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ORIGINAL ARTICLE

Top-down influences on attentional capture by color changes

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Abstract Previous studies have shown that a change in an existing object is not as effective in capturing attention as the appearance of a new object. This view was recently challenged by Lu and Zhou (Psychonomic Bulletin and Review 12:567–572, 2005), who found strong capture effects for an object changing its color. We suspected that this finding critically depends on a procedural particularity in Lu and Zhou's study, namely that the color of the unique item and the color of the no-unique items randomly switched between trials. In the current study we replicate Lu and Zhou's capture effect (Experiment 1) and show that no capture occurs when the color-to-stimuli assignment is fixed (Experiment 2). Two further experiments suggest that the capture effect in Experiment 1 is not because the unique item switched color (Experiment 3), but because all the no-unique items switched color (Experiment 4). The results are discussed considering top-down modulation and inter-trial priming effects.

Introduction

The dynamic allocation of visual attention hinges to a great extent on our immediate goals and expectations (e.g., Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). Yet, some events are still able to break through and attract our attention, regardless of our current task set. Which kinds of events are these? Everyday experience may suggest that any salient change in the visual field should capture attention, as it might carry important information that is critical for one's survival. However, this idea is not supported by research in the psychophysical laboratory, which showed that only events signaling the appearance of a new object are effective in capturing attention (e.g., Jonides & Yantis, 1988; Egeth & Yantis, 1997). Salient changes to already-registered objects, such as a change in color (e.g., Jonides & Yantis, 1988; Theeuwes, 1990, 1995), a change in luminance (Enns, Austen, Di Lollo, Rauschenberger, & Yantis, 2001; Jonides & Yantis, 1988), or a change in motion (Hillstrom & Yantis, 1994; Yantis & Egeth, 1999) have no or only little effect on attention. One explanation for these findings was that simple changes in our natural environment are far too common to be informative of behaviorally urgent events, and that only the appearance of new objects are potentially important to our survival (Hillstrom & Yantis, 1994; Jonides & Yantis, 1988).

Many studies addressing the issue of attentional capture have used the visual search paradigm, where participants must search for a target letter among a varying number of distractor letters (e.g., Treisman & Gelade, 1980). In one variant of this paradigm the search display is preceded by a preview display with figure-eight placeholders that remain on view for 1 s (Todd & Van Gelder, 1979). Subsequent some line segments of each figure eight are deleted to reveal the letters of the search display. Importantly, at the same time one of the letters undergoes a change (e.g., change in color), and the key variation is whether the change happens to the target or to one of the distractor

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letters. Attentional capture is indexed by the relative ratio of reaction time (RT) slopes—taken over the number of letters in the display—for changing distractors over changing targets. This is based on the assumption that when a unique change draws attention to itself, it will slow search if it happens to be at a distractor, and it will speed search if it happens to be at the target. A distractor/target slope ratio of 1:1 means that the unique change had no differential effect on the search slope, and, thus, no effect on attention. In previous studies the slope ratio for color changes was typically between 0.7 and 1.4, indicating that color changes do not capture attention (e.g., Folk & Annett, 1994; Franconeri & Simons, 2003; Jonides & Yantis, 1988; Todd & Kramer, 1994; von Mühlenen, Rempel, & Enns, 2005; Yantis & Egeth, 1999).

Yet there have been lately some exceptions to these findings, showing that color changes sometimes do capture attention (Horstmann, 2002; Lu and Zhou, 2005; Turatto and Galfano, 2000, 2001; von Mühlenen et al., 2005). For example, Turatto and Galfano (2000, 2001) reported that a color change can capture attention when participants are relatively inexperienced in visual search tasks. In another study reported by Horstmann (2002) a color change captured attention when it was unexpected and surprising. However, comparison of these studies to the previous studies is difficult, because they used a different measure of attentional capture, one that is not based on the systematic variation of display size (see Rauschenberger, 2003, for a critical discussion of measures not based on the search slope ratio).

An examination of the literature revealed that there are only two studies, which used the search slope ratio measure described above and found an attentional capture effect for color changes. In one study by von Mühlenen et al. (2005) the timing of events was systematically varied. They found that color changes can be as effective as new objects in capturing attention, provided that the change occurs during a period of temporal calm before (or even after) search begins. They further showed that such color changes lose their ability to capture attention when they occur simultaneously with the onset of the preview display or with the removal of line segments during the preview–search transition. However, von Mühlenen et al. themselves pointed out that their finding is not necessarily in contradiction to previous findings, it rather offers an extension of previous accounts, highlighting the importance of temporal factors in the study of attentional capture.

