrial carry-over effects. This indicates that shorter VRTs to the distractor than to the target cannot be cited as evidence for feature contrast information guiding attention and eye movements.

Secondly, and more importantly, eye movements to the inconspicuous nontargets were initiated even earlier than eye movements to the salient distractor. Across all conditions, the nontargets elicited erroneous saccades prior to the point in time when the distractor captured the eyes.[4] This finding, too, casts doubt on the notion that irrelevant distractors involuntarily capture the eyes in virtue of their feature contrast: Applying the line of reasoning of Van Zoest et al. (2004), we would have to conclude that the inconspicuous nontargets capture attention and the eyes at an earlier stage than salient distractors. Moreover, assuming that the ordering of VRTs allows inferences about the point in time where different kinds of information become available to the visual system, we would be forced to conclude that information about the nontargets is available prior to information about the feature contrast of the distractor.

However, it is difficult to see what kind of information about the nontargets could have possibly guided attention and the eyes to the nontarget items. This calls into question the view that erroneous selections of the distractor can or should be equated with oculomotor capture. Rather, oculomotor capture by irrelevant distractors should perhaps be viewed as erroneous saccades, with the ordering of VRTs reflecting the magnitude of the saccade error. Recall that the precision of saccades improves with longer VRTs, presumably because longer saccade initiation times allow information about the search display to accumulate, so that saccades with longer initiation times are based on more detailed information about the search display (e.g., Findlay, 1997). Selection of the inconspicuous nontargets could be viewed as a more severe saccade error than saccades to the distractor, because there are many nontarget items, which are all very similar to one another, so that the information gain at a single nontarget location is very low. By contrast, selection of the salient distractor would seem a less severe saccade error, especially on switch trials, when the distractor inherits the feature formerly associated with the target. Moreover, the information gain at the distractor location is generally higher, because the distractor has a unique feature. Since the target also had a unique feature, it could also be argued that distractor selections constitute less severe saccade errors because the distractor was more similar to the target than the nontargets (e.g., Bacon & Egeth, 1994; Folk & Remington, 2006, 2008; Leber & Egeth, 2006).

In sum, the view that distractors elicit involuntary saccades in the fashion of bottom-up oculomotor capture has difficulties to explain erroneous saccades to the nontargets, and specifically, that such saccades are initiated earlier in time than saccades to the salient distractor. For the future, it may be prudent to avoid the theory-laden term “oculomotor capture” and to speak of erroneous saccades to the distractor instead, so that the term oculomotor capture can be reserved for instances where the irrelevant distractor is selected at a very early stage in visual search and in virtue of its saliency (e.g., Mulckhuyse et al., 2008).

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References

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics, 55*, 485–496.

Becker, S. I. (2007). Irrelevant singletons in pop-out search: Attentional capture or filtering costs? *Journal of Experimental Psychology: Human Perception and Performance, 33*, 764–787.

Becker, S. I. (2008a). The stage of priming: Are intertrial repetition effects attentional or decisional? *Vision Research, 48*, 664–684.

Becker, S. I. (2008b). The mechanism of priming: Episodic retrieval or priming of pop-out? *Acta Psychologica, 127*, 324–339.

Becker, S. I. (2008c). Can intertrial effects of features and dimensions be explained by a single theory? *Journal of Experimental Psychology: Human Perception and Performance, 34*, 1417–1440.

Becker, S. I., Ansorge, U., & Horstmann, G. (2009). Can intertrial priming account for the similarity effect in visual search? *Vision Research, 49*, 1738–1756.

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[3] The VRTs reported here were generally longer than in previous studies. This does not signify an important difference, however, but reflects that in previous studies, typically only the saccade initiation times were measured (e.g., the onset of the first saccade), whereas in the present study, mean VRTs included the time needed to execute the saccade. Since saccades usually take a fixed duration to be executed, this method of measuring VRTs is equivalent to measurements of the saccade initiation times (whereby the present strategy of measuring VRTs also allows more straightforward assessments of possible speed-accuracy trade-offs; see Section 1).

[4] Mulckhuyse, Van Zoest, and Theeuwes (2008) recently found that eye movements to an irrelevant onset distractor were initiated earlier than eye movements to one of the inconspicuous nontargets. However, this finding is consistent with the present view, because onset distractors certainly do not capture attention in virtue of their feature contrast. Instead, onsets presumably capture in virtue of their transients that signal the sudden appearance of a new object in the display, which is available at a very early stage in saccade programming (e.g., Wu & Remington, 2003).

Becker, S. I. (2010). The role of target–distractor relationships in guiding attention and the eyes in visual search. *Journal of Experimental Psychology: General, 139*, 247–265.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36*, 1827–1837.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*, 433–458.

Folk, C. L., & Remington, R. W. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 847–858.

Folk, C. L., & Remington, R. W. (2006). Top-down modulation of pre-attentive processing: Testing the recovery account of contingent capture. *Visual Cognition, 14*, 445–465.

