

# Preemptive control of attentional capture by colour: Evidence from trial-by-trial analyses and orderings of onsets of capture effects in reaction time distributions

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According to the preemptive-control hypothesis, participants can specify their control settings to attend to relevant target colours or to ignore the irrelevant distractor colours in advance of the displays. Two predictions of this hypothesis were tested. First, with the control settings being specified in advance, capture by a stimulus that better matches the settings was expected to temporally precede capture by a stimulus that matches the setting less well. Second, with the control settings being specified in advance, stronger capture by the better matching than by the less matching stimulus was predicted not to be a stimulus-driven consequence of the target colour in a preceding trial. Both predictions were shown to hold true under different conditions in three experiments.

It is well established that human observers are particularly good at searching for a task-relevant colour stimulus and at ignoring stimuli with an irrelevant (i.e., not-to-be-searched-for) colour (cf. Ansorge & Heumann, 2003, 2004; Eriksen, 1953; Folk & Remington, 1998, 1999; Gibson & Kelsey, 1998; Green & Anderson, 1956; Remington, Folk, & McLean, 2001; Theeuwes & Burger, 1998; Williams, 1966; Yantis & Egeth, 1999; for a more general argument, see Duncan & Humphreys, 1989). This has been shown, for instance, in studies concerning colour singleton capture (Folk, Remington, & Johnston, 1992). A colour singleton is a stimulus that has a colour different from that of all other stimuli in a display. Usually, colour singleton capture (i.e.,

capture of visuospatial attention by a colour singleton) is studied in displays with one colour singleton and several nonsingleton colour stimuli, where colour nonsingletons are relatively more colour-similar to each other than they are to the colour singleton (cf. Bacon & Egeth, 1994, Theeuwes, 1992; Turatto & Galfano, 2001).

Folk and Remington (1998), for example, used a red target and presented a green or a red singleton as a cue in advance of the target to direct the attention of the participants to only one of four possible target locations. In valid conditions, the colour singleton cue was at the target position, whereas in invalid conditions it was at a distance from the target. Under these conditions, a valid cue captures attention to the target and, thus,

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decreases reaction time (RT), but with an invalid cue, the opposite holds true: The cue directs attention away from the target, thereby compromising the target's efficient processing (cf. Posner, 1980). Note that the colour singleton cue in the study of Folk and Remington did not predict the most likely position of the target (i.e., it was a so-called nonpredictive singleton). Therefore, participants had no incentive to attend to the colour singleton cue as such.

In confirmation of the aforementioned capability to successfully ignore an irrelevant colour stimulus and to attend to the relevant target colour, a singleton cue with a colour similar to that of the target captured attention and was not easily ignored: A red singleton cue that was presented in advance of a red target yielded a significant capture or validity effect (i.e., performance was better in valid than in invalid conditions). By contrast, a singleton cue with a colour different from that of the target did seemingly not capture attention and was more efficiently ignored: A green singleton cue that was presented in advance of a red target did not yield a validity effect, although it did incur an unspecific RT cost, presumably because colour-heterogeneous displays cannot be as efficiently processed as colour-homogeneous displays (cf. Folk & Remington, 1998; Treisman, Kahneman, & Burkell, 1983).

These and analogue observations of a *capture difference* (i.e., a stronger attentional effect of the target-similar than of the target-dissimilar colour singleton) can be explained by one of several modes of top-down control over the allocation of attention (cf. Folk et al., 1992; Logan, 1978; Scharlau & Ansorge, 2003). Currently, it is a matter of debate which of the different control mechanisms accounts for the capture difference. To start with, some authors have argued for the possibility that top-down control over visuospatial attention can be exerted by the *preemptive control* of the capture of visuospatial attention. For example, according to the contingent-capture explanation, participants specify their control settings in accordance with the instructions, in advance of the displays. In doing so they are

better able to attend to the target and to ignore the irrelevant stimuli, right from the moment that any of these stimuli appear in sight (e.g., Folk et al., 1992). Henceforth, we refer to this possibility as the *preemptive-control hypothesis*. A prediction of this hypothesis is that, if the participants preemptively control their top-down settings to attend to the relevant colour(s) of the target(s), an irrelevant nontarget singleton that has the same colour as one of the searched-for targets (i.e., a *better matching singleton*) can more often erroneously capture visuospatial attention, right from the moment that the singleton appears in sight, because of its partial match to the target-directed control settings (cf. Ansorge, Horstmann, & Carbone, 2005). However, an irrelevant nontarget singleton, which does not have one of the searched-for target colours (i.e., a *less matching singleton*), can be better ignored. Again, if capture settings can be preemptively controlled, it might be possible to pay less attention to the less matching singleton, right from the very first moment that such a singleton comes into sight.

Note that it cannot be concluded that any effect of a top-down control setting for colour is evident right at the beginning of a trial. In particular, a nontarget singleton with a searched-for colour needs to have features by which it differs and can be discriminated from the target (e.g., its shape). Hence, with a better matching nontarget singleton in the display, capture by its better matching colour and successful ignorance of this nontarget, which is brought about by its less matching shape, for example, are pitted against one other. As a consequence, the net effect of the two antagonistic processes can increase the absolute point in time (during a trial) at which the effect of the top-down control setting for colour can be observed with the better matching nontarget singleton. What can be predicted from the preemptive-control hypothesis, however, is a particular ordering of the onsets of (a) the capture effect in the better matching condition and (b) the capture effect in the less matching condition: Capture of visuospatial attention by a better matching nontarget singleton should temporally precede capture by the less matching nontarget singleton.

In summary, with a preemptive-control account of the capture difference, the top-down controlled settings for attentional capture would not be changed much during a trial or as a mere consequence of the target colour in a preceding trial. During a trial, whether a colour stimulus captures attention should be a relatively uniform consequence of the result of a comparison between the stimulus colour and the preemptively controlled settings to attend to that colour. Likewise, during a block (i.e., across trials) the preemptively specified attentional control settings for the target colour(s) might be occasionally altered (cf. Ansorge, 2004), at least, if the set of to-be-searched-for target colours is large or if there is an incentive to vary the search strategy on a trial-by-trial basis (e.g., because it is possible to predict the colour of the upcoming target). However, with the settings for target colours being top-down specified in advance of the displays, attention to a particular colour stimulus should not be a mere stimulus-driven consequence of colour priming by the target colour in the preceding trial.<sup>1</sup>

On the other hand, some authors have argued that preemptive control of attentional capture in advance of all displays is impossible or insufficient to explain the capture difference, and that top-down control over attention must be exerted reactively either during a trial or in between trials (e.g., Olivers & Humphreys, 2003; Theeuwes, 1994). This hypothesis comes in two forms. According to the deallocation hypothesis, effective top-down control settings for attentional capture cannot be specified in advance of the displays. Instead, at the beginning of each trial, attentional capture is a consequence of an object's saliency (cf. Bravo & Nakayama, 1992; Nothdurft, 1991; but see Yantis, 1996), or of its physical signal being stronger than the physical signals at other locations in a scene (cf. Bergen & Julesz, 1983; Koch & Ullmann, 1985; Wolfe, 1994). Note that according to this assumption, all equally salient singletons are predicted to initially

capture attention to similar amounts, regardless of how well their colours match the set of searched-for target colours. Only in a later phase of each trial (after the initial capture effect has occurred), top-down control settings start to influence the amount of attentional allocation: Participants are assumed to be faster in deallocating attention away from the less matching nontarget colour singleton, because it is easier to tell apart the target and the less matching nontarget colour singleton than it is to tell apart the target and the better matching nontarget colour singleton. As a consequence of this difference in discrimination time, a decision that the currently attended-to stimulus is not a target but an irrelevant nontarget singleton has a more rapid onset with a less matching nontarget colour singleton than with a better matching nontarget colour singleton. Hence, the capture effect or the validity effect can be curtailed in the former relative to the latter conditions. To summarize the deallocation hypothesis: Preemptive control of attentional capture by a stimulus is not possible, but after an initial capture effect or in reaction to the effect, participants can more or less efficiently deallocate attention away from a stimulus.

Note that deallocation might be a fast operating process. Therefore, nothing can be said about the absolute time at which the process will occur (in a trial). Yet, again, what can be predicted from this explanation is a relative ordering of (a) the capture effect of the better matching nontarget singleton and (b) the capture effect of the less matching nontarget singleton. The capture effect of the less matching nontarget singleton and that of the better matching nontarget singleton should co-occur. The reason for this prediction is that deallocation of attention away from a less matching singleton and, hence, a selective diminution of the capture effect in the less matching conditions can only occur after the very same stimulus has already captured attention. In other words, the capture difference—that is, stronger capture by better matching than by less matching

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<sup>1</sup> We are grateful to Chris Olivers for pointing out this alternative hypothesis to us.

singletons, must temporally lag behind a capture effect by the nontarget singletons in both better matching and less matching conditions.

An alternative mode of reactive “control” over the amount of attentional allocation can be derived from the concept of priming of pop-out (cf. Maljkovic & Nakayama, 1994). According to this concept, the ease of attentional capture by a particular colour is a consequence of the most recently encountered target colour. This is inferred from the observation that participants are particularly fast in finding a colour singleton target if the singleton target in a preceding trial  $N - 1$  has the same colour as that in the actual trial  $N$ .