In the other study by Lu and Zhou (2005) the search slope ratio measure suggested strong capture effects for color changes, even though the changes occurred simultaneous with the preview–search transition. A closer examination of their experiments revealed several methodical differences in comparison to previous studies, of which two were particularly prominent: first, the color of the stimuli was randomly varied between trials. That is, in a given trial the stimuli could either be all red or all green, except the unique change stimulus, which was vice versa green or red. Maybe these color switches between trials made it very difficult to ignore the uniquely colored item. Second, instead of letters composed of thin lines, large filled disks were used with thin black letters inside. It is likely that a color change in a filled disk produces a much stronger signal than the same color change in a few thin lines. Thus it is possible that in Lu and Zhou's study attentional capture only occurred because their change signal was much larger than in previous studies. The aim of the current study was to explore these two possible explanations for why Lu and Zhou found attentional capture by unique color changes, which is somewhat puzzling, considering that the absence of capture by color changes had been a prevalent finding in the literature.

Experiment 1

Our starting point was to replicate Lu and Zhou's Experiment 1 using exactly the same methodology they used. We expected to find a significant capture effect for color changes that was similar to the one reported by Lu and Zhou.

Method

Participants

Ten participants (6 females; mean age = 26.6 years) with normal or corrected-to-normal visual acuity participated in the experiment receiving payment of 8 €/h. None of the participants was aware of the purpose of the study.

Apparatus and stimuli

The experiment was controlled by an IBM-PC compatible computer using Matlab routines and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) and stimuli were presented on a 17 in. monitor. Each trial started with a central white fixation cross (luminance 8.5 cd/m^2) drawn on black background (0.02 cd/m^2). The subsequent preview display contained three or six placeholder stimuli (see Fig. 1 for an example of a preview display). Each placeholder consisted of a colored disk subtending 2.2° in diameter (from a viewing distance of 57 cm) with a black figure eight stimulus in its center (1.8° × 1.0°, line thickness 1 pixel). Placeholders were distributed in a circular arrangement (5.3° in radius) around the fixation cross. Preview displays with three elements were arranged as an

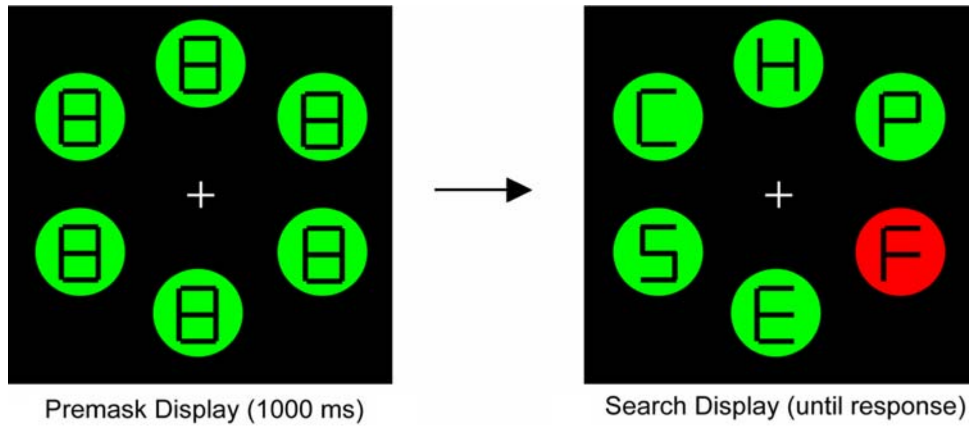

Fig. 1 Schematic example dsplays for Experiment 1 with a target "S" present at a no-unique position

upward-pointing equilateral triangle, whereas those with six elements formed a hexagon. The placeholder disks were either all green or all red (both 6.5 cd/m^2).

The preview display was followed by the search display, which came along with two changes to the preview display: first, each figure eight stimulus, had two to four line segments removed such that letters were revealed (e.g., removing the top and bottom horizontal line segment of the "8" revealed the letter "H"). The target letter was an S, and the distractor letters were randomly chosen from the letters H, U, E, P, C, F or L, with the constraint that a letter was presented only once on a given trial. Second, simultaneously with the removal of line segments, one of the disks abruptly changed its color. When all disks were green, one changed to red, or vice versa, when all were red, one changed to green (see Fig. 1 for an example of a search display).

Procedure and design

A typical trial sequence is shown in Fig. 1. A trial started with the fixation cross presented for 500 ms, followed by the preview display presented for 1,000 ms. Subsequently, the search display appeared, remaining on screen until a response was recorded. The inter-trial interval was 1,000 ms. The task was to search for the target letter "S" and to decide whether it was present or absent. Responses were collected via mouse keys and response times were measured from the onset of the search display. In case of an erroneous response, visual feedback was given by an alerting sign ("–") presented at the center of the screen for 500 ms. Participants were instructed to respond as quickly and as accurately as possible. They were also told that the position of the uniquely colored disk was uninformative with respect to the location of the target.

