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Attentional Guidance by Irrelevant Features Depends on Their Successful Encoding Into Working Memory

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Attentional selection is guided by templates of the target in working memory. It has been proposed that attentional templates integrate target features (e.g., purple chair) to guide attention in an object-based fashion. Alternatively, it may be that attentional templates are established for each target feature individually (e.g., *purple* and *chair*). To provide support for the latter account, we used a task where participants memorized a target shape while ignoring an irrelevant color. In the combined condition, the shape was shown in the irrelevant color. In the separate condition, the irrelevant color was spatially separate from the shape. After the initial presentation and a blank retention interval, participants were asked to make a saccade to the initially viewed shape, which was shown together with a distractor. Attentional guidance by the irrelevant color was strongly reduced with separate presentation, suggesting that guidance is object-based. However, it may be that irrelevant color was less reliably encoded with separate presentation. Therefore, we asked participants to store the irrelevant color for later recall. With the additional memory task, guidance by irrelevant color occurred regardless of whether it was presented as part of an object or separately. Thus, effects of irrelevant features are easier to observe with combined presentation because all features of an object are automatically encoded into working memory, where they form integrated feature templates. Nonetheless, guidance by separate features is possible, but the poor encoding of irrelevant features with separate presentation makes it more difficult to observe.

Public Significance Statement
This study shows that any irrelevant feature stored in visual working memory can interfere with attentional selection of the target object. Interference is not limited to situations where the irrelevant feature is part of the target object.

Keywords: visual search, attentional template, attentional selection, working memory

Visual search is guided by representations of the target features in working memory (WM; Bundesen, 1990; Duncan & Humphreys, 1989; Eimer, 2014; Schneider, 2013; Wolfe, 1994). For instance, when we look for a red pen on a cluttered desk, we may keep *red* and *elongated* in WM to guide attention to potential target objects. The question we address here is whether efficient guidance requires a combined representation of these features in WM or whether a separate representation is enough. Introspectively, the former idea rings true because we mostly look for objects that combine two or more features. The alternative idea that attention is guided by separate features is less intuitive. The present research confirms the advantage of integrated over separate feature templates. However, we show that this advantage results from the automatic encoding of features pertaining to an object into WM. When encoding into WM is ensured, guidance by separate features is equally effective.

Evidence for the object-based guidance of attention with integrated feature templates was provided by Foerster and Schneider (2018, 2019, 2020). Foerster and Schneider asked their participants to memorize a target shape that was presented at the beginning of the trial. The target shape was randomly selected on each trial to ensure that it was stored in WM and not in long-term memory (Carlisle et al., 2011; Woodman et al., 2013). After a retention interval, the target shape was presented together with a distractor shape, randomly to the left or right, and participants were asked to look at the target shape. Saccades to one of the two objects occurred with a latency of about 200 ms. The important manipulation in Foerster and Schneider's experiments concerned the irrelevant color of the shapes (see also Figure 1). When the color of the target shape was the same in the initial presentation and the saccadic choice display, saccadic responses were mostly correct and

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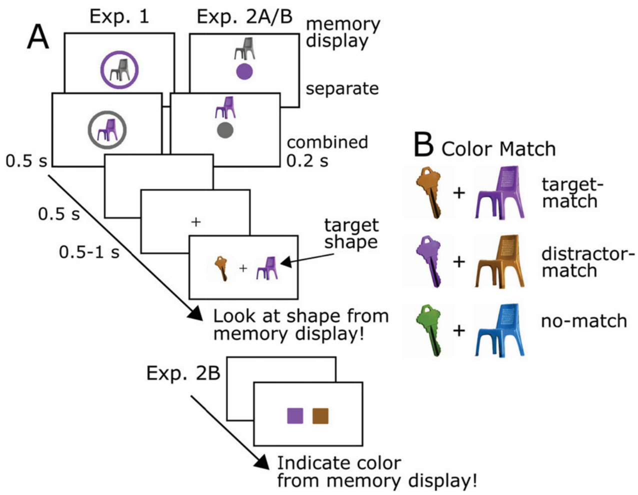
Figure 1
Sample Stimuli, Time Course, and Experimental Conditions



Note. Sample stimuli are not to scale. A: The target shape (a chair) was presented in the memory display. Color and shape in the memory display were combined in the same object or presented separately. In the separate condition, the irrelevant color was shown on a ring (Experiment 1) or on a disk (Experiments 2A and 2B). Participants were instructed to saccade to the target shape in the saccadic choice display. In Experiment 2B, memory for the color in the memory display was probed at the end of the trial. B: In the target-match condition, the color from the memory display matched the color of the target shape in the choice display, whereas it matched the distractor shape in the distractor-match condition. In the no-match condition, two new colors were presented in the choice display. Target shapes were drawn from an image database (Brady et al., 2013). See the online article for the color version of this figure.