Priming of pop-out might reflect a completely stimulus-driven process, or it might be due to the default maintenance of the top-down control settings for the colour that was most recently used to find the target. In any case, as a consequence of this inertia of the preference of the participants to attend to the recent target colour, “control” over the settings to attend to a particular colour should be severely limited and reactive at best: Search settings to attend to a particular target colour would be updated reactively only if a preceding-to-current target colour change necessitates such a change toward a new colour preference. In other words, the amount of capture by a better matching colour singleton in trial  $N$  should be a direct consequence of the target’s colour in trial  $N - 1$ . For example, if in trial  $N - 1$ , participants searched for a red target, a red nontarget singleton in trial  $N$  captures attention more readily (than a white singleton), because the red singleton (but not the white singleton) corresponds to the most recently encountered target colour. However, if in trial  $N - 1$  participants searched for a green target, a red nontarget singleton in trial  $N$  captures attention no more readily than any equally salient nontarget singleton (e.g., a white singleton) under similar conditions, because the red singleton does not correspond to the most recently encountered target colour.

In the current study, two predictions of the preemptive-control hypothesis were tested. First, if the control settings for attentional capture by colour can be preemptively specified, we expected

capture by the better matching nontarget colour singleton to precede capture by the less matching nontarget colour singleton (cf. Ansorge et al., 2005). To test this hypothesis, the capture effects of a better matching and that of a less matching colour singleton, respectively, were studied by observing their effects on RTs as a function of their rank in the RT distribution. Now it is certainly true that even a simple feature, such as a particular stimulus colour, needs some time before it is processed and before it becomes behaviourally relevant (i.e., captures attention) and that the kind of nontarget singletons that we used might be efficiently ignored in some of the trials on the basis of their nontarget features (i.e., their shapes and their colour singleton status being different from that of the targets). Therefore, even the attentional effect of the better matching colour singleton might not be present among the lowest RTs. In any case, however, on the basis of the preemptive-control hypothesis, a capture effect of the better matching nontarget colour singleton was predicted to have its onset before that of the less matching nontarget colour singleton among the faster responses of the RT distribution.

By contrast, if top-down control is exerted reactively in the sense that it is a deallocation reaction to the initial capture effect (cf. Theeuwes, 1994; Theeuwes, Atchley, & Kramer, 2000), the capture effect should be basically the same with both the better matching nontarget colour singleton and the less matching nontarget colour singleton among the lower RTs: Following the onset of a singleton, performance should be determined by singleton capture alone. Thus, among the faster responses, capture effects should all have similar onsets (and strengths), regardless of whether or not the singleton colour matches the settings for target colours. With respect to the ordering of the onsets of the capture effect, if the capture difference is not due to preemptive control of attentional capture but to the reactive process of deallocation of attention, the evidence for a capture effect can temporally precede the evidence for the capture difference. Among the faster responses, we should be able to find a capture

effect of both the better matching and the less matching nontarget singleton, but no or little evidence for a difference between the onsets of the two capture effects. Only at a later point in time, with a higher mean RT, is the capture difference expected to build up.

Second, further evidence for the preemptive-control hypothesis can be gathered by showing that the control settings directed to the target colours are not changed reactively on a trial-by-trial basis as a consequence of the preceding target colour (cf. Horstmann & Ansorge, 2006). Therefore, we tested for capture effects and capture differences in trial  $N$  as a consequence of whether the target colour in trial  $N - 1$  was or was not the same as that of the better matching nontarget colour singleton in trial  $N$ . (The corresponding variable was called preceding target colour.) If it turns out that capture effects of the better matching nontarget colour singleton are not modified by the variable preceding target colour, we can conclude that preemptively specified settings for attentional capture are at least not a mere consequence of the preceding trial's target colour.

## EXPERIMENT 1

Predictions of the preemptive-control hypothesis were tested with a colour singleton capture paradigm under conditions, in which targets were defined as specific colour nonsingletons. We used colour as a target-defining feature, because a feature that is to be used for the preemptive control of visuospatial attention must be discernible prior to the shifting of attention, even with a parafoveal presentation of the feature. This is the case for colour: It can be discerned prior to the shifting of attention (cf. Treisman, 1988) and the eyes (e.g., Vollbrecht, Nerger, Imhoff, & Ayde, 2000).

Concerning our present research question, former studies have often considered RT increments induced by a nontarget colour singleton at a distance from the target (relative to a colour-homogeneous display without such a

singleton) as an index of the capture of visuospatial attention by the colour singleton (cf. Theeuwes, 1992, 1994). However, this index of singleton capture might reflect the nonspatial costs of the processing of colour-heterogeneous as compared to colour-homogeneous displays (cf. Folk & Remington, 1998). Hence, interference as measured by heterogeneous-to-homogeneous performance differences cannot unequivocally be ascribed to visuospatial attention. For example, nonspatial colour-filtering costs may incur during the perception of the whole object consisting of all the stimuli being displayed (cf. Treisman et al., 1983).

Therefore, we chose another index of singleton capture, which was proposed by Turatto and Galfano (2001). These authors varied the spatial distance between the target and the nontarget singleton and found that interference by the nontarget singleton was a function of the target-singleton distance. RT was lowest, for example, if a target letter was presented inside a green singleton disc that was presented among a multitude of red nonsingleton discs. This was condition  $p_0$  in the terminology of Turatto and Galfano, designating that the target-singleton distance was zero (in terms of display positions between target and singleton) or minimal (in terms of actual spatial distances). By contrast, RTs increased if a target was presented inside a green nonsingleton disc that was presented away from a red singleton disc. The corresponding conditions were called  $p_1$  to  $p_4$ , depending on the distance between the target and the singleton: Position indices increased with target-singleton distance. This result cannot be easily explained by the nonspatial filtering of the irrelevant singleton colour from the colour-heterogeneous displays, because such a nonspatial process does not account for the spatial gradient of the interference (i.e., the fact that the strength of interference is a function of the spatial target-singleton distance). For this reason, we regard a spatial gradient of the interference by the colour singleton as a relatively unequivocal indicator of attentional allocation.

In each trial of Experiment 1, either one better matching nontarget colour singleton or one less



matching nontarget colour singleton was presented at one of four spatial distances from the target (p0 to p3 from small to large distances). In line with Turatto and Galfano (2001), if a nontarget singleton does capture attention, we expected to find interference by the irrelevant nontarget singleton to be a function of target–singleton distance. In other words, RT interference by the nontarget colour singleton was expected to follow a spatial gradient. If a spatial gradient is observed, we can rule out that nonspatial filtering of colour accounts better for the RT interference.

On the basis of the preemptive-control hypothesis, we predicted three patterns of results. First, we expected a capture difference—that is, a stronger capture effect of the better matching singleton than of the less matching singleton. Second, we expected that the onset of the capture effect in the better matching condition preceded that in the less matching condition. Third, we expected that the capture difference in trial  $N$  is not a mere consequence of the colour of the target in the preceding trial  $N - 1$ . That is, the capture difference was expected to be the same, irrespective of whether the colour of the better matching nontarget singleton in trial  $N$  was or was not the same as that of the target in trial  $N - 1$  (variable preceding target colour).

## Method

### *Participants*

A total of 24 volunteers (15 female, 9 male) with a mean age of 23 years participated. Here and in the following experiments, participants were mostly students at Bielefeld University. All had normal or fully corrected vision and were paid for their participation.

### *Apparatus*

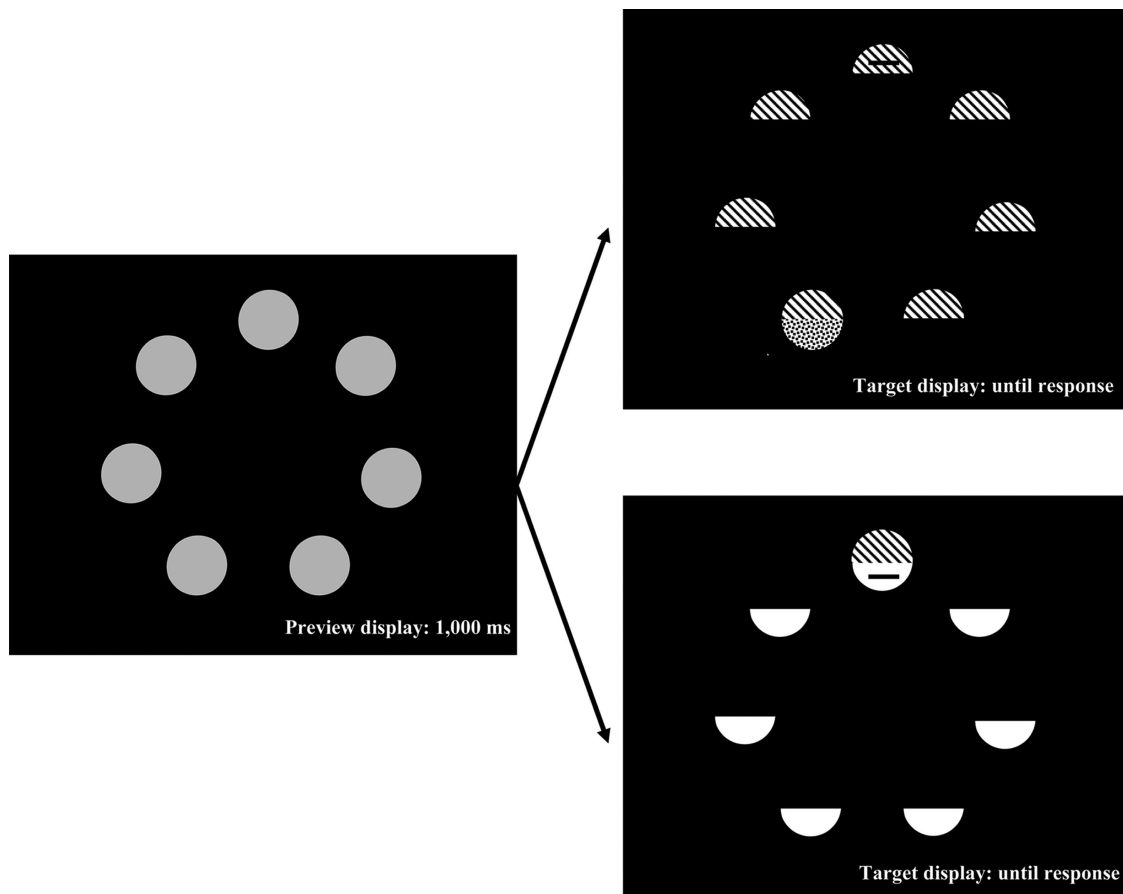
The experiment was controlled by a computer that also registered responses. Stimuli were presented on a 15-inch colour monitor. A serial mouse was used for the responses. Participants pressed left and right mouse buttons with the index fingers

of the corresponding hands. Latencies were measured from the beginning of the target to the nearest millisecond. The participants were seated in a dimly lit room, 65 cm in front of the screen, with their line of gaze straight ahead, head supported by a chin rest.