Each participant completed 25 practice trials followed by 360 experimental trials. The experiment was divided into three blocks of 120 trials each, with short breaks between blocks. All (but 1) disks were in half of the trials red and in the other half of the trials green (except the unique disk, which was either green or red, respectively). Importantly, as in Lu and Zhou's (2005) study, these color-to-stimuli assignments changed unpredictably from trial to trial. For example, all disks (but one) could be green in the first trial, red in the second and third trial, again green in the fourth trial, and so forth.

The experiment systematically varied two factors, display size and target type, with all possible factor combinations presented in random order. Display size had two levels (3 or 6 items) and target type three levels: (1) absent target, where no target was shown, (2) present no-unique target, where the target was one of the items that did not change its color, and (3) present unique target, where the target was the item that changed its color. The target was present on half of the trials. Table 1 shows the different number of trials for each factor combination, which were chosen such that the target (when present) had an equal chance to appear in any of the placeholder disks. This means that the occurrence of the color change was completely task-irrelevant, as it did not correlate with the occurrence of the target.[1]

Results and discussion

Errors

Mean error rates were calculated for each participant and condition. Table 2 presents the averaged error rates (across participants) separately for each condition in rows 1–3. Participants had on average 0.8% false alarms and 4.5%

[1] Keeping the occurrence of unique and no-unique target trials statistically independent, resulted inescapably in a confound between display size and target type, such that unique target trials occurred twice as often with three-item displays than with six-item displays. It is therefore possible that the slope of the unique target trials and hence the overall slope ratio is affected by this inequality. However, it is important to note that this confound cannot be avoided and applies to all slope-ratio based experiments reported here and elsewhere in exactly the same way.

Table 1 Number of trials for each display size × target type combination in Experiment 1

Target type	Display size	
	3	6
Absent	60	120
Present no-unique	40	100
Present unique	20	20

Table 2 Mean percentage of errors for Experiments 1–5

Experiment	Target type	Display size	
		3	6
1	Absent	0.7	1.3
	Present no-unique	7.8	7.5
	Present unique	7.0	7.5
2	Absent	2.7	1.8
	Present no-unique	5.0	3.3
	Present unique	7.5	8.5
3	Absent	1.7	1.4
	Present no-unique	3.5	3.3
	Present unique	7.0	8.5
4	Absent	1.8	1.8
	Present no-unique	2.3	3.3
	Present unique	8.0	7.5
5	Absent	1.0	0.7
	Present no-unique	3.3	5.2
	Present unique	2.0	6.0

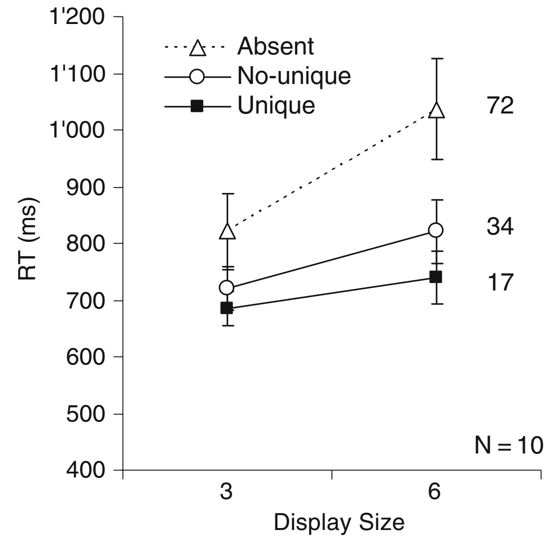

Fig. 2 Results from Experiment 1. Mean reaction time (RT) is plotted as a function of display size separately for target absent, present unique and present no-unique trials. The *number next to each line* gives the RT search slope (in ms/item)

misses. The misses were subjected to a two-way repeated measure ANOVA with main terms for display size (3, 6) and target type (no-unique, unique).[2] The results revealed no significant effects (all $P > 0.69$). It therefore seems unlikely that the target-present RTs in this experiment were affected by a speed–accuracy trading relationship.

RTs

Correct trials were used to calculate mean RTs for each participant and condition. Figure 2 presents the averaged RTs as a function of display size with separate lines for target types. The target-present RTs were subjected to a two-way ANOVA with main terms for display size (3, 6) and target type (no-unique, unique). Both main effects, for display size, $F(1,9) = 16.94$, $P < 0.01$, and for target type, $F(1,9) = 15.46$, $P < 0.01$, were highly significant: RTs increased with display size on average by 25 ms per item, and search for unique targets was 60 ms faster than for no-unique targets. In addition, the two-way interaction was highly significant, $F(1,9) = 17.24$, $P < 0.01$, due to faster search rates with unique than with no-unique targets (17 vs. 34 ms/item, respectively).