went to the target shape. In contrast, when the distractor was shown in the initial color of the target shape, saccadic responses were frequently wrong and went to the distractor. Thus, color influenced responses although only shape was relevant, suggesting that attention is automatically guided by all features of the object acting as attentional template. The guidance by integrated feature templates was observed not only for saccadic responses (Foerster & Schneider, 2018), but also for perceptual judgments (Foerster & Schneider, 2019) and mouse clicks (Kerzel & Andres, 2020). The relevant and irrelevant dimensions (i.e., color and shape) can be selected arbitrarily, but with the limitation that features on the relevant dimension are less discriminable than features on the irrelevant dimension (Foerster & Schneider, 2020).

Further support for the idea that both task-relevant and task-irrelevant features of an object guide attentional selection comes from memory-based interference in visual search tasks (reviews in Olivers et al., 2011; Soto et al., 2008). For instance, Gao et al. (2016) presented a colored geometrical shape at the start of a trial. Participants were instructed to memorize its color, which was tested at the end of the trial. In contrast, the shape of the object was task irrelevant. Between encoding and test of the color feature, participants performed a visual search task where they had to indicate the orientation of the only tilted line among otherwise vertical lines. Each line was surrounded by a colored geometric shape. In some search displays, one of the geometric shapes shared the color or shape of the object presented at the start. The location of the matching feature was not useful to locate the target because the target was never shown at this location. Nonetheless, search times increased when the surrounding color or shape matched the object presented at the start. Importantly, memory-based interference occurred not only for the memorized color feature, but also for the irrelevant shape feature, suggesting that all features of the object were encoded into WM and guided attention away from the target location (see also Soto & Humphreys, 2009). However, evidence for object-based memory interference was not always observed. For instance, Olivers (2009) ran an experiment similar to Gao et al. (2016), but only observed memory-based interference for the relevant feature of the object presented at the start (see also Sala & Courtney, 2009). Possibly, the discrepancy is due to the longer interval between presentation of the object and the search task in Olivers (2009) or Sala and Courtney (2009) compared with Gao et al. (2016). With longer delays, the irrelevant information may have decayed in WM (e.g., Logie et al., 2011) or may have been recoded verbally (Olivers et al., 2006), which explains why memory-based interference for the irrelevant feature was absent. Alternatively, it may be that top-down control increased with retention interval. Top-down control has been shown to decrease interference from the irrelevant attribute (Han & Kim, 2009).

In sum, previous research has suggested that attentional selection may be guided in an object-based manner. The principal finding was that features pertaining to an object guide attentional selection although they are irrelevant (Foerster & Schneider, 2018, 2019, 2020; Gao et al., 2016; Soto & Humphreys, 2009). The underlying assumption in these studies was that relevant and irrelevant features were stored in an integrated feature template. However, it may be that irrelevant features stored in separate feature templates have similar effects. In both cases, attentional selection would be guided to the object that matches relevant and irrelevant features. To determine whether guidance by the irrelevant feature depends on the integration of relevant and irrelevant features, we compared separate and combined presentation of the two features.

Experiment 1

In previous research, relevant and irrelevant features were always delivered as an integrated object (e.g., a "purple chair") and some studies observed guidance by the irrelevant feature of the object. However, it may be possible that the separate presentation of the two features has similar effects (e.g., *purple* and *chair*). To provide evidence for attentional guidance by separate feature templates, we compared a condition where the relevant and irrelevant features were combined in an object to a condition where they were presented separately. We used the paradigm developed by Foerster and Schneider (2018) with the exception that the shapes were randomly selected from a large database (see Kerzel & Andres, 2020). To separate color and shape, the relevant shape was presented in gray and the irrelevant color was shown on a surrounding ring (see Figure 1A). Guidance by integrated feature templates predicts little or no capture by the irrelevant color if color and shape are separated, whereas strong capture should be observed if they are combined. In contrast, guidance by separate feature templates predicts little difference between separate and integrated presentation. To measure guidance by the irrelevant color independently of the relevant shape, we compared the proportion of correct responses when the distractor was in the irrelevant color to a condition where the irrelevant color was absent from the choice display (i.e., distractor-match vs. no-match).