### *Stimuli and procedure*

See also Figure 1. Each trial started with the presentation of seven grey discs (each with a radius of  $0.5^\circ$ ), one at each of seven equidistant positions ( $3.2^\circ$  of visual angle between positions) on an imaginary circle (centred on the screen with a radius of  $3.9^\circ$ ). The grey discs remained on the screen for 1,000 ms. Next, the top halves or the bottom halves of all seven discs changed colour (e.g., turned red) with the effect that the top halves or the bottom halves of all discs had the same colour; these were the nonsingletons. At the same time, the complementary semidisc of only one of the seven grey discs (e.g., one bottom half of a disc in the case that seven top halves of discs were shown) changed into a different colour; this was the nontarget colour singleton. This stimulus was also a shape singleton by virtue of its being the only full disc among several semidiscs. All other complementary semidiscs were turned off.

In each trial, the target was presented inside one of the colour-homogeneous nonsingleton semidiscs. The target was a straight line that was either horizontally or vertically oriented. Participants had to give a fast and accurate choice response to the orientation of the target. Half of the participants had to give a right-hand response to a vertical line and a left-hand response to a horizontal line. This stimulus–response (S–R) mapping was reversed for the other half of the participants. For one half of the participants (Group 1), the seven nonsingletons were all red in 50% of the trials and all white in the other 50% of the trials. For the other half of the participants (Group 2), the seven nonsingletons were all green in 50% of the trials and all white in the other 50% of the trials. As a consequence, Group 1 was expected to willingly attend to red and



**Figure 1.** Depicted are different possible conditions of Experiment 1. Left: The preview displays consisted of 7 grey discs. Right: The target displays consisted of 7 nonsingleton semidisks of the same colour (symbolized by hatched semidisks in the upper and white semidisks in the lower panel) and one singleton semidisk of a different colour (symbolized by a dotted semidisk in the upper and a hatched semidisk in the lower panel). Right/top: Depicted is an example of a less matching colour singleton display with top-half nonsingleton semidisks. The target is the one stimulus with a black horizontal line (at the top of the display). The colour singleton is presented at a position three positions away from the target (condition p3). Right/bottom: Depicted is an example of a better matching colour singleton display with bottom-half nonsingleton semidisks. The colour singleton is presented with a minimal distance to the position of the target (condition p0). For further information refer to the Method section of Experiment 1.

white stimuli, whereas Group 2 should have willingly attended to green and white stimuli.

The nontarget singleton was equally likely to match better or to match less well to the set of searched-for target colours. In Group 1, the better matching colour singleton was red, and the less matching colour singleton was green. For example, if seven white bottom-half nonsingleton semidisks were presented in the display, a red top-half semidisk was considered to be a better

matching nontarget colour singleton, because a red semidisk contained the target in 50% of all other trials. By contrast, if seven red top-half nonsingleton semidisks were presented in the display, a green bottom-half semidisk was considered to be a less matching nontarget colour singleton, because a green semidisk was never used as a target in any of the other trials. Likewise, in Group 2, the better matching colour singleton was green, and the less matching

colour singleton was red. Thus, the use of green versus red colours for the better matching and the less matching colour singleton, respectively, was balanced across participants.

The colour singleton was equally likely to be presented at any one of the seven possible disc locations. Thus, the singleton completed one of the seven nonsingleton semidisks to a full disc. In condition p0, the singleton completed the target semidisk to a full disc. For instance, a less matching green bottom-half semidisk at position p0 completed a red top-half target semidisk above it to appear as a full disc. In condition p1, the singleton completed one of the nonsingleton semidisks next to the target. In condition p2, the singleton completed one of the nonsingletons that were at one of the one-but-next positions from the target. In condition p3, the singleton completed one of the nonsingletons that were presented with a distance of three positions away from the target.

Participants were instructed to ignore the irrelevant nontarget colour singleton. To that end, before the data acquisition started, participants were fully informed, both by instruction and by practice, about the different possible colours of the targets, of the nonsingletons, and of the singletons. Also, participants knew that the target was always presented in one of the seven nonsingleton semidisks—that is, that it was never a colour singleton. Finally, participants were informed that the colour singleton did not predict the likely position of the target.

The intertrial interval was 2,100 ms. After an incorrect response, an error message was presented for 700 ms. If the RT exceeded 1,250 ms, a feedback was presented for 700 ms, which instructed participants to respond faster.

The two possible S–R mappings and the two possible singleton–colour mappings (Group 1 vs. Group 2; see above) were balanced across participants. Also, nonsingleton and singleton were equally likely top-halves or bottom-halves. Each of the combinations that resulted from a complete crossing of 2 (target shape: vertical, horizontal)  $\times$  7 (target position)  $\times$  7 (singleton position)  $\times$  2 (nonsingleton colour: red or white; green or white; between participants)  $\times$  2 (singleton

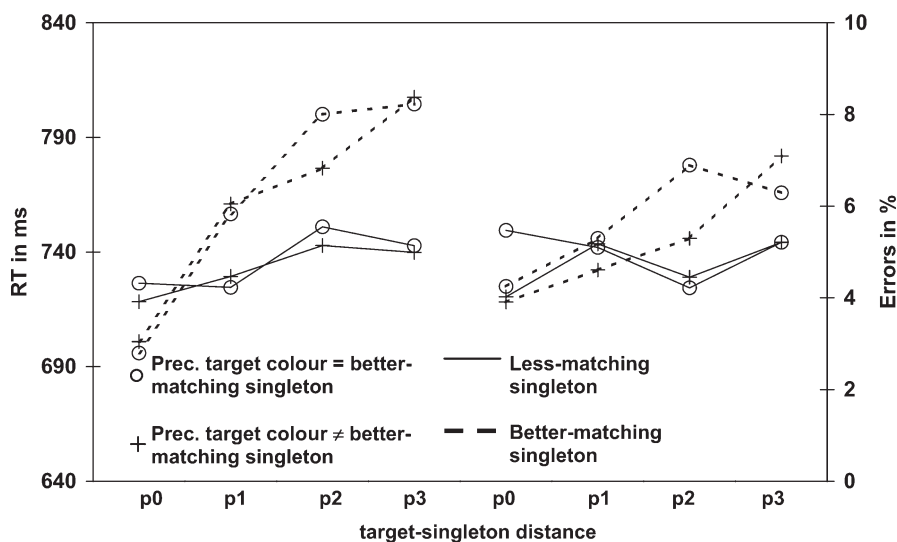
colour: green, red) was repeated twice during each of two sessions. Prior to the first session, participants practised the task. Each session had a duration of about one hour.

## Results

Figures 2 to 4, and Table 1 show the main results. Initial analyses concerned the influence of the variable preceding target colour on mean correct RTs and error rates. In the analysis of the mean correct RTs, 0.4% of all trials were excluded because responses were faster than 100 ms or slower than 2,000 ms. Beyond that, the first trial of each session was also excluded from the analyses of both mean correct RTs and error rates, because the initial trial of a session had no preceding trial.

Individual median latencies of the correct responses were subjected to an analysis of variance (ANOVA), with singleton type (better matching or less matching), target–singleton distance (p0, p1, p2, or p3), and preceding target colour (same as that of the better matching singleton or different from that of the better matching singleton) as within-participant variables. There were significant main effects of singleton type,  $F(1, 23) = 15.16$ ,  $p < .01$ , and distance,  $F(3, 69) = 13.95$ ,  $p < .01$ ,  $\epsilon = .49$  (Greenhouse–Geisser corrections were made in the case of a significant sphericity test,  $p < .05$ ), and a significant interaction of Singleton  $\times$  Distance,  $F(3, 69) = 13.52$ ,  $p < .01$ . The main effect of preceding target colour and all interactions with that variable were nonsignificant, with all  $F$ s  $< 1.00$ . Mean RT was lower with a less matching (734 ms) than with a better matching (763 ms) singleton. With the exception of the largest target–singleton distance (condition p3), RT increased with an increasing target–singleton distance: This was confirmed by pairwise  $t$  tests between adjacent distance conditions, p0 and p1, and p1 and p2, both  $t(23) > 3.10$ , both  $p$ s  $< .05$  (Bonferroni adjusted). A comparison between p2 and p3 was nonsignificant,  $t(23) < 1.00$ . Following up on the two-way interaction of Singleton Type  $\times$  Distance,  $t$  tests revealed that a distance effect was restricted to the better matching singleton conditions, p0 vs. p1 and p1 vs. p2, both





**Figure 2.** Mean reaction time (RT; on the left) and mean percentage of error (on the right) as a function of singleton condition (better matching vs. less matching singleton condition), preceding target colour (same as that of the better matching singleton vs. different from that of the better matching singleton), and target–singleton distance (p0 to p3 from small to large) of Experiment 1. Prec.: preceding.