Overall the results of Experiment 1 nicely replicate Lu and Zhou's (2005) findings of significant capture for unique color changes. Although the slope ratio in the current study (17:34) is numerically smaller than in Lu and Zhou's first and third experiment (4:27 and 6:21, respectively), the overall pattern of results is very similar. Thus, our results confirm that capture can occur by means of a color change under certain circumstances. The next four experiments will look into potential limitations on the generality of this finding and will attempt to incorporate it into the literature.

Experiment 2

One assumption was that the color capture effects found in Lu and Zhou's (2005) study and in our Experiment 1 was due to the random color switches of the stimuli from trial to trial between red and green. As a consequence of these switches the unique item could no longer be ignored, maybe because the color-to-stimuli assignments must be known in advance in order to enable top-down driven processes preventing the rather futile capture of attentional resources. This hypothesis was tested in Experiment 2, which was identical to Experiment 1, except that the color-to-stimuli assignment for the disks was now fixed throughout a block of trials.

[2] In statistical analyses we report only significant effects, unless they are of theoretical importance, in which case we report the P value.

Method

Ten participants (6 females; mean age = 29.7 years) with normal or corrected-to-normal vision received 8 € for taking part in this experiment. Apparatus, stimuli, design, and procedure were as in Experiment 1, with the only difference that now the color-to-stimuli assignment was fixed throughout each half of the experiment. Five participants started with a unique green disk among red disks, and switched to a unique red disk among green disks, and vice versa for the other five participants. Experiment 2 was divided into six blocks of 60 trials each.

Results and discussion

Errors

One participant was replaced by a new participant, because of unusually high error rates of more than 25% in two of the six conditions. The averaged error rates are shown in Table 2 separately for each condition. Participants had on average 2.0% false alarms and 4.7% misses. A two-way repeated measure ANOVA on the misses with main terms for display size and target type revealed a marginally significant effect for target type, $F(1,9) = 4.21$, $P = 0.07$, due to more misses with unique than with no-unique targets (8.0 vs. 4.2%, respectively). However, for the purpose of our study we can argue that speed-accuracy trade offs are most likely not an issue, because display size—the critical variable for the evaluation of capture effects—had no significant effects on misses.

RTs

Figure 3 presents the averaged correct RTs as a function of display size with separate lines for target type. Target-present RTs were subjected to a two-way ANOVA with main terms for display size and target type. Only the main effect for display size reached significance, $F(1,9) = 19.62$, $P < 0.01$, due to RTs increasing with display size (mean search rate: 32 ms/item). Effects involving target type did not reached significance (both $P > 0.50$). This result is consistent with earlier studies, which found no capture effects (e.g. Jonides & Yantis, 1988), or only weak capture effects (e.g. Todd & Kramer, 1994) for color changes.

The target-present RTs of Experiments 1 and 2 were directly compared with a mixed design three-way ANOVA, with experiment as a between-subject factor, and display size and target type as within-subject factors. Of the effects (of interest) involving experiment, only the interaction between experiment and target type reached significance, $F(1,18) = 8.29$, $P < 0.01$: RTs were faster with a unique

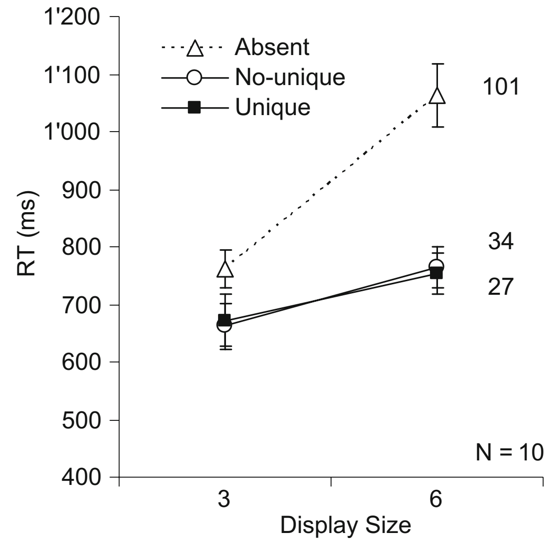

Fig. 3 Results from Experiment 2. Mean reaction time (RT) is plotted as a function of display size separately for target absent, present unique and present no-unique trials

than with a no-unique target in Experiment 1, but not in Experiment 2 (61 and 1 ms, respectively). The three-way interaction did not reach significance ($P > 0.30$).

In conclusion, the results of Experiments 1 and 2 suggest that the ability to ignore a color change depends to some extent on a fixed color-to-stimuli assignment across trials. If search is performed in a "noisy" environment where the color-to-stimuli assignment keeps changing between trials, the ability to ignore a task-irrelevant color change breaks down. This is in line with other priming studies (Olivers & Meeter, 2006) showing that stimulus ambiguity between trials can affect search performance, suggesting that perceptual uncertainty increases the susceptibility to bottom-up processes.