Folk, C. L., & Remington, R. W. (2008). Bottom-up priming of top-down attentional control settings. *Visual Cognition, 16*, 215–231.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1993). Contingent attentional capture: A reply to Yantis. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 682–685.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*, 1030–1044.

Folk, C. L., Remington, R. W., & Wu, S.-C. (2009). Additivity of abrupt onset effects supports nonspatial distraction, not the capture of spatial attention. *Attention, Perception, & Psychophysics, 71*, 308–313.

Findlay, J. M. (1997). Saccade target selection during visual search. *Vision Research, 37*, 617–631.

Geyer, T., Müller, H. J., & Krummenacher, J. (2008). Expectancies modulate attentional capture by salient color singletons. *Vision Research, 48*, 1315–1326.

Godijn, R., & Theeuwes, J. (2003). Parallel allocation of attention prior to execution of saccade sequences. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 882–896.

Godijn, R., & Theeuwes, J. (2002). Oculomotor capture and inhibition of return: Evidence for an oculomotor suppression account of IOR. *Psychological Research, 66*, 234–246.

Hillstrom, A. P. (2000). Repetition effects in visual search. *Perception & Psychophysics, 62*, 800–817.

Huang, L., Holcombe, A., & Pashler, H. (2004). Repetition priming in visual search: Episodic retrieval, not feature priming. *Memory & Cognition, 32*, 12–20.

Kristjansson, A., & Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception, & Psychophysics, 72*, 5–18.

Kristjansson, A., Ingvarsdottir, A., & Teitsdottir, U. D. (2008). Object- and feature-based priming in visual search. *Psychonomic Bulletin & Review, 15*, 378–384.

Kristjansson, A., Wang, D., & Nakayama, K. (2002). The role of priming in conjunctive visual search. *Cognition, 85*, 37–52.

Lamy, D., Bar-Anan, Y., Egeth, H. E., & Carmel, T. (2006). Effects of top-down guidance and singleton priming on visual search. *Psychonomic Bulletin & Review, 13*, 287–293.

Leber, A. E., & Egeth, H. E. (2006). It's under control: Top-down search strategies can override attentional capture. *Psychonomic Bulletin & Review, 13*, 132–138.

Ludwig, C. J. H., & Gilchrist, I. D. (2003). Goal-driven modulation of oculomotor capture. *Perception & Psychophysics, 65*, 1243–1251.

Ludwig, C. J. H., & Gilchrist, I. D. (2002). Stimulus-driven and goal-driven control over visual selection. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 902–912.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition, 22*, 657–672.

Mulckhuyse, M., Van Zoest, W., & Theeuwes, J. (2008). Capture of the eyes by relevant and irrelevant onsets. *Experimental Brain Research, 186*, 225–235.

Olivers, C. N. L., & Humphreys, G. W. (2003). Attentional guidance by salient feature singletons depends on intertrial contingencies. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 650–657.

Pinto, Y., Olivers, C. N. L., & Theeuwes, J. (2005). Target uncertainty does not lead to more distraction by singletons: Intertrial priming does. *Perception & Psychophysics, 67*, 1354–1361.

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics, 50*, 184–193.

Theeuwes, J. (1992). Perceptual selectivity for colour and form. *Perception & Psychophysics, 51*, 599–606.

Theeuwes, J., & Burger, R. (1998). Attentional control during visual search: The effect of irrelevant singletons. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1342–1353.

Theeuwes, J., de Vries, G.-J., & Godijn, R. (2003). Attentional and oculomotor capture with static singletons. *Perception & Psychophysics, 65*, 735–746.

Van Zoest, W., & Donk, M. (2006). Saccadic target selection as a function of time. *Spatial Vision, 19*, 61–76.

Van Zoest, W., & Donk, M. (2005). The effects of salience on saccadic target selection. *Visual Cognition, 12*, 353–375.

Van Zoest, W., & Donk, M. (2004). Bottom-up and top-down control in visual search. *Perception, 33*, 927–937.

Van Zoest, W., Donk, M., & Theeuwes, J. (2004). The role of stimulus-driven and goal-driven control in saccadic visual selection. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 746–759.

Van der Stigchel, S., Meeter, M., & Theeuwes, J. (2006). Eye movement trajectories and what they tell us. *Neuroscience and Behavioral Reviews, 30*, 666–679.

Wolfe, J. M. (1998). Visual search. In H. Pashler (Ed.), *Attention* (pp. 30–73). London, UK: University College London Press.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review, 1*, 202–238.

Wu, S.-C., & Remington, R. W. (2003). Characteristics of covert and overt visual orienting: Evidence from attentional and oculomotor capture. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 1050–1067.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19*, 676–681.

Yantis, S., & Egeth, H. E. (1999). On the distinction between visual salience and stimulus-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 661–676.