$t_s(23) > 2.90$ , both  $p$ s  $< .05$  (Bonferroni adjusted). Again, a comparison between p2 and p3 was non-significant,  $t(23) = 1.52$ ,  $p = .14$ . In the less matching singleton conditions, the effect of distance fell short of significance in the pairwise comparisons of adjacent distance conditions, if corrected for multiple comparisons, all  $t_s(23) < 2.30$ .

A corresponding ANOVA of the arcsine transformed error rates revealed a significant main effect of distance,  $F(3, 69) = 4.90$ ,  $p < .05$ . The effect numerically corresponded to that in the RTs, but at least the more conservative post hoc (i.e., Bonferroni corrected)  $t$  tests between adjacent distance conditions failed to confirm a spatial gradient, all  $t_s(23) < 2.00$ . Again, the interaction of Singleton Type  $\times$  Distance became significant,  $F(3, 69) = 3.67$ ,  $p < .05$ ,  $\epsilon = .69$ . Pairwise  $t$  tests between cell means of adjacent distance conditions, which were conducted separately for better matching and less matching singleton conditions, were not significant, all  $t_s(23) < 2.00$ . Numerically, however, the interaction was in the same direction as that in the RTs: There was more evidence for a distance

effect in the better matching singleton conditions than in the less matching singleton conditions. Thus, a speed–accuracy trade-off does not explain the RT results. Moreover, main effects of singleton type,  $F < 1$ , preceding target colour,  $F = 1.47$ ,  $p = .24$ , and all other interactions involving one of the variables, all  $F$ s  $< 1.00$ , were not significant.

Next, we tested the ordering of the onsets of the capture effects in the RT distribution, with data collapsed across levels of the nonsignificant variable preceding target colour, which did not interact with any of the other variables. These tests were conducted separately for uncorrected RTs, including error RTs and misses (by the default value of 3,000 ms—the maximal possible RT), and corrected RTs (without error RTs and misses) to rule out that the inclusion of error RTs and misses alters the ordering of the onsets of the capture effects. Single-trial responses of (a) all trials (uncorrected RTs) and of (b) all correct trials were rank-ordered from fast to slow responses, separately for each of the eight conditions resulting from the combinations of the

Table 1. Rank ranges and mean reaction times of onsets of capture effects in Experiments 1–3

| Experiment | Dist.         | Better matching |                       | Less matching |                       | Z    | <i>p</i> |
|------------|---------------|-----------------|-----------------------|---------------|-----------------------|------|----------|
|            |               | Rank range      | Onset RT <sup>a</sup> | Rank range    | Onset RT <sup>a</sup> |      |          |
| 1          | p0–p1/corr.   | 14–54           | 601                   | —             | —                     | —    | —        |
|            | p0–p1/uncorr. | 15–55           | 606                   | —             | —                     | —    | —        |
|            | p0–p2/corr.   | 14–55           | 601                   | 41–51         | 846                   | 4.02 | < .01    |
|            | p0–p2/uncorr. | 14–55           | 600                   | 41–51         | 844                   | 4.29 | < .01    |
|            | p0–p3/corr.   | 8–55            | 550                   | 38–55         | 815                   | 4.11 | < .01    |
|            | p0–p3/uncorr. | 8–55            | 555                   | 37–55         | 805                   | 4.29 | < .01    |
| 2          | p0–p1/corr.   | 9–54            | 555                   | 19–32         | 605                   | 2.32 | .02      |
|            | p0–p1/uncorr. | 7–53            | 535                   | 18–32         | 591                   | 4.23 | < .01    |
|            | p0–p2/corr.   | 10–55           | 560                   | 15–48         | 576                   | 1.37 | .17      |
|            | p0–p2/uncorr. | 5–55            | 514                   | 12–48         | 557                   | 4.03 | < .01    |
|            | p0–p3/corr.   | 15–55           | 586                   | 18–46         | 592                   | 0.40 | .69      |
|            | p0–p3/uncorr. | 15–56           | 586                   | 18–47         | 595                   | 1.49 | .14      |
| 3          | p0–p1/corr.   | —               | —                     | —             | —                     | —    | —        |
|            | p0–p1/uncorr. | —               | —                     | —             | —                     | —    | —        |
|            | p0–p2/corr.   | 52–99           | 727                   | —             | —                     | —    | —        |
|            | p0–p2/uncorr. | 49–99           | 714                   | —             | —                     | —    | —        |
|            | p0–p3/corr.   | 59–99           | 756                   | —             | —                     | —    | —        |
|            | p0–p3/uncorr. | 54–99           | 733                   | —             | —                     | —    | —        |

Note: Better matching and less matching indicate whether the nontarget singleton better matched or less matched the set of searched-for target colours. Rank ranges are of significant spatial gradient differences, indicative of capture effects, indicative of capture effects. RT = reaction time. Dist. = target–nontarget distance conditions used to determine the capture effect (or the spatial gradient). Corr./uncorr. = whether estimates were based on correct RTs (corr.) or on all RTs (uncorr.). Z and *p* values are shown for the difference between corresponding onset times in better matching and less matching conditions. A dash indicates that no corresponding value is available. For further details refer to the Methods section.

<sup>a</sup>In ms.

Z values > 2.50; alpha levels, *p* < .0125.

variables singleton type and distance. For each rank of this RT distribution, individual single-trial raw RTs were averaged across participants, leading to 8 (singleton type/singleton-target distance conditions) × 56 (trials) mean uncorrected RTs and the same number of correct RTs.<sup>2</sup>

Beginning with the lowest rank (fastest RTs), pairwise comparisons by nonparametric

Wilcoxon tests were conducted for each rank in turn between RTs in (a) p0 and p1, (b) p0 and p2, and (c) p0 and p3, separately for better matching and less matching conditions. Onset times of capture effects were defined as RT in condition p0 of the lowest rank of at least three immediately succeeding ranks with a significant spatial gradient RT difference, separately for the different

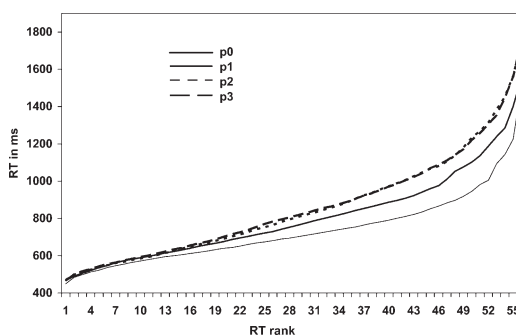
<sup>2</sup> By averaging single-trial performance across participants and by focusing of the additional analyses on (shifts of) onsets of capture effects, information about (a) individual distributions and (b) distribution characteristics besides onsets, such as skewness or maxima, was lost. We think, however, that these shortcomings of our additional analyses were justified for at least three reasons. First, some of the lost information was contained in the more traditional mean analysis of our results presented above. For example, different maxima of the capture effects in set-matching relative to less set-matching conditions were reflected in a main effect of singleton type. Second, no advance predictions can be derived from the preemptive control hypothesis for parameters of the RT distributions besides onsets and maxima. This is true, for instance, for skewness. Finally, averaging across single trials provided a better temporal resolution for the analysis of the onsets of the capture effects than averaging across a range of individual trials, which is what is essentially done in vincentizing (cf. Ansorge et al., 2005).

comparisons (a) to (c). The onset times of capture effects in the better matching conditions were then compared to those of the less matching conditions also by Wilcoxon tests. (Alpha levels were Bonferroni adjusted to the repeated use of the data from the p0 conditions.)

It turned out that the onsets of attentional capture (or the onsets of the spatial gradient; i.e., reliably higher RTs with increasing target–singleton distance) in the better matching condition preceded that in the less matching condition (see Table 1 and Figures 3 and 4). (Here and in the following experiments, loss of data from corrected to uncorrected RTs was very moderate: Single-trial RT comparisons of uncorrected data were always based on 24 participants, and single-trial RT comparisons of corrected data were based on a minimum of 20 participants or more.)

## Discussion

Experiment 1 rendered a number of noteworthy results that were in line with the preemptive-control hypothesis (i.e., an account of the capture difference by an influence of top-down control settings for colour that are specified in advance of the displays). First, we observed a capture difference: Capture effects of the better matching nontarget colour singleton were stronger than capture effects of the less matching nontarget colour singleton (cf. Folk et al., 1992).<sup>3</sup> A nontarget colour singleton that was presented further away from the target interfered to a larger degree

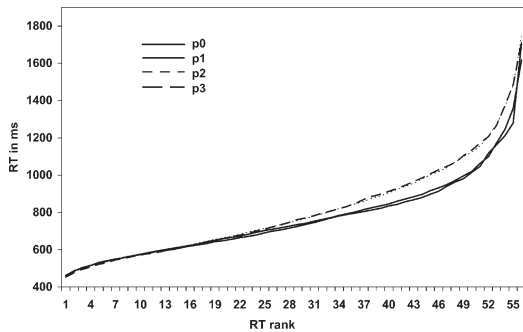


**Figure 3.** Single-trial mean reaction time (RT) of better matching nontarget singleton conditions as a function of target–singleton distance (p0 to p3 from small to large), and of rank in the RT distribution of Experiment 1.

than a more target-adjacent colour singleton—that is, the capture effect of the singleton had a spatial gradient. We consider this spatial gradient to be an unambiguous hallmark of visuospatial capture. Thus, we regard it as unlikely that a nonspatial process of filtering out the singleton’s colour from the image provided a better explanation of the effect of the colour singleton (cf. Folk & Remington, 1998). Nonspatial filtering costs in colour-heterogeneous displays should be the same for conditions with a nontarget colour singleton presented near the target and for conditions with a nontarget colour singleton presented at a distance from the target (cf. Turatto & Galfano, 2001).