One possible explanation for the findings in these two experiments is that search performance—and hence the ability to ignore a task-irrelevant color change—is to some extent modulated through top-down processes. For example, it could be that ignoring the color change is a learning process, which involves inhibitory mechanisms applied to the unique item. That is, the unique item might initially capture attention, but then participants learn to ignore it (through inhibition), which in turn either eliminates or simply counteracts the effect of attentional capture. This inhibition would have prevented capture in Experiment 2, as well as in many other experiments reported in the literature where a color change did not capture attention. However, in Experiment 1 (as well as in Lu and Zhou's study) the color change could not be ignored, because the colors kept switching randomly between trials and, hence, were not known in advance.

Experiment 3

The goal of the next two experiments was to look more closely into why the unique color change captured attention in Experiment 1. One prediction, based on the inhibition account proposed above, is that a unique item can only be inhibited when its color is known in advance (what was the case in Experiment 2, but not in Experiment 1). This means that the failure to ignore the unique color change would be due to the unique item switching colors, and not due to the no-unique items. This hypothesis was tested in Experiment 3, which was identical to Experiment 1, except that the color of the no-unique items was fixed throughout the experiment (i.e., they were always gray), while the color of the unique item randomly changed between trials (i.e., it was either red or green).

Method

Ten participants (8 females; mean age = 28.2 years) took part in Experiment 3. Apparatus, stimuli, design, and procedure were the same as in Experiment 1, except that now all disks were colored gray (luminance 6.5 cd/m^2), except for the unique disk, which was either red or green (luminance 6.5 cd/m^2). As in Experiment 1, the unique disk switched its color unpredictably from trial to trial.

Results and discussion

Errors

Table 2 shows the averaged error rates separately for each condition. Overall, participants had 1.5% false alarms and 4.3% misses. The two-way repeated measure ANOVA on the misses with main terms of display size and target type revealed a significant main effect for target type, $F(1,9) = 8.86$, $P < 0.05$, due to more misses with unique than with no-unique targets (7.8 vs. 3.4%, respectively). RT analysis revealed that overall, participants were also a bit slower (12 ms) with unique than with no-unique targets. Thus, the error pattern reinforces the RT pattern, ruling out possible confounds due to speed-accuracy trade-offs.

RTs

Figure 4 presents the averaged RTs as a function of display size with separate lines for each target type. Target-present RTs were subjected to a two-way ANOVA with main terms for display size and target type. The main effect for display size was highly significant, $F(1,9) = 17.83$, $P < 0.01$, due to RTs increasing with display size (mean search rate of 26 ms/item). However, no effect involving target type reached significance ($P > 0.28$).

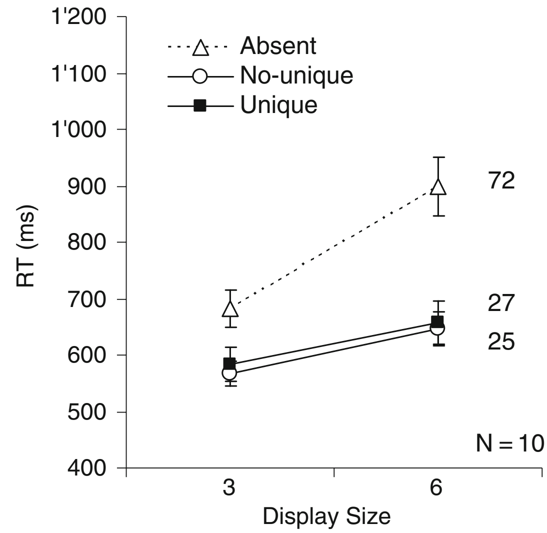

Fig. 4 Results from Experiment 3. Mean reaction time (RT) is plotted as a function of display size separately for target absent, present unique and present no-unique trials

Thus, RTs in Experiment 3 show no significant capture effect for color changes, despite the fact that the color of the unique item was randomly varied between trials (i.e., it changed from gray to either red or green). It seems that the ability to ignore a color change does not depend on the advance knowledge of the specific color that the unique item is going to have. This speaks against our hypothesis that the unique item can only be inhibited when its color is known in advance. If capture is not driven by the color switches of the unique item, then the question remains what caused capture in Experiment 1? The only remaining possibility is that it was due to the color switches of the no-unique items, what was investigated in the next experiment.

Experiment 4

In Experiment 4, the color of the no-unique items randomly varied between trials (i.e., they were either red or green), while the color of the unique item was kept constant throughout the experiment (i.e., it was always gray). Given the absence of capture in Experiment 3, it was expected that it would occur in this experiment, because the color switches of the no-unique items was the only remaining factor that could be responsible for the capture effect found in Experiment 1.