Method

Participants

First-year psychology students at the University of Geneva took part for class credit. We based the calculation of sample size on Foerster and Schneider (2018). Their Cohen's d_z for the difference between no-match and distractor-match conditions was >2 (see their Experiment 2), which requires a sample size of five (assuming α = .05 and power = .8) according to G*Power (Faul et al., 2009). We expected the difference between no-match and distractor-match conditions to be larger in the combined than in the separate condition. To test the differences between combined and separate presentation, we planned to use paired *t* tests. With a sample size of 13, we would be able to detect effect sizes of Cohen's d_z = .73 (assuming α = .05 and power = .8). Because the effect of color match was large ($d_z > 2$), we think that a Cohen's d_z of .73 for a difference in this effect is adequate, but we cannot know for sure. Thirteen students participated (four men; age: M = 20.5 years, SD = 1.5). All students reported normal or corrected-to-normal vision. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was given before the experiment started.

Apparatus

A 22.5-in. LED monitor (1,920 pixels × 1,200 pixels, 100 Hz; VPixx Technologies, Saint-Bruno, Canada) was used to present the stimuli. Colors and luminance were specified in xyY according to CIE1931. The xyY-coordinates of the red, green, and blue channels were R = (.674, .312, 25.7), G = (.095, .75, 56.3), and B = (.1, .094, 9). The coordinates of the white background were W = (.286, .359, 90.1). The monitor was gamma corrected according to measurements with a ColorCAL MKII colorimeter (Cambridge Research Systems, Rochester, Kent, United Kingdom). Viewing distance was maintained by a chin/forehead rest at 66 cm. We used a desktop-mounted EyeLink1000 (SR Research, Ontario, Canada) to record eye movements at 1 kHz. Saccades were detected with the standard settings for cognitive research (30°/s and 8000°/sec^2).

Stimuli

The target shapes were drawn from the image database presented in Brady et al. (2013), which is available at https://bradylab.ucsd.edu/stimuli.html. From the 540 images in the database, we deleted 30 because they were either odd (e.g., a bra) or contained text. To create purple, brown, green, and blue objects, we rotated the hue of the original images by −30°, 60°, 150°, and 240° in CIELAB-space (Fairchild, 2005; Witzel & Gegenfurtner, 2015, 2018).

In the memory display, the target shape was presented in the screen center. It was surrounded by a ring. The size of the ring was the same on every trial, while the target shape varied from trial to trial. Therefore, it seems unlikely that the ring was perceived as part of the object. In the combined condition, the shape was colored whereas the ring was gray. In the separate condition, the shape was gray whereas the ring was colored. The luminance of gray was set to 30.24 cd/m^2, which corresponded to the average luminance of the colors. The inner rim of the ring was at 1.4° from the center of the screen and the ring was drawn with a stroke width of .2°. In the saccadic choice display, a shape was shown on the left and right of central fixation at an eccentricity of 5.7° (center-to-center). While the size of the images was always 1.4° × 1.4°, the size of the shapes differed strongly. The fixation display contained only the black fixation cross (.4° × .4°) in the screen center.

Procedure

The procedure is shown in Figure 1A. The trial started with the presentation of the fixation display, followed by the memory display and a blank screen. Each of these displays was shown for .5 s. Then, the fixation display was presented randomly between .5 s and 1 s. Finally, the saccadic choice display appeared, and participants had to make a saccade to the target shape. The target shape was shown together with a distractor shape. Participants were told that the color of the two shapes was irrelevant and should be ignored. Participants were asked to respond rapidly without making too many errors. The choice display was extinguished .1 s after the eye landed within 1.4° of the center of the target image. If no saccade was detected until .5 s after onset of the choice display, the trial was cancelled. Further, we checked eye fixation before the choice display was shown. The choice display was only shown when eye fixation was within 1.4° of the fixation cross for at least .3 s. If no correct fixation could be determined until 5 s after onset of the fixation cross, the trial was canceled, and the eye tracker was recalibrated. We calibrated the eye tracker before the experimental trials and after blocks of 96 trials. Participants were familiarized with the task in two steps. First, participants performed the task with mouse clicks instead of saccades. Then, we calibrated the eye tracker and participants performed 10 to 20 practice trials with saccadic responses.

Design

The mode of color presentation was manipulated in two conditions (see Figure 1A). The irrelevant color in the memory display was either combined with the target shape or it was shown separately on the ring. The color match between memory and saccadic choice display was manipulated in three conditions (see Figure 1B). In the target-match condition (25% of trials), the target shape in the saccadic choice display was in the color from the memory display and the distractor was in a different color. In the distractor-match condition (25%), it was the other way around. In the no-match condition (50%), target and distractor shape were in colors different from the memory display.

For each mode of color presentation, there were 96 trials in the no-match condition, and 48 trials each in the target- and distractor-match conditions. In blocks of 192 trials, the target and distractor objects were selected randomly and without replacement from the 510 available shapes. The four colors and the two lateral target positions were equally likely. Participants worked through 384 trials.