Second, the onset of the capture effect in the better matching condition preceded that in the

<sup>3</sup> In Experiment 1’s matching condition, targets were white, whereas in the less set-matching condition, targets were coloured. To rule out that perceptual factors were responsible for different capture effects in matching and less matching conditions, we ran a brief control with 8 participants searching for coloured (red and green targets) in both matching and less set-matching conditions. Main results were essentially the same as before: There was a significant main effect of singleton type,  $F(1, 7) = 5.72, p < .05$ , and a significant interaction of Singleton Type  $\times$  Distance,  $F(3, 21) = 6.01, p < .01$ . In set-matching and less set-matching singleton conditions, RT started from about the same level in condition p0 (set-matching: RT = 699 ms; less set-matching: RT = 725 ms), and a stronger capture effect of the set-matching singleton was apparent from its significantly stronger interference than that for the less set matching singleton for all distances beyond p0 (RT in set-matching conditions was 719 ms, 754 ms, and 761 ms from p1 to p3, respectively, and RT in less set-matching conditions, was 668 ms, 686 ms, and 676 ms from p1 to p3, respectively), all three  $t(7) > 2.42$ , all  $p$ s  $< .05$ . Also, in a follow-up analysis, including the factor preceding target colour, neither a significant main effect of preceding target colour, nor a Singleton Type  $\times$  Distance  $\times$  Preceding target colour interaction was observed, both  $F$ s  $< 1.00$ . Finally, a corresponding ANOVA of the arc-sine transformed error rates yielded neither a significant main effect, nor a significant interaction, all  $F$ s  $< 1.20$ , all  $p$ s  $> .34$ . Thus, a speed–accuracy trade-off does not explain the RT results. Hence, results of Experiment 1 cannot be attributed to differences between conditions with white and coloured targets, a conclusion that is also corroborated by the present Experiment 3.



**Figure 4.** Single-trial mean reaction time (RT) of less matching nontarget singleton conditions as a function of target-singleton distance ( $p_0$  to  $p_3$  from small to large), and of rank in the RT distribution of Experiment 1.

less matching condition. This difference between capture onset times in the RT distributions is well in line with the assumption that participants preemptively specified their control settings for attentional capture by the target colours in advance of the displays, so that a better matching colour singleton can have a stronger capture effect than a less matching colour singleton right from the very start of the capture effect among the faster responses of the RT distribution. By contrast, the onset data pattern was certainly less well in line with the implication of the deallocation account that capture effects in better matching and less matching nontarget singleton conditions could have had concomitant onsets among the fast responses.

However, even in the better matching condition, no capture effect was evident among the fastest responses. As detailed in the Introduction, the corresponding trials with a zero capture effect in the better matching conditions probably reflected the ability of the participants to completely ignore the better matching nontarget singleton. In these trials, participants were presumably successfully attending either to the target shapes or to the nonsingleton status of the targets. Both of these strategies should have prevented attentional capture by the better matching nontarget singleton on a fraction of all trials, because the nontarget singleton differed from the target by both its shape and its being a colour singleton.

Note also that the ordering of the onsets of the capture effects that we found, although being in agreement with the assumptions of the preemptive-control hypothesis, is not necessarily at variance with a refined deallocation explanation. First, it is always possible that deallocation contributes to the capture difference at a later point in time, among the slower responses of the RT distribution. Second, arguably, very fast deallocation processes (operating on a non-significant capture effect of the less matching nontarget singleton among the fastest responses) might have shifted the onset of a significant capture effect of the less matching nontarget singleton to the slower responses in the RT distribution. This assumption, although hard to test and created post hoc, is not implausible given that deallocation is probably a stochastic process with its onset time being distributed across a range of time points, such that a fraction of the deallocation processes might have had a rapid onset too. Most importantly, however, the existence of such fast operating deallocation processes might be fully in line with the preemptive-control hypothesis if we assume that very fast deallocation is conditional on the participant's advance preparation of an attentional setting to selectively ignore (or to otherwise suppress the processing of) irrelevant features or stimuli (instead of being purely reactive). In summary, what can be safely concluded from the observed ordering of onsets of capture effects in Experiment 1 is that the data pattern is in line with the preemptive-control hypothesis and that at least no straightforward evidence for more reactive modes of deallocation was found.

A third finding of interest was that the capture difference was approximately equally strong, regardless of whether the target in the preceding trial had or had not the same colour as the better matching colour singleton. Again, the results were in line with the assumptions of the preemptive-control hypothesis, according to which control settings for attentional capture can be specified in accordance with the instructions in advance of the displays and are not changed on a trial-by-trial basis as a mere stimulus-driven

consequence of the most recently encountered target colour.

Two further issues need to be addressed. First, we observed a capture effect of the less matching colour singleton, which cannot be explained by a match between the colour of this singleton and the top-down controlled search settings for the target colours. It is possible that the capture effect of the less matching singleton was due to stimulus-driven capture by this singleton. It has been claimed, for example, that the amount of attention directed to a position in visual space is a function of the strength of the feature signal at that position relative to other positions (cf. Bergen & Julesz, 1983; Wolfe, 1994). In line with this assumption, some authors have argued for the possibility of stimulus-driven singleton capture (cf. Theeuwes, 1994; Turatto & Galfano, 2001).

However, as we understand it now such a far-reaching conclusion cannot be made on the basis of the results of our investigation. The less matching singleton might have captured attention, for example, by virtue of its shape singleton status (i.e., being the single differently oriented semicircle in the display or creating the single full disc among the semidisks) matching a top-down controlled set to search for another shape singleton (i.e., the line of the target; cf. Bacon & Egeth, 1994). Likewise, it could be argued that the horizontal line, being produced by the colour difference between the colour singleton semidisk and the adjacent nonsingleton semidisk, matched the setting for the to-be-searched-for target shapes (i.e., a setting for horizontal lines). Finally, participants might also have problems to keep up relatively narrow or precise control settings for particular colours in advance of the displays in situations where they have to attend to different target colours (e.g., red or white as in the current experiment; cf. Theeuwes & Burger, 1998). As an inevitable consequence, even an unspecified colour singleton might capture attention at least to some extent or in some of the trials by virtue of a match to a preemptively controlled, relatively imprecise attentional setting.

In summary, it is possible that the capture effect of the less matching singleton reflects a mode of

stimulus-driven processing or that it is due to some other kind of top-down matching process beyond the one that is responsible for capture of visuospatial attention by a particular colour. In any case, however, the capture by the less matching singleton could never have been as strong as that of the better matching singleton: Only the latter also had a colour that matched the setting for the to-be-searched-for target colours in addition to all of the conceivably capturing or matching features that were shared by the better matching and the less matching singleton.

A second issue that needs to be addressed is a difference between the results of Experiment 1 and previous observations by Turatto and Galfano (2001). The spatial gradient of the singleton-capture effect was not the same in all of the conditions of the two studies. In our Experiment 1, interference increased as a function of target-singleton distance, whereas in Experiment 1 of Turatto and Galfano (2001), beyond p1, interference decreased as a function of target-singleton distance. We do not have an explanation for the difference, but, of course, slight differences between the tasks, such as the harder discrimination between letters T and L in the investigation of Turatto and Galfano than in the easier task used here might be responsible for the differences. Moreover, it seems that the present finding is the more typical one (cf. Downing, 1988; Egly & Homa, 1991; Hughes & Zimba, 1985, 1987; Scharlau, 2004; Turatto, Galfano, Gardini, & Mascetti, 2004). Usually, interference uniformly increasing across target-singleton distances is ascribed to analogue movements of visual attention through space (cf. Egly & Homa, 1991). Furthermore, a serial search through the possible target positions would also produce the observed pattern of results.

## EXPERIMENT 2

In Experiment 2, we tested the predictions of the preemptive-control hypothesis with a positive stimulus onset asynchrony (SOA) between the nontarget singleton and the target. Much of



the previous evidence for the top-down contingencies of attentional capture has been obtained with procedures that used a small but positive interval between the nontarget singleton (or distractor) and the target (e.g., Ansorge & Heumann, 2003, 2004; Folk et al., 1992; Remington et al., 2001).

Yet, with a positive SOA, it becomes more likely that reactive processes of deallocation can contribute to the capture difference (i.e., stronger capture effects under better matching than under less matching conditions) for the following reasons. To start with, the capture effect of a less matching nontarget singleton tends to increase at least up to SOAs of about 150 ms (cf. Kim & Cave, 1999; Theeuwes et al., 2000). Likewise, we observed (though not formally tested for) relatively more capture by the less matching colour singleton among the slower responses (see Figure 4). More importantly, with an increasing SOA, relative contributions by reactive processes of deallocation become more likely, too, because deallocation necessarily has to trail behind the capture effect (cf. Posner & Cohen, 1984).

To rule out a strictly stimulus-driven explanation of the previous results, it is desirable to show that predictions of the preemptive-control hypothesis as outlined in the Introduction also hold under comparable positive-SOA conditions. This was tested in the present experiment, with an SOA of 68 ms as was used by Ansorge and Heumann (2004).

## Method

### *Participants*

A total of 24 volunteers (14 female, 10 male) with a mean age of 24 years participated in Experiment 2.