Method

Ten participants (8 females; mean age = 26.6 years) took part in Experiment 4. Apparatus, stimuli, design, and procedure were as in Experiment 1, with the only difference that now the preview and no-unique disks were either all red or all green (luminance 6.5 cd/m^2), and the unique disk was always gray (luminance 6.5 cd/m^2). The color of the preview and no-unique disks changed unpredictably from trial to trial.

Results and discussion

Errors

Table 2 shows the averaged error rates separately for each condition. Participants had overall 1.8% false alarms and 4.1% misses. The two-way repeated measure ANOVA on the misses with main terms for display size and target type revealed no significant effects.

RTs

Figure 5 presents the averaged RTs as a function of display size with separate lines for each target type. Target-present RTs were subjected to a two-way ANOVA with the factors display size and target type. The main effect for display size was significant, $F(1,9) = 9.01$, $P < 0.05$, due to RTs increasing with display size (mean search rate: 12 ms/item). Furthermore, the interaction was highly significant, $F(1,9) = 12.83$, $P < 0.01$, due to faster search rates with unique targets than with no-unique targets (2 vs. 22 ms/item, respectively).

The results of Experiment 4 show a significant capture effect for color changes. This suggests that the capture effect in Experiment 1 (and in Lu & Zhou's, 2005, study) is primarily due to the random color switches of the no-unique items between trials. One possible interpretation for this pattern of results could be that attentional capture by color changes is driven through facilitatory rather than inhibitory processes. That is, in order to escape attentional capture (which only hinders the task of finding the target), a facilitatory process would enhance all no-unique items. This facilitatory process would then counterbalance the automatic capture effect caused by the unique color change.

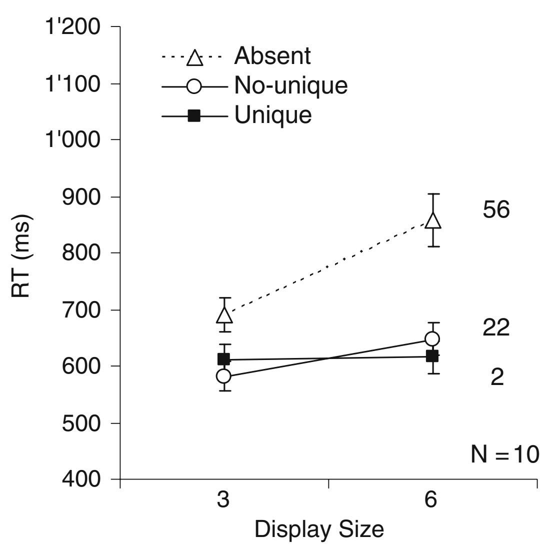

Fig. 5 Results from Experiment 4. Mean reaction time (RT) is plotted as a function of display size separately for target absent, present unique and present no-unique trials

Inter-trial analysis of color switching effects in Experiments 1 and 4

Another way to explore the involvement of inhibitory and facilitatory processes in ignoring task-irrelevant color changes is to look at possible inter-trial dependencies in those experiments that showed a capture effect (i.e., Experiments 1 and 4). One possible account for these capture effects could be that they do not depend on top-down driven facilitatory or inhibitory processes, but that they are linked to color switching interferences that are more bottom-up driven. If this were true we would expect that the capture effect were not present in all trials, but only in trials where the color had switched. We therefore re-analyzed the data of Experiments 1 and 4 distinguishing between two types of trials: switch trials—where the color of the no-unique item switched, and repetition trials—where the color of the no-unique item stayed the same as in the previous trial.

In order to increase statistical power the data of Experiments 1 and 4 were combined. The combined RTs are shown in Fig. 6, separately for the switch trials (top graph) and for the repetition trials (bottom graph). A three-way ANOVA on the target-present RTs with main terms for trial type (switch, repetition), display size (3, 6), and target type (unique, no-unique), revealed among others a highly significant three-way interaction, $F(1,19) = 9.27$, $P < 0.01$. As can be seen from Fig. 6, a capture effect occurred in repetition trials (32:8 ratio), but not in switch trials (27:27 ratio). This is exactly the opposite of what had been predicted if attentional capture were due to bottom-up interference caused by the color switches between trials.

The inter-trial analysis further qualifies the findings of Experiments 1 and 4, showing that the general capture effect for color changes was actually only due to a strong capture effect in the repetition trials (see also Kristjánsson, 2006 for a similar argument). This finding also disproves the idea that the unique color changes (within a trial) could not be ignored because they were "overshadowed" by the much larger color switches between trials. Overshadowing would have predicted capture only in switch trials—not in repetition trials.