Results

We removed the following errors in the indicated order. Anticipations (response times [RTs] shorter than 100 ms), late trials

Table 1
Error Percentages in Experiments 1, 2A, and 2B

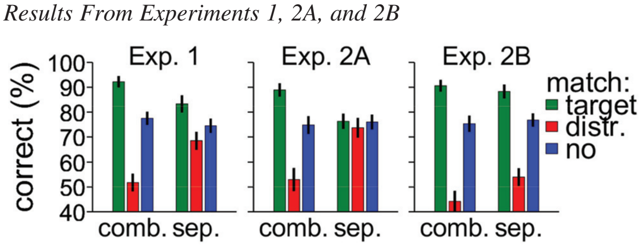
				Initial fixation		
Experiment	Anticipations	Late trials	No response	Imprecise	Delayed	Amplitude
1	5.5%	2.4%	1.5%	0.5%	0.6%	5.3%
2A	4.4%	3.6%	2.3%	1.4%	1.5%	3.5%
2B	3.2%	4.4%	4.6%	0.7%	0.9%	4.5%

(RTs longer than 350 ms), imprecise initial fixations (outside the 1.4° × 1.4° fixation window), delayed initial fixations (where it took longer than 2 s to identify a valid initial fixation), and amplitude errors (saccadic amplitudes smaller than half the eccentricity). Error percentages are reported in Table 1. Overall, 15.8% (*SD* = 10.5%) of trials were removed, ranging from 3% to 41%.

Figure 2 shows that relative to the no-match condition, more correct responses occurred when the target in the choice display matched the color from the memory display. More importantly, fewer correct responses occurred when the distractor matched the color from the memory display, suggesting that the irrelevant color guided attention to distractors that contained this color. However, the effect of color match was strongly attenuated with separate color presentation. To corroborate these observations, we first conducted an omnibus analysis of variance (ANOVA) on all conditions. The planned *t* tests between no-match and distractor-match conditions were carried out after obtaining a significant two-way interaction. A 2 (color presentation: combined, separate) × 3 (color match: target match, distractor match, no match) repeated-measures ANOVA yielded a significant main effect of color match, $F(2, 24) = 142.88$, $p < .01$, $\eta_p^2 = .923$, and a significant interaction, $F(2, 24) = 21.94$, $p < .01$, $\eta_p^2 = .646$. The interaction showed that the effect of color match was stronger when color and shape were combined than when they were separated. Planned *t* tests confirmed fewer correct responses in the distractor-match than the no-match condition. The difference was reliable when color was combined with shape in the memory display (52% vs. 78%), $t(12) = 8.81$, $p < .01$, Cohen's $d_z = 2.44$, and when color and shape were separate (68% vs. 75%), $t(12) = 2.96$, $p = .01$, Cohen's $d_z = .82$. Importantly, the difference between distractor-match and no-match conditions was larger in the combined than in the separate condition (difference of 26% vs. 6%), $t(12) = 5.00$, $p < .01$, Cohen's $d_z = 1.39$. The no-match condition did not differ significantly between combined and separate presentation (78% vs. 75%), $t(12) = 1.92$, $p = .08$, Cohen's $d_z = .53$.

Next, we subjected individual medians of saccadic RTs to the same 2 × 3 ANOVA. There was a significant main effect of color match, $F(2, 24) = 5.12$, $p = .01$, $\eta_p^2 = .299$, showing that RTs were shorter in the target-match (207 ms) than in the distractor-match (214 ms) or no no-match (213 ms) conditions. No other effect reached significance, $ps > .21$.

Figure 2
Results From Experiments 1, 2A, and 2B



Note. The percentage of correct responses refers to the percentage of saccades directed at the target shape. Means from the target-match, distractor-match and no-match conditions are shown for the two modes of color presentation (combined, separate). Error bars show the between-subject standard error of the mean. See the online article for the color version of this figure.

Discussion

We measured attentional guidance by an irrelevant feature stored either in integrated or separate feature templates. The target shape was presented at the start of a trial and had to be memorized until the saccadic choice display was presented. In the combined condition, the target shape was shown in the irrelevant color. In the separate condition, the target shape was gray, and the irrelevant color was shown on a surrounding ring. We observed that attentional guidance by the irrelevant color feature was strongly reduced when it was separated from the relevant target shape. This pattern of results is consistent with the idea that attention is guided by integrated feature templates, resulting in more saccades to objects containing the irrelevant color. In contrast, guidance of attention by separate feature templates is less efficient. However, alternative interpretations exist. Notably, it may be that encoding of the irrelevant color into WM was less likely when color was presented separately on the ring compared to when it was combined into a single object. Previous research on WM has suggested that whenever a relevant feature of an object is encoded into WM, the irrelevant features follow (Ecker et al., 2013; Saiki, 2016; Shen et al., 2013). Indeed, object-based attention may be necessary to maintain these representations (He et al., 2020; Matsukura & Vecera, 2009). Thus, separating color from shape may have prevented color from being encoded in WM so that the reduced attentional guidance by color comes as no surprise.