### *Apparatus, stimuli, and procedure*

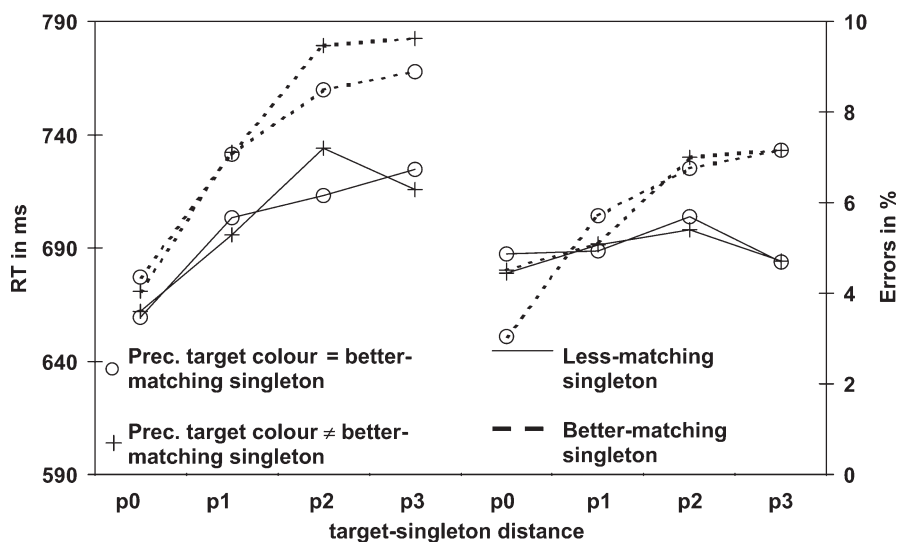
These were the same as those in Experiment 1, with the sole exception that a positive SOA of 68 ms was introduced between a first colour change in the display by which the nontarget colour singleton appeared on the screen and a second colour change in the display that revealed the seven coloured nonsingletons on the screen.

## Results

Figure 5 and Table 1 show the main results. For the analysis of the mean correct RTs as a function of preceding target colour, 0.5% of all trials were excluded because responses were faster than 100 ms or slower than 2,000 ms. In the corresponding RT ANOVA, there were significant main effects of singleton type,  $F(1, 23) = 27.73$ ,  $p < .01$ , and distance,  $F(3, 69) = 20.64$ ,  $p < .01$ ,  $\epsilon = .43$ , and a significant interaction of Singleton Type  $\times$  Distance,  $F(3, 69) = 3.88$ ,  $p < .05$ . RT was lower with a less matching singleton in the display (701 ms) than with a better matching singleton (738 ms). With the exception of the largest distance (condition p3), RT increased with an increasing distance: This was confirmed by pairwise  $t$  tests between adjacent distance conditions, p0 versus p1, and p1 versus p2, both  $t(23) > 3.40$ , both  $p$ s  $< .01$  (Bonferroni adjusted). A comparison between p2 and p3 was nonsignificant,  $t < 1$ . Following up on the two-way interaction of Singleton Type  $\times$  Distance,  $t$  tests revealed that a spatial gradient of the distance effect applied for both conditions with a better matching colour singleton and conditions with a less matching colour singleton up to distance p2: RT increased significantly from condition p0 to p1, and from condition p1 to p2, all  $t(23) > 2.50$ , all  $p$ s  $< .05$ . Comparisons between p2 and p3 were nonsignificant, both  $t(23) < 1.00$ . Also, interference was significantly stronger in the case of the better matching singleton in each of the distance conditions p1, p2, and p3, all  $t(23) > 4.10$ , all  $p$ s  $< .01$  (Bonferroni adjusted), but not in condition p0,  $t(23) = 1.16$ ,  $p = .26$  (uncorrected). The main effect of preceding colour,  $F < 1.00$ , and the interactions with that variable, all  $F$ s  $< 1.03$ , all  $p$ s  $> .38$ , were not significant.

In a corresponding ANOVA of the arcsine transformed error rates, a significant main effect of distance,  $F(3, 69) = 8.25$ ,  $p < .01$ , and a significant interaction of Singleton Type  $\times$  Distance  $F(3, 69) = 2.80$ ,  $p < .01$ , were observed. Main effects of preceding target colour,  $F < 1$ , singleton type,  $F(1, 23) = 2.66$ ,  $p = .12$ , and the remaining interactions, all  $F$ s  $< 1.50$ , all  $p$ s  $> .24$ ,





**Figure 5.** Mean reaction time (RT; on the left) and mean percentage of error (on the right) as a function of singleton condition (better matching vs. less matching singleton condition), preceding target colour (same as that of the better matching singleton vs. different from that of the better matching singleton), and target–singleton distance (p0 to p3 from small to large) of Experiment 2. *Prec.:* preceding.

were not significant. The main effect of distance corresponded to that in the RTs; *t* tests confirmed significant error rate increments from p0 to p1, and from p1 to p2, both  $t(23) = 2.50$ ,  $p < .05$ , but not from p2 to p3,  $t(23) = 1.04$ ,  $p > .31$ . Following up on the two-way interaction, however, we compared adjacent distance conditions separately for better matching and less matching colour singleton conditions and found only one significant error rate increment with a better matching colour singleton in the display, from p0 to p1,  $t(23) = 3.54$ ,  $p < .01$ . There was no significant difference between adjacent distances in the less matching singleton conditions, all other  $t(23) < 2.00$ , all other  $p$ s  $> .05$  (uncorrected).

As in Experiment 1, onsets of attentional capture in the better matching condition preceded those in the less matching condition (see Table 1). However, the corresponding onset differences were not significant in all of the comparisons.

## Discussion

Experiment 2 supported some of the main conclusions of Experiment 1. Results were again in

line with several predictions of the preemptive-control hypothesis: (a) There was a capture difference; the capture effect was stronger in the better matching than in the less matching conditions; (b) the strength of the capture difference was not affected by whether the target in the preceding trial had or had not the same colour as the better matching colour singleton; and finally, (c) numerically the onset of the capture effect in the better matching nontarget singleton conditions always preceded that in the less matching singleton condition in all of the comparisons.

However, in contrast to Experiment 1, some of these onset differences failed to reach significance. Therefore, it is possible that the contributions of reactive deallocation processes to the capture difference are stronger with a positive singleton–target interval (i.e., with a nontarget colour singleton preceding the target) than with a 0-ms singleton–target interval. In fact, if it is true that (a) both preemptive control of attention and deallocation contribute to the net capture difference, and (b) onsets of capture effects of nontarget singletons are not instantaneous but somewhat delayed (cf. Experiment 1; Kim & Cave, 1999;

Theeuwes et al., 2000), then the likelihood that deallocation, following capture, contributes to the capture difference should increase as a function of time since nontarget singleton onset (cf. Ansorge & Heumann, 2004, Exp. 3; but see Remington et al., 2001).

In other words, weaker differences between the onsets of capture effects in Experiment 2 relative to Experiment 1 are presumably due to the head start of the processing of the nontarget singletons relative to that of the targets in the current but not in the preceding experiment. As a consequence, target RTs were given in a time range since nontarget colour singleton onset at which even the temporally trailing capture effect of the less matching nontarget singleton had commenced, making it less likely that any part of the target RT distribution can be found at which no capture effect had yet occurred. (Note that even in Experiment 2, the capture effect in the better matching conditions appeared to be stronger than that in the less matching conditions among the faster responses, meaning that our test of the ordering of onsets was also relatively conservative with respect to the preemptive-control hypothesis.) In conclusion, the data are in line with the assumption that control settings for the target colours can be set offline, as assumed in the preemptive-control hypothesis, but it is not unlikely that deallocation can contribute to the capture differences under positive SOA conditions too.

### EXPERIMENT 3

In the preceding Experiments 1 and 2, preemptive control of attentional capture by colour was seemingly not as effective as it was in some of the former investigations: A substantial capture effect of the less matching colour singleton was observed in the present Experiments 1 and 2, whereas in several previous experiments, less matching nontarget colour singletons did not capture attention at all (cf. Ansorge & Heumann, 2003; Folk et al., 1992; Folk & Remington, 1998). Several putative top-down control settings for other aspects of the task that might have fostered the capture effect

of the less matching singletons were discussed in Experiment 1. In particular, previous studies demonstrated more unequivocal evidence for efficient top-down control with a very small set size of only one to-be-searched-for target colour (cf. Folk & Remington, 1998; Folk et al., 1992; Theeuwes & Burger, 1998). To optimize conditions for efficient top-down control in Experiment 3, we reduced the number of to-be-searched-for target colours to one. For example, with only one target colour, participants can use a narrowly defined set of searched-for target colours and need not discriminate between the different target colours. Hence, if it is true that the need to discriminate target colours between trials allows for an occasional match of the nontarget colour singleton to a relatively broad top-down controlled attentional setting for different colours (see Discussion of Experiment 1), we might be able to further reduce the effect of the less matching colour singleton in the present experiment.

Also, in Experiment 3, we used the same stimulus colour differences between singleton and nonsingletons in the less matching and in the better matching conditions. By contrast, in the previous Experiments 1 and 2, better matching red or green nontarget singletons were presented concomitantly with white nonsingleton stimuli, whereas less matching green or red nontarget singletons were presented concomitantly with red or green nonsingleton stimuli, respectively. Although it is not obvious why or how these singleton–nonsingleton colour differences between better matching and less matching conditions in the preceding experiments should have produced the capture differences or any of the other results that we observed, in Experiment 3, we wanted to replicate the capture difference, with colour-discrimination requirements being the same in better matching and less matching conditions.

### Method

#### *Participants*

A total of 24 volunteers (16 female, 8 male) with a mean age of 26 years participated in Experiment 3.