This capture in repetition trials appears to be contradictory to the absence of capture in Experiment 2, where in a

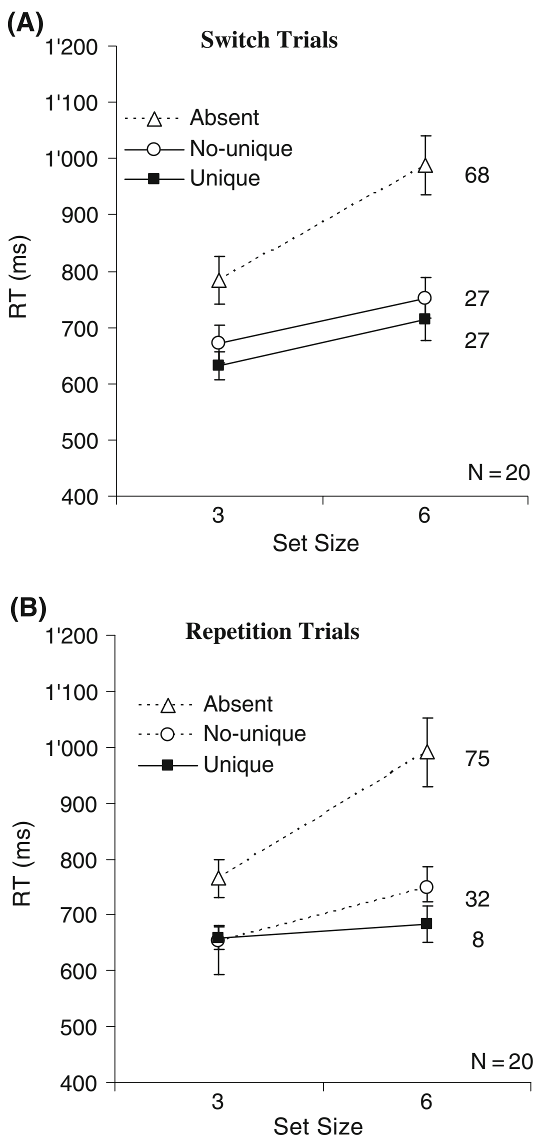

Fig. 6 Re-analysis of RTs in Experiments 1 and 4, where trials are divided into switch trials (disk colors were different in previous trial) and repetition trials (disk colors were the same in previous trial). RTs are plotted as a function of display size separately for target absent, present unique and present no-unique trials

sense all trials were repetition trials. The only difference was that in Experiment 1 the color-to-stimuli assignment was not known in advance, whereas in Experiment 2 it was known, since it did not change. This color knowledge must have been used in Experiment 2 to get prepared in some top-down manner to escape automatic capture by the unique item, maybe through advance activation of the color of the preview placeholder items. However, in Experiment 1 this top-down control broke down, because the advance color-to-stimuli assignment was not known, which allowed inter-trial contingencies to capture attentional resources.

Experiment 5

The final experiment explores possible reasons for why the capture effect did not fully disappear in Experiment 2 (slope ratio of 37:28). One possibility is that the residual capture is due to the type of stimuli used in Lu and Zhou's (2005) study, which were large filled disks with letters inside (whereas most comparable studies used colored letters without any disks). This hypothesis was tested in Experiment 5, which replicated Experiment 2 using simple colored letters instead of filled disks.

Method

Ten participants (5 females; mean age = 24.9 years) took part in Experiment 5. Apparatus, stimuli, design, and procedure were as in Experiment 2, with two differences: first, only letters without disks were presented, both in the preview and in the search display. Second, the letters were colored (instead of the disks), either red or green (luminance 6.5 cd/m^2). As in Experiment 2, the stimuli colors were fixed within a block of trials.

Results and discussion

Errors

Table 2 shows the averaged error rates separately for each condition. Participants had overall 0.8% false alarms and 4.5% misses. A two-way repeated measure ANOVA on the misses with main terms for display size and target type revealed a marginally significant main effect for display size, $F(1,9) = 4.01$, $P = 0.08$: participants did more errors with six item than with three item displays (5.6 vs. 2.6%, respectively). Confounds due to speed-accuracy trade-offs are very unlikely as the display size RT pattern shows effects in the same direction.

RTs

Figure 7 presents the averaged RTs as a function of display size. Target-present RTs were subjected to a two-way ANOVA with the main variables display size and target type. The main effect for display size was highly significant, $F(1,9) = 14.49$, $P < 0.01$, as RTs were increasing with display size (average search rate of 23 ms/item). Target type effects did not reach significance ($P > 0.18$).

The target-present RTs from Experiments 1 and 5 were subjected to a mixed design three-way ANOVA with experiment as the between-subject factor, and display size and target type as within-subject factors. Several effects involving experiment reached significance, including the three-way interaction, $F(1,17) = 4.38$, $P < 0.05$. Thus, now

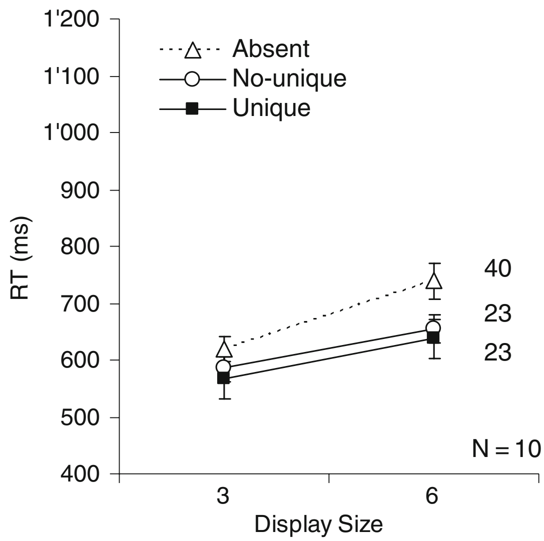

Fig. 7 Results from Experiment 5. Mean reaction time (RT) is plotted as a function of display size separately for target absent, present unique and present no-unique trials

we can say that the capture effect in Experiment 5 was significantly reduced in comparison to Experiment 1, suggesting that the ability to ignore an irrelevant color stimulus decreases with an increase in signal strength.

General discussion

The present study replicates Lu and Zhou's (2005) finding where equiluminant color changes captured attention (Experiment 1). This capture effect is reduced when the color-to-stimuli assignment becomes fixed throughout the experiment (Experiment 2). Follow-up experiments suggest that the capture effect in the first experiment is not due to the unique item switching colors (Experiment 3), but due to all no-unique items switching colors (Experiment 4). Re-analysis of the data looking at inter-trial effects show that the capture effect in Experiments 1 and 4 only occurs in repetition trials, where the color-to-stimuli assignment does not change in comparison to the previous trial. Finally, the small residual capture effect found in Experiment 2 with a fixed color-to-stimuli assignment vanishes when the size of the colored stimulus area is reduced (Experiment 5).

Whether or not a unique color change can be ignored was found to critically depend on the ability to establish top-down control: when the assignment of colors was fixed throughout the experiment, ignoring an irrelevant color change was not difficult (and no capture effect occured). However, when the color-to-stimuli assignment was unpredictable, this ability broke down and capture arose. Interestingly, this top-down control was found to be far less efficient when the no-unique items (rather than the unique item) changed unpredictably from trial to trial. This finding suggests that top-down control is achieved through a facilitatory process enhancing all no-unique items rather than through an inhibitory process suppressing the uniquely colored item.

The influence of top-down control processes on bottom-up capture has been documented in earlier papers (e.g., Folk et al., 1992, 1994). However, in these studies capture was typically shown to depend on task expectancies, whereas in the current study capture co-varied with stimulus expectancies. This is in some sense related to capture effects reported for unexpected, surprising events (Horstmann, 2002). Within this context, the discrepancy between Lu and Zhou's (2005) finding of capture for color changes and the absence of such effects in the literature (e.g., Folk & Annett, 1994; Franconeri & Simons, 2003; Jonides & Yantis, 1988; Todd & Kramer, 1994; Yantis & Egeth, 1999) can be attributed to procedural differences, which affected the extent of top-down control that was involved in efficient stimulus processing. In addition, residual effects of capture could be explained by the relatively strong signal that is elicited by the colored disks (as opposed to colored letters in other studies), suggesting that the strength of a given feature change can modulate capture to some extent (see also Folk & Annett, 1994).

The re-analysis of Experiments 1 and 4 showed that capture only occurred in color repetition trials but not in color switch trials. At first sight this finding may seem somewhat surprising, given that no capture occurred in Experiment 2, where the color-to-stimuli assignment was repeated throughout the experiment. However, a broader view on the visual search literature suggests that the repetition-dependent capture effect is very similar to other inter-trial facilitation effects (Found & Müller, 1996; Maljkovic & Nakayama, 1994). This is also in line with Kristjánsson, Wang, and Nakayama's (2002) view that the role of priming in visual search is often underestimated. As suggested previously, priming effects may be particularly related to the processing of distractor items (Kristjánsson et al., 2002; Geyer, Müller, & Krummenacher, 2006), a finding that intuitively fits to the predominant role of the no-unique items in the current set of experiments. And finally capture effects for item repetitions are also reflected in the results from studies that investigated the impact of inter-trial contingencies on attentional capture (Olivers & Humphreys, 2003; Pinto, Olivers, & Theeuwes, 2005).

Conclusion

The ability to ignore an irrelevant color change depends strongly on the ability to maintain top-down control. This maintenance becomes unsustainable when the color of the stimuli is randomly varied across trials. This decrease in attentional control in turn allows inter-trial contingencies of the no-unique items to capture attentional resources. Therefore, inefficient top-down control (given unpredictive changes between trials) facilitates bottom-up capture when the color-to-stimuli assignment is repeated from trial to trial.

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