Experiments 2A and 2B

Thus, there are two possible explanations for the reduced attentional guidance by color with separate presentation of color and shape. The idea of object-based guidance holds that irrelevant features stored in integrated feature templates guide attention more efficiently than irrelevant features stored separately. The idea of object-based encoding, however, holds that color was less likely to be encoded into WM when it was not part of the task-relevant shape. As a result, color was unlikely to be stored in WM and trivially, no guidance of attention by color was observed.

To provide evidence for guidance by separately stored features, we forced participants to always remember the color presented in the memory display by probing it at the end of the trial. The additional color memory task ensured that color was retained with separate presentation. Reliable encoding may enable subsequent guidance by color even though color was not combined with shape in an object. We tested effects of the additional memory task in a between-subjects design to avoid carry-over of strategies.

Further, we slightly changed the displays to rule out alternative hypotheses. In Experiment 1, the ring was more eccentric than the shape. Therefore, it may have been possible that participants reduced the size of the attentional window (Belopolsky et al., 2007) to only focus on the central shape, which may explain why the effect of the surrounding color was reduced. To avoid effects of attentional window, we presented the color on a disk in the center while the target shape was presented randomly above or below fixation. Central presentation ensured that the disk was always in the focus of attention, at least at the start of the trial.

Method

Participants

Thirteen students (four men; age: $M = 20.5$ years, $SD = 2$) participated in Experiment 2A, and 16 participated in Experiment 2B (four men; age: $M = 22.8$ years, $SD = 3.6$). We increased the number of participants in Experiment 2B because the effect size for the additional color judgments was unknown, but we expect it to be smaller than for the saccade task. The sample size of 16 allows us to detect effect sizes of Cohen's $d_z = .65$.

Apparatus and Stimuli

The same apparatus and stimuli were used as in Experiment 1 with the exception that the ring in the memory display was replaced by a disk (radius of .5°). As shown in Figure 1A, the disk was always shown at central fixation, whereas the target shape was shown at an eccentricity (center-to-center) of 1.4° randomly above or below fixation. The irrelevant color in the memory display was either shown on the target shape (in the periphery) or on the disk (in the center). The presentation time of the memory display was reduced from .5 s to .2 s to prevent saccades to the target shape. In Experiment 2B, acceptable saccades to the target object were followed by a blank screen of .5 s. Then, a probe display appeared to test participant's memory for the color shown in the memory display. The probe display contained two colored squares (side length of .5°) presented at 1.5° to the left and right of fixation (center-to-center). Participants were asked to select a color by pressing the left or right mouse button. The probe display disappeared once a response was registered. The probe display contained the color from the memory display and a foil color selected from the choice display. In the target- and distractor-match conditions, the color from the memory display was shown with a new color in the choice display and the new color was used as foil. In the no-match condition, two new colors were shown in the memory display and the foil color was randomly selected among these colors. Because we had no basis for estimating the effect size for the color judgments, we decided to increase the reliability of individual means by increasing the number of trials in the theoretically relevant distractor-match condition. In Experiments 1 and 2A, 50% of the trials were no-match trials, but in Experiment 2B, we reduced this proportion to 33% to have an equal split between conditions (i.e., 33% target match, 33% distractor match, 33% no match). We consider this change minor because Foerster and Schneider (2018) showed that the effect of color match did not change across variations of trial composition. Thus, Experiment 2B had 64 trials in each of the six cells of the experimental design instead of 96 for the no-match and 48 for the distractor- and target-match conditions.

Results

In Experiment 2A, 16.8% ($SD = 9.8\%$) of trials were removed because of errors, ranging from 5% to 37%. In Experiment 2B, 18.4% ($SD = 8.8\%$) of trials were removed, ranging from 6% to 38%. Table 1 shows the percentages for each type of error.

Mean percentages of first saccades landing on the target shape are shown in Figure 2. A 2 (color memory task: absent in Experiment 2A, present in Experiment 2B) × 2 (color presentation: combined, separate) × 3 (color match: target match, distractor match, no match) mixed ANOVA was conducted. Besides other main effects and interactions, there was a significant three-way interaction, $F(2, 54) = 6.45$, $p < .01$, $\eta_p^2 = .193$. Inspection of Figure 2 suggests that the reason for the three-way interaction was that in the absence of the additional color memory task (Experiment 2A), the effect of color match was strongly attenuated when the color was separated from the target shape. This result replicates Experiment 1. When the color memory task was added in Experiment 2B, however, the effect of color match reemerged with separate presentation. To provide statistical evidence for these observations, we conducted separate mixed ANOVAs for each mode of color presentation.

The first ANOVA was conducted on conditions with combined color presentation, where the results appear unaffected by the presence of the color memory task. A 2 (color memory task: absent, present) × 2 (color match: no match, distractor match) mixed ANOVA showed that fewer correct saccades were made in the distractor-match than in the no-match condition (49% vs. 75%), $F(1, 27) = 91.58$, $p < .01$, $\eta_p^2 = .77$. The interaction of color memory task and color match was not significant, $F(1, 27) = 2.83$, $p = .10$, $\eta_p^2 = .1$, suggesting that neither changes in the proportion of trial types nor the additional memory task changed the results with combined color presentation.

The second ANOVA on the conditions with separate color presentation yielded a main effect of color match, $F(1, 27) = 41.2$, $p < .01$, $\eta_p^2 = .6$, and a significant interaction, $F(1, 27) = 27.35$, $p < .01$, $\eta_p^2 = .5$, showing that the difference between distractor-match and no-match condition increased when the color memory task was performed. To follow up on the significant interaction, we performed separate t-tests between distractor-match and no-match conditions. There was no difference without color memory task in Experiment 2A (74% vs. 76%), $t(12) = 1.4$, $p = .19$, Cohen's $d_z = .34$. Importantly, however, distractor-match and no-match conditions differed significantly with color memory task in Experiment 2B (54% vs. 77%), $t(15) = 7.2$, $p < .01$, Cohen's $d_z = 1.75$. Thus, the effect of color match reemerged with separate color presentation when color had to be retained in WM (difference of 2% vs. 23%). Further, the no-match condition did not differ, neither with nor without color memory task, *p*s > .43. The mean proportion of correct saccades in the no-match condition was 76%.

Next, the same 2 × 2 × 3 mixed ANOVA as above was conducted on individual median RTs. The effects of color match, $F(2, 54) = 8.35$, $p < .01$, $\eta_p^2 = .236$, and color presentation, $F(1, 27) = 3.17$, $p = .09$, $\eta_p^2 = .105$, were qualified by an interaction of color match and color presentation, $F(2, 54) = 4.15$, $p = .02$, $\eta_p^2 = .133$. With combined color presentation, RTs were shorter in the target-match (203 ms) than in the distractor-match (209 ms) or no-match (214 ms) conditions. This difference was attenuated with separate color presentation (target-match: 209 ms; distractor-match: 213 ms; no-match: 212 ms).

Finally, we evaluated performance on the additional memory task in Experiment 2B. Because performance was close to ceiling, we arcsine-transformed individual proportion correct for the ANOVA, but uncorrected percentages are reported for clarity. We conducted a 2 (color presentation: combined, separate) × 3 (color match: target match, distractor match, no match) within-subjects ANOVA. The color in the memory display was better recalled when it was combined with the target shape than when it was shown separately on the central disk (94.8% vs. 91.3%), $F(1, 15) = 9.3$, $p < .01$, $\eta_p^2 = .383$. No other effect reached significance (*p*s > .39).

Discussion

We tested whether the reduced effect of color match with separate color presentation was due to reduced encoding of color into WM. To this end, we compared performance in two groups of observers. One group performed the same task as in Experiment 1. The other group was asked to additionally remember the color presented at the start of the trial. Performance on the color memory task was close to perfect, showing that the color feature was reliably encoded into WM in this group of participants. With the additional memory task, the effect of irrelevant color on saccadic selection was comparable with separate and combined presentation. These results suggest that separate feature templates may efficiently guide attentional selection.

General Discussion

We tested whether attentional guidance by a task-irrelevant feature is restricted to integrated feature templates that combine relevant and irrelevant features into a single template or whether features stored separately may also guide attention. We used a paradigm where participants memorized a target shape, which they had to locate subsequently in a choice display by making a saccadic eye movement. In the initial presentation, the target shape was colored. In the subsequent choice display, either target or distractor shape could be in the initially viewed color. Although color was irrelevant for the saccade task (only shape was relevant), it was observed that saccades went frequently to distractors sharing the initially viewed color, showing that a task-irrelevant feature guided attentional selection (e.g., Foerster & Schneider, 2018, 2019, 2020; Kerzel & Andres, 2020). We separated the task-relevant shape from the task-irrelevant color by presenting the color on a separate and invariable shape. Experiment 1 showed that guidance by the irrelevant color was strongly reduced with separate compared with combined presentation. Experiment 2 showed that guidance by color with separate presentation may be reinstated by forcing participants to store the initially viewed color for later recall. Thus, guidance by separate feature templates is possible if the experimental procedure ensures that the irrelevant feature is encoded into WM. With combined presentation, the irrelevant feature is automatically transferred because of object-based encoding (Ecker et al., 2013; Saiki, 2016; Shen et al., 2013). With separate presentation, the irrelevant feature may not be encoded into WM, resulting in small and inconsistent effects on attentional guidance. A case in point is the comparison of Experiments 1 and 2A. In both experiments, we found less guidance by color with separate than with combined presentation. In Experiment 1, however, capture by the irrelevant color was reliable whereas it was not in Experiment 2A. Whereas the presence of capture in Experiment 1 attests to the encoding of the irrelevant color into WM, we do not know whether the irrelevant attribute was transferred into WM in Experiment 2A because memory for color was not probed. Lack of guidance may therefore arise from lack of encoding or from some other factor, such as the inefficient guidance by separately stored features.

Encoding Into WM Versus Priority in WM

We assumed that the encoding of the irrelevant feature is less efficient with separate presentation. However, it may also be that the maintenance of irrelevant features in WM depends on how they are stored. For instance, irrelevant features stored separately may be more strongly attenuated compared to irrelevant features stored together with a relevant feature. Evidence for feature-based changes of maintenance in WM comes from retro-cueing paradigms. In general, increasing the priority of a stored representation by retro-cues improves the precision of the representation (Souza & Oberauer, 2016). For objects with more than a single feature, the precision of individual features may improve through dimension-specific retro-cueing (Heuer & Schubö, 2017; Niklaus et al., 2017; Park et al., 2017; Ye et al., 2016). As a consequence, memory-based attentional capture may increase for the cued feature (Sasin & Fougnie, 2020). Conversely, it may also be possible to decrease the priority of representations in memory according to the relevance for the experimental task. Possibly, it is easier to decrease the priority of irrelevant features stored separately compared to features that are part of an object, which would account for the reduced attentional guidance by separate compared to combined features. However, more research on the precision of the memory representations in the current paradigm is necessary to assess this idea.

Temporal Succession of Feature- and Object-Based Selection

Our conclusion that attentional guidance may be based on both integrated and separate feature templates is supported by related research using an electrophysiological index of attentional selection, the N2pc. The N2pc is a negativity at posterior electrode sites contralateral to candidate target objects occurring between 200 ms and 300 ms after stimulus onset (Eimer, 1996; Luck & Hillyard, 1994; Zivony et al., 2018). Eimer and Grubert (2014) asked observers to indicate the presence of an object composed of two features, color and shape (see also Berggren & Eimer, 2018). Target objects with the correct combination of color and shape (e.g., a blue square) elicited large N2pc components. More interestingly, foils with only one feature matching the target object (e.g., a blue triangle or a red square) also elicited N2pc components. These N2pc components were smaller, but the sum of the N2pc components to feature-matching foils was equal to the N2pc component of the combined target object, at least between 200 ms and 250 ms after stimulus onset. In the subsequent interval from 250 ms to 300 ms, the N2pc to the target object was larger than the sum of feature-based components. These results suggest that there are two stages of spatially selective processing. In the feature-based stage, selection is controlled by separate feature modules whereas in the object-based stage, these signals are combined to yield object-based selection. The results from Experiment 2B are consistent with a feature-based stage of attentional selection. In Experiment 2B, the additional memory task ensured encoding of the irrelevant color feature into WM. Once encoded, color guided attentional selection although it was not part of the object. Possibly, feature-based selection was favored by the short-latency saccades in the current study because the saccadic latency of ∼200 ms corresponds to the onset of the feature-based stage in work on the N2pc (Berggren & Eimer, 2018; Eimer & Grubert, 2014).

Reinterpretation of Previous Results

Further, the different encoding and maintenance of irrelevant features in WM may explain past discrepancies in the literature. In some studies, attentional guidance by an irrelevant feature that was combined with a relevant feature in the same object was absent (Olivers, 2009, Experiment 4), whereas it was present in other studies (Gao et al., 2016; Soto & Humphreys, 2009). A similar discrepancy was observed with separate presentation in Experiments 1 and 2A. We suggest that these discrepancies may result from differences in the storage of the irrelevant feature, which are difficult to evaluate because there is no independent measure to ascertain the storage of the irrelevant feature. If guidance by the irrelevant feature occurred, it is safe to conclude that it was stored in WM. If guidance by the irrelevant feature was absent, there is ambiguity about the cause. One possible cause for the absence of guidance is that the irrelevant feature was never encoded into WM or was forgotten. For instance, long retention intervals, as in Olivers (2009) or Olivers et al. (2006), may promote the decay of the irrelevant information (e.g., Logie et al., 2011). Another reason for the absence of guidance may be that the irrelevant feature did not act as attentional template although it was encoded into WM. However, the present investigation tested whether irrelevant features only guide attention if they are part of an integrated feature template but found no support for this idea. That is, Experiment 2B showed that the integration of irrelevant features into an object is not necessary for the guidance of attentional selection. Both integrated objects and separate features in WM can drive attentional selection. However, encoding into WM is a necessary condition for guidance and encoding may be less reliable with separate than with combined features. Thus, future studies need to consider the possibility that lack of guidance was in fact due to lack of encoding.

Memory Advantage for Objects

In Experiment 2B, the color memory task showed that memory for color was better when color was combined with shape to form an object than when color was presented separately. This finding is reminiscent of the object benefit in research on WM. Luck and Vogel (1997) reported that memory performance for objects with one feature was identical to performance with multiple features, in support of models that conceptualize the capacity of WM as a fixed number of discrete units (Luck & Vogel, 2013) instead of flexible resources (Ma et al., 2014). However, the advantage for features stored in objects was replicated in some studies (Luria & Vogel, 2011), but not in others (Olson & Jiang, 2002; Wheeler & Treisman, 2002; Xu, 2002b). Possibly, the object benefit is contingent on perceptual factors, such as objecthood, and the structure of objects and surfaces (Balaban & Luria, 2016; McDunn et al., 2020; Xu, 2002a), as well as task demands (Chen et al., 2021). Here, we find a small advantage of color-shape conjunctions over separate features in Experiment 2B, which is in line with the previous literature (e.g., Xu, 2002a). However, the central claim of the current article is that the irrelevant color is more efficiently transferred to WM when it is part of the object containing the response-relevant feature. In this sense, the selection bias may serve as a measure of encoding into WM for a feature that cannot be probed because it is irrelevant. That is, guidance by an irrelevant feature may reveal that it has been encoded into WM without explicit memory test.

Relation to Dual Target Search

Our conclusion that attentional selection is based on separate features and not necessarily on integrated objects is consistent with research showing that participants are able to search for several features at the same time (reviewed in Huynh Cong & Kerzel, 2021; Ort & Olivers, 2020). In dual target search, two features are relevant, whereas only a single feature was relevant in the present study. For instance, numerous studies have shown that participants can establish attentional templates for two colors (Ansorge et al., 2005; Beck et al., 2012; Berggren et al., 2020; Grubert & Eimer, 2015, 2016; Huynh Cong & Kerzel, 2020; Kerzel & Witzel, 2019; Kim et al., 2019; Moore & Weissman, 2010; Roper & Vecera, 2012). In these studies, the colors were presented on separate objects to establish two attentional templates. Therefore, it seems plausible that attentional guidance can also be achieved when color and shape are stored separately in WM. However, one previous study concluded that attentional selection was impaired for color-shape conjunctions compared to color-color conjunctions (Biderman et al., 2017). Possibly, this discrepancy was caused by the cue-target paradigm in Biderman et al. (2017) where it may have been difficult to convey shape information together with color information because of the short presentation times for the cue, which was rapidly followed by the target. In search paradigms with few target objects, however, it seems that efficient search can be achieved for color-shape conjunctions (Berggren & Eimer, 2018; Eimer & Grubert, 2014).

Priming Versus Working Memory

We attribute the guidance of attention by the irrelevant attribute to separate feature templates stored in WM. Alternatively, one may conceptualize these effects as priming (e.g., Fecteau, 2007;

Klotz & Neumann, 1999), where exposure to the memory display influenced responses to the subsequent target/distractor stimuli. In related research, it was observed that the discrimination of irrelevant color words was sufficient to establish an attentional template for the color designated by the word (Ansorge & Becker, 2012). However, one key property of priming is that it arises without conscious guidance or intention. We have no data to decide whether the influence of the irrelevant color on search in our experiments was conscious or unconscious. However, effects of the additional memory task in Experiment 2B reflect a conscious task requirement, so that we think it is more appropriate to consider the results in relation to WM and not priming. On the other hand, it is clear that participants easily forget features (Chen & Wyble, 2015) even when presented in the fovea (Born et al., 2020), which may suggest a link to the priming literature.

Conclusion

In sum, we investigated whether guidance by irrelevant features depends on their integration with a relevant feature into an integrated feature template. We manipulated the presentation of the irrelevant color. The color was either combined with the relevant shape (i.e., a "purple chair") or it was presented separately (i.e., a gray *chair* surrounded by a *purple* ring). Guidance by the irrelevant feature was enhanced for integrated compared to separate templates. However, the reason for the reduction was not that separate feature templates provide less guidance than integrated feature templates. Rather, the irrelevant feature may not be encoded into WM to begin with. If encoding was ensured by an additional memory task, guidance was also observed for irrelevant features stored separately (i.e., *purple* can guide attention; it does not have to be a "purple chair").

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