



Object features reinstated from episodic memory guide attentional selection

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ABSTRACT

When observers search for an object in the environment, they compare the incoming sensory information to the attentional template, a representation of the target in visual working memory (VWM). Previous studies have shown that visual search is more efficient when the attentional template is precise. We pursued the hypothesis that the attentional template in VWM is automatically complemented by features from long-term memory, possibly to increase its precision. At the beginning of the experiment, observers learned associations between shape and color. Then, we tested whether selecting one of these shapes was influenced by the previously associated color. To this end, we ran a saccadic selection task consisting of a memory and choice display. In the memory display, the target shape was presented at central fixation and participants were instructed to foveate this shape in the subsequent choice display. In the choice display, the target shape appeared together with a distractor shape at eccentric positions. Importantly, the target shape was colorless (gray) in the memory display so that only shape, but not color was loaded into VWM. However, saccades went more frequently to the target shape when it was shown in the learned color than when this color was shown in the distractor. Thus, the color of the target shape was reinstated from episodic memory to complement the attentional template in VWM.

1. Introduction

In order to locate a target during visual search, the incoming sensory information is continuously matched to the stored representation of the target features, which is referred to as attentional template (Duncan & Humphreys, 1989) or target template (Vickery, King, & Jiang, 2005). When a match between sensory input and attentional template is detected, the corresponding object is selected by attention for in-depth processing. Most theories assume that the attentional template is stored in visual working memory (Bundesen, 1990; Carlisle, Arita, Pardo, & Woodman, 2011; Duncan & Humphreys, 1989; Geng & Witkowski, 2019; Hout & Goldinger, 2015; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Schneider, 2013). Classic theories propose that the content in working memory can be retrieved from long-term memory (Baddeley, 2010). Consistently, the attentional template can be constituted based on verbal labels, which require observers to retrieve target features from semantic memory (Castelhano, Pollatsek, & Cave, 2008; Schmidt & Zelinsky, 2009; Vickery et al., 2005; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004; Yang & Zelinsky, 2009). Compelling evidence for attentional guidance by target features retrieved from semantic memory was provided by Yang and Zelinsky (2009) who observed that first eye movements were directed at the target object with above-chance probability, even though only the target category was known. While attentional templates can be based on

verbal labels, search is less efficient than when the target is specified by a visual image. The reason is that verbal labels provide less visual information than an image (Castelhano et al., 2008; Hout & Goldinger, 2015; Schmidt & Zelinsky, 2009; Vickery et al., 2005; Wolfe et al., 2004; Yang & Zelinsky, 2009). In a similar vein, Hout and Goldinger (2015) showed that targets corresponding exactly to the previewed search cue (e.g., a red coffee mug) were found faster than targets oriented differently or targets with a feature that did not match the search cue (e.g., a blue coffee mug). Thus, imprecise or inaccurate features in the attentional template decrease search efficiency (see also Jenkins, Grubert, & Eimer, 2018; Malcolm & Henderson, 2009; Nako, Wu, Smith, & Eimer, 2014).

In the current study, we pursue the idea that target features available in long-term memory are automatically reinstated in VWM to complement the attentional template. As laid out above, increasing the precision of the attentional template increases search efficiency. Therefore, it would be advantageous to complement the attentional template by information pertaining to the target. This idea is plausible given that entire target templates can be constructed based on information from long-term memory (i.e., verbal labels or semantic categories). For instance, when searching for a key on a cluttered desk, search is probably based on the typical shape of a key retrieved from long-term memory. However, search efficiency may be improved by retrieving other features of the key, for instance its color.

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As a tool to answer our research question, we measured interference by target features reinstated from long-term memory into VWM. One example of memory-based interference comes from the additional singleton paradigm developed by Theeuwes (1991). In the additional singleton paradigm, participants search for a shape-defined target and on some trials, a salient color distractor is shown. RTs increase when the color distractor is present, suggesting that the distractor captured attention despite being irrelevant (Theeuwes, 2010; but see Büsel, Voracek, & Ansorge, 2018; Gaspelin & Luck, 2018; Lamy, Leber, & Egeth, 2012; Liesefeld & Müller, 2019). When participants kept a color in VWM during the search task, capture increased when the distractor color matched the color stored in VWM (Olivers, Meijer, & Theeuwes, 2006), suggesting that attention was automatically guided by the contents of working memory. Memory-based capture has been replicated in many studies (e.g., Bahle, Beck, & Hollingworth, 2018; Hollingworth & Beck, 2016; Jung, Han, & Min, 2019; Kerzel & Witzel, 2019; Kim & Cho, 2016; van Moorselaar, Theeuwes, & Olivers, 2014; Whitehead, Ooi, Egnér, & Woldorff, 2019) (reviewed in Olivers et al., 2011; Soto, Hodson, Rotshtein, & Humphreys, 2008). Most of the studies on memory-based attentional capture focused on capture by individual features stored in VWM and there is some controversy as to whether all features of an object encoded in VWM guide attention. For instance, Olivers et al. (2006) asked observers to retain one of two possible object features for later recall. Memory-based attentional capture in the search task was reliable only for the retained feature, suggesting that object features in the memory display were processed individually (see also Sala & Courtney, 2009). In contrast, Gao et al. (2016) proposed that encoding of perceptual information in VWM is object-based, resulting in memory-based capture by all features of an object, even those that did not have to be retained for later recall (see also Soto & Humphreys, 2009). Possibly, the discrepancy between studies was caused by different retention intervals, with longer retention intervals favoring feature- over object-based representations (Gao et al., 2016).

More evidence for object-based guidance of attention by VWM comes from studies by Foerster and Schneider (2018, 2019a, 2019b), who used saccadic selection instead of search times to investigate memory-based attentional capture. In their studies, observers were first presented with a colored shape in the center of the memory display. Instead of geometric shapes, the authors used the shapes of real-world objects, such as a bucket or a baby bottle. After a retention interval, two lateral shapes were shown in the choice display and participants were instructed to look at the shape from the memory display. The shapes in the memory and choice display were colored, but color was irrelevant for the task and participants were instructed to ignore it. However, the results showed that saccadic selection was more accurate when the target shape in the choice display was shown in the same color as in the memory display. Conversely, more saccades went to the distractor shape when it was shown in the color of the target shape from the memory display. Thus, the irrelevant color of the target object biased saccadic target selection. Because of the close link between attention and saccades (Deubel & Schneider, 1996; Kowler, Anderson, Doshier, & Blaser, 1995; Schneider, 1995), saccadic selection is likely to reflect the same underlying mechanism as changes in search times attributed to attentional capture.

We used the paradigm developed by Foerster and Schneider (2018, 2019a, 2019b) to investigate whether features associated with the target in long-term memory bias saccadic selection even though they have not been loaded into VWM and are irrelevant to the task. To avoid inter-individual differences in the features associated with an object, we used a learning procedure to associate each target shape with one of four colors. The color-shape associations were therefore stored in episodic and not semantic memory (Tulving, 2002). As the number of color-shape associations that can be reliably learned in a short time is limited, only a small number of trials would be available for testing memory-based interference. We reasoned that finding significant results with few trials requires strong interference. Because effect sizes in Foerster and Schneider (2018) were very large (Cohen's $d_z > 2$), their paradigm seemed ideally suited for our purpose.

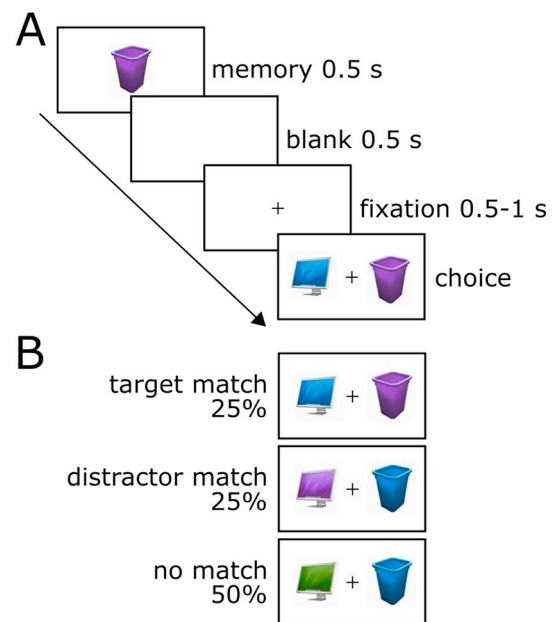


Fig. 1. Time course (panel A) and main conditions (panel B) in Experiment 1. The color of the target shape in the memory display was irrelevant. Participants were instructed to select the target shape in the choice display by making a saccade or by clicking on the spatially corresponding mouse button. In 25% of the trials, the color of the target shape in the choice display matched its color in the memory display (target-match condition). In another 25% of the trials, the color of the distractor shape in the choice display matched the color in the memory display (distractor-match condition). In 50% of the trials, neither color in the choice display matched to the color from the memory display (no-match condition).

2. Experiment 1

Experiment 1 served to replicate the results from Foerster and Schneider (2018) with our stimulus set (see Fig. 1). Foerster and Schneider (2018) had only four different objects, but we needed many more to test effects of episodic memory. Therefore, we presented new objects on each trial, but closely replicated the procedure from Foerster and Schneider (2018). The target shape was presented in the memory display and participants were asked to retain its shape, but to ignore its color. After a retention interval, a choice display with the target shape and a distractor shape appeared. Participants were asked to make a saccadic eye movement to the shape from the memory display. There were three main conditions. In the target-match condition (96 trials), the target in the choice display was shown in the same color as in the memory display and the distractor in a new color. In the distractor-match condition (96 trials), the distractor was shown in the target color from the memory display and the target was shown in a new color. In the no-match condition (192 trials), both shapes were shown in a new color. In addition to the saccadic selection task, we also ran a version of the task with manual selection to confirm that the underlying mechanism was attentional and not specific to oculomotor control. Instead of looking at the lateral target shape, observers were asked to click on the spatially corresponding mouse button while maintaining fixation. We expect RTs to be longer in the distractor-match condition than in the target-match condition.

2.1. Methods

2.1.1. Participants

Students at the University of Geneva participated for class credit. Sample size was based on effect sizes