*Apparatus, stimuli, and procedure*

These were the same as those in Experiment 1, with the following exceptions. First, whether the nontarget singleton matched well or less well to the control settings was realized as a between-participants variable in the present experiment. Half of the participants had fixed nonsingleton target and singleton nontarget colours throughout. These participants always searched either for a red or for a green nonsingleton target (between participants), presented together with a green nontarget colour singleton if the target was always red, or with a red nontarget colour singleton if the target was always green. These were the less matching conditions, because in each trial the non-singleton target always had the same fix predictable colour, which was different from the also foreseeable fix colour of the nontarget colour singleton.

Second, the performance of the other half of the participants was tested in a control condition with the very same target-singleton displays, but with the colour singleton matching the setting of to-be-searched-for target colours. As in the experimental condition, displays with a red nonsingleton target contained a green nontarget colour singleton, and displays with a green nonsingleton target contained a red nontarget colour singleton. However, in the control condition, participants searched for both red and green nonsingleton targets, and the colour of the upcoming target was not known in advance, so that both red and green nontarget colour singletons matched well the set of to-be-searched-for target colours.

Because the set-matching of the singletons was realized as a between-participants variable, and the experiment had the same length as the preceding experiments, there were altogether 112 trials available in each of the different target-singleton distance conditions of both the less matching and the better matching conditions.

## Results

For the analysis of correct mean RTs, 0.2% of all trials were excluded because responses were faster than 100 ms or slower than 2,000 ms. RT and

error rate analyses in the control condition (with a varying target colour), with target-singleton distance (p0, p1, p2, p3) and preceding target colour (same as or different from that of the current trial's better matching singleton) as within-participant variables, yielded neither a significant main effect of preceding target colour, both  $F_s(1, 11) < 1.75$ , both  $p_s > .21$ , nor a significant interaction with the variable preceding target colour, both  $F_s(3, 33) < 1.06$ , both  $p_s > .38$ . Therefore it was justified to collapse data across levels of the variable preceding target colour for ANOVAs of correct means of individual median RTs and mean error rates, with singleton type (better matching vs. less matching) as a between-participants variable and target-singleton distance (p0, p1, p2, or p3) as a within-participant variable. There was a significant main effect of distance,  $F(3, 66) = 4.79$ ,  $p < .05$ ,  $\epsilon = .75$ , and a significant interaction of Singleton Type  $\times$  Distance,  $F(3, 66) = 6.97$ ,  $p < .01$ ,  $\epsilon = .75$ . The main effect of singleton type fell short of significance,  $F(1, 22) = 3.38$ ,  $p = .079$ . The distance effect was due to the fact that RT increased significantly with an increasing target-singleton distance between adjacent distance conditions only from p1 to p2,  $t(23) = 2.58$ ,  $p < .05$  (Bonferroni adjusted). The other comparisons between adjacent distance conditions were non-significant, both  $t_s(23) < 2.28$ , both  $p_s > .05$  (Bonferroni adjusted). Following up on the two-way interaction of Singleton Type  $\times$  Distance,  $t$  tests revealed that only with a better matching colour singleton did RT increase significantly from condition p1 to p2,  $t(11) > 2.45$ ,  $p < .05$ . In the better matching conditions, the other comparisons between adjacent distance conditions fell short of significance, both  $t_s(11) < 2.45$ , both  $p_s > .05$ . In the less matching colour singleton conditions, RT significantly decreased from p2 to p3,  $t(11) = 3.24$ ,  $p < .01$ , whereas no significant difference between any of the other adjacent distance conditions was observed, both  $t_s(11) < 1.01$ , both  $p_s > .33$ .

In an ANOVA of the arcsine transformed error rates, we observed a significant interaction of Singleton Type  $\times$  Distance,  $F(3, 66) = 3.66$ ,

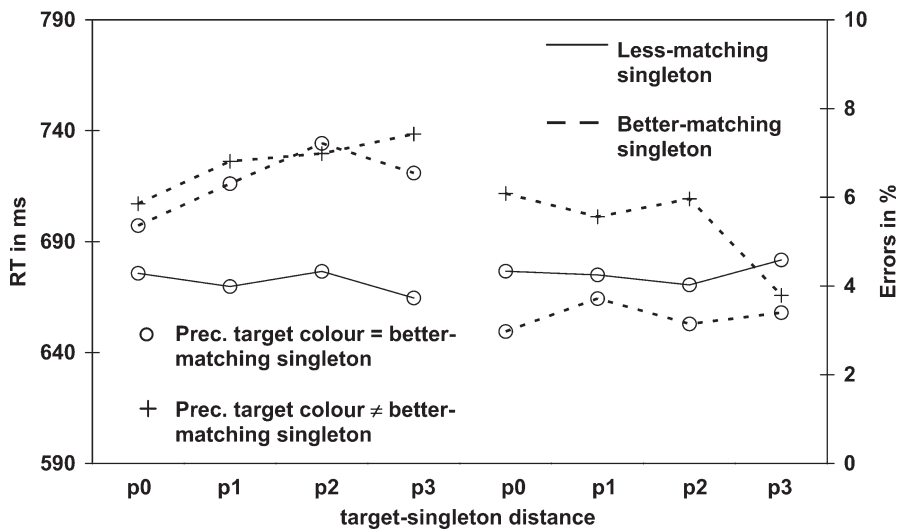
$p < .05$ . Main effects of singleton and distance, both  $F_s < 1.00$ , were nonsignificant. As can be seen from Figure 6, from the smallest to the largest target-singleton distance, error rate tended to follow a u-shaped function in the less matching colour singleton conditions but it tended to follow an inverted u-shaped function in the better matching colour singleton conditions. However, post hoc tests failed to confirm any of the differences: There was neither a significant difference between adjacent distance conditions in any of the singleton conditions, all  $t_s(11) < 1.89$ , all  $p_s > .08$  (Bonferroni corrected), nor a significant difference between singleton conditions for any of the distances, all  $t_s(22) < 1.45$ , all  $p_s > .16$ .

Onsets of capture effects were determined by the same criteria as those used in the preceding experiments within 112 rank-ordered single-trial RTs of each of the different target-singleton distance conditions, separately for the better matching and the less matching conditions. Only in the better matching condition were significant capture effects and their corresponding onsets

observed. By contrast, no significant capture effects were found in the less matching condition. By implication of the fact that the estimated onset times of the capture effect in the better matching conditions were well below maximal RTs in the less matching conditions, it follows that onsets in the better matching condition must have preceded onsets of any putative capture effect beyond the empirically observed RT distribution of the less matching condition (see Table 1).

## Discussion

In Experiment 3, the capture effect of the less matching nontarget colour singleton was estimated in conditions in which participants searched for a single known target colour. Under these conditions, we obtained virtually no capture effect of the less matching colour singleton. By contrast, a clearly significant capture effect was found in the better matching control conditions. Moreover, different target-singleton colour discrimination requirements were exactly the same in the better matching and in the less matching singleton



**Figure 6.** Mean reaction time (RT; on the left) and mean percentage of error (on the right) as a function of singleton condition (better matching vs. less matching singleton condition), preceding target colour only in the better matching conditions (same as that of the better matching singleton vs. different from that of the better matching singleton; in the less matching conditions only one target colour was used, making the preceding target colour always the same as the actual target colour), and target-singleton distance (p0 to p3 from small to large) of Experiment 3. Prec.: preceding.

conditions, ruling out different target–singleton discrimination requirements as the responsible factor for the capture difference.

In conclusion, it seems that conditions with a single to-be-searched-for target colour (or, more generally, with a relatively small set of relevant features) are disadvantageous for any less matching colour singleton to capture attention. This observation suggests that an occasional match of the less matching colour singleton to a relatively imprecise or broad top-down controlled setting for different target colours could have been responsible for the effect of this singleton in the preceding Experiments 1 and 2. (By the same token, it is seemingly not sufficient that the less matching colour singleton matches a setting for shape or for shape-singleton status, as was discussed in Experiment 1.) In line with that argument, a small but significant RT increment was seen between the experimental condition (with only a single to-be-searched-for target colour) and the control condition (with a set of two target colours), which seems to support the conclusion that increasing the set size of to-be-attended to target colours was slightly more demanding.

However, we do not want to argue that it is impossible to observe capture by a less matching singleton under conditions with only one to-be-searched-for target colour. A variety of side conditions—for instance, conditions that also increase the demands imposed by a top-down feature search strategy—might also foster the participant's adoption of a singleton-search mode (cf. Ansorge, Scharlau, & Labudda, 2006): For example, if it is difficult to search for a particular feature because it is hard to discriminate, participants might be equally inclined to search for a singleton, regardless of the particular appearance of the singleton or of whether searching for a singleton would be always a useful strategy in that situation. Also, in many nonlaboratory situations, our prior knowledge of the exact appearance of an object might be so limited that we do not look for an object's known feature (e.g., its colour) but rather prefer to search for any salient object.

In summary, Experiment 3 supported the main conclusions from Experiments 1 and 2. There was

a capture difference, with the better matching colour singleton capturing attention to a larger extent than the less matching colour singleton. Also, the capture difference had an early onset as estimated from its presence among the faster responses in the RT distribution. Finally, the capture effect of the better matching colour singleton was not affected by whether the target in the preceding trial had or had not the same colour as the singleton in the actual trial. Thus, as it is assumed in the preemptive-control hypothesis, participants seemingly specified their attentional control settings in advance of the displays, so that the onset of the capture effect of the better matching singleton can precede that of the less matching singleton, and the particular attentional control setting for target colour needs not be revised after every single encounter of a nonmatching input.

## GENERAL DISCUSSION

Several former studies have compared capture effects of better matching colour singletons (i.e., stimuli that had features that better matched a set of to-be-searched-for target colours) and of less matching colour singletons (i.e., stimuli that did match less well to a set of the searched-for target colours) and found a capture difference: more capture by the better matching colour singleton than by the less matching colour singleton (cf. Folk et al., 1992; Remington et al., 2001). These results can be explained by the preemptive-control hypothesis. According to this hypothesis, participants set up their attentional control settings in advance of the displays to comply with the instructions, to selectively direct their visuospatial attention to the target features and to efficiently ignore the nontarget stimuli (see also Folk et al., 1992). As a consequence, nontarget stimuli that match the control settings set up for and directed to the target colours capture attention more readily than do nontarget stimuli that do match less well to the same control settings (cf. Ansorge & Heumann, 2003, 2004; Ansorge, Heumann, & Scharlau, 2002; Ansorge &

Neumann, 2001, 2005; Scharlau & Ansorge, 2003).

In the current investigation, we confirmed several predictions of the preemptive-control hypothesis. Assuming that control settings can be specified in advance of the displays, we expected that capture by the better matching nontarget colour singleton should have an onset preceding that of capture by the less matching colour singleton (cf. Ansorge et al., 2005). This assumption was borne out by the data of Experiments 1 and 3, in which target and nontarget colour singletons were concomitantly displayed. With a nontarget colour singleton having a head start relative to the target, however, results were less unequivocal: In Experiment 2, onset times of attentional capture effects by the better matching and the less matching nontarget colour singletons were not significantly different from one another in some of the comparisons. Therefore, it is possible that deallocation contributed to the capture difference of Experiment 2.

Moreover, it might be possible to reconcile the observed ordering of the onsets of capture effects with a refined deallocation hypothesis, according to which on a fraction of trials the deallocation process starts rapidly. Thereby, the onset of a significant capture effect in the less matching condition might have been shifted to the slower responses of the RT distribution. Carrying the argument one step further, however, it might be the case that such a refined deallocation explanation is fully compatible with the preemptive-control hypothesis: Participants might not only reactively deallocate attention away from a position, once it turns out that an attended-to position does not contain a target. Instead, they might be able to specify attentional control settings in advance of the displays to also selectively

deallocate attention or to otherwise suppress the processing of irrelevant features or stimuli.

On the basis of the preemptive-control hypothesis, we also expected that the capture effect of the better matching colour singleton in a current trial is not a mere stimulus-driven consequence of whether the preceding trial's target had or had not the same colour as the present trial's nontarget singleton (cf. Horstmann & Ansorge, 2006). This expectation was confirmed in all of the experiments. Capture effects of the better matching colour singleton were the same, irrespective of whether the target in the preceding trial had or had not the same colour as the nontarget colour singleton in the actual trial. This observation stands in marked contrast to some previous results and claims (cf. Maljkovic & Nakayama, 1994; Olivers & Humphreys, 2003). First, in Maljkovic and Nakayama's study, trial-by-trial repetitions of the target singleton colour decreased the RT to the target (relative to trial-by-trial changes of the target colour). However, in that study, the colour singletons were targets, and, thus, participants had to attend to the singletons. By contrast, in the current investigation, the target was never a colour singleton, and participants were asked to ignore the colour singletons. Therefore, different results can be reconciled under the assumption that additional amounts of visuospatial attention can be captured by a singleton with a colour that corresponds to that of the preceding trial's target, where participants use a top-down control setting to attend to the singleton status of the target (cf. Maljkovic & Nakayama, 1994). However, with a top-down control setting for attentional shifts being directed to a particular target colour, as in the current experiment, an additional attentional effect of colour repetition (relative to a colour change) was apparently ruled out.<sup>4</sup>

<sup>4</sup> On the basis of the procedures used by Maljkovic and Nakayama (1994), one might speculate that what matters for a stronger singleton capture effect in a current trial  $N$  is the colour of the singleton in the preceding trial  $N - 1$ , and not the colour of the target in trial  $N - 1$ . However, this alternative interpretation of the results of Maljkovic and Nakayama does not explain the different results between the studies. In the present investigation, trial-by-trial singleton-colour repetitions were restricted to those conditions in which the singleton displayed in trial  $N$  had a different colour from that of the target in trial  $N - 1$ . Therefore, if it were true that trial-by-trial singleton colour repetitions account for the stronger capture effect of the better matching colour singleton, we would have found a significant influence of the variable preceding target colour, only with an inverted pattern of results as compared to the priming-by-pop-out hypothesis outlined in the Introduction.



Second, several former studies have found that a trial-by-trial change of the singleton dimension (i.e., colour, size, or orientation) defining a target among the concomitant nonsingletons incurred an RT cost (cf. Found & Müller, 1996; Müller, Heller, & Ziegler, 1995) and coincided with a lower attentional capture effect by that singleton (cf. Olivers & Humphreys, 2003). However, we used different features (colours), not different dimensions (e.g., size vs. colour, or colour vs. onset) to define the targets and to evoke the specification of particular top-down control settings of our participants. Costs incurred by trial-by-trial feature changes of an attended stimulus (relative to feature repetitions) are an order of magnitude smaller than costs incurred by trial-by-trial dimension changes of the attended stimulus (relative to dimension repetitions; Found & Müller, 1996). Hence, there is no reason in the first place to assume that trial-by-trial colour repetitions or changes have such a pronounced effect on the amounts of capture by a particular singleton colour.

Beyond that, in Experiment 3, we also found some evidence that a preemptively controlled setting to discriminate between different target colours might be responsible for some of the residual capture effect of a less matching colour singleton: Decreasing the number of to-be-searched-for target colours from two (Experiments 1 and 2) to one (experimental condition of Experiment 3) virtually abolished the capture effect of the less matching colour singleton. To reiterate, this is not to say that capture by a less matching colour singleton can never be observed, once participants search for a single target colour. In fact, many previous studies have shown that a less matching colour singleton can capture attention even in conditions in which only a single target colour was to be searched for (cf. Theeuwes, 1994; Turatto & Galfano, 2001). A variety of side conditions need to hold for an efficient use of a top-down control setting for colour by the participants. For example, it is a necessary prerequisite that the participants know in advance which colours to attend to and which colours to ignore (cf. Theeuwes & Burger, 1998).

It should be noted that all of the present results have been obtained using a singleton interference effect with a spatial gradient as the hallmark of the singleton capture effect (cf. Turatto & Galfano, 2001). In the current study, RT increased with an increasing distance between the target and the singleton (cf. Egly & Homa, 1991). Therefore, we consider it to be very unlikely that the effect of the singleton is better explained by a nonspatial colour-filtering process. By the same token, however, we cannot rule out that other benchmark effects of attentional capture that have been applied in the past may yield a different pattern of results. This question is beyond the scope of the present study, but it should be a matter of future investigations.

A final topic in the present discussion concerns the question of the generality of our findings—that is, whether colour is or is not a unique feature for the control of visuospatial attention. First, as mentioned in the introduction of Experiment 1, colour is coded early in the course of visual analysis, at least with sufficiently strong colour differences between relevant and irrelevant stimuli (cf. Wolfe & Horowitz, 2004). For example, Ansorge and Heumann (2003) presented a peripheral irrelevant red or green cue for 34 ms; 60 ms after cue onset, a red target was shown. Hence, in that study, cue duration and cue–target interval were much too short for (a) making an exploratory eye movement to the cue to (b) discern its colour, because the fastest saccades (so-called express saccades) have a minimal latency of about 80 ms (cf. Fischer & Weber, 1993). Despite the fact that target-preceding saccades to the cues were therefore prevented in Ansorge and Heumann's experiments, they found reliable differences in target RTs between red and green cueing conditions. In line with the preemptive control hypothesis, cues with a target-similar colour (e.g., red) were processed to a larger extent than cues with a colour different from that of the target (e.g., green). In conclusion, colour is a feature that must be available early during the course of visual analysis, and it might not be a coincidence that striking evidence for the possibility of top-down

control of attention has been brought about by using colour as a feature discriminating between relevant and irrelevant stimuli (Folk & Remington, 1998, 1999; Folk et al., 1992; Theeuwes & Burger, 1998). However, colour is not necessarily unique in that respect: Features besides colour, such as location, shape, or even motion, can be also searched for with great efficiency, provided that the corresponding feature differences between relevant and irrelevant stimuli are strong enough (e.g., Wolfe & Horowitz, 2004).

A second potential respect in which colour might be unique concerns the kind of behaviour that colour affords. Colour-sensitive cones are more densely packed in the fovea than in the periphery of the retina. Therefore, colour affords a shifting of the eyes: A saccade toward a peripheral colour stimulus is beneficial for coding that stimulus's colour. Because overt shifting of the eyes and covert shifting of attention are coupled at least in some conditions (e.g., Deubel & Schneider, 1996), colour might be unique as a feature used by mechanisms concerned with the rapid allocation of visuospatial attention (or the eyes). However, at least shape or fine spatial detail also affords a shifting of the eyes, because receptive field sizes underlying spatial discrimination are much smaller in the fovea than in the periphery of the retina. In line with that assumption, while looking at two-dimensional displays of three-dimensional natural scenes observers spend large amounts of time fixating areas of fine spatial detail, such as scripture (cf. Henderson, 2003). The conclusion is the same as above: Colour is not necessarily a unique feature for the control of visuospatial attention. Therefore, we think that the preemptive control of visuospatial attention could be a relatively general principle, and future studies should be aimed at testing the preemptive-control hypothesis with features besides colour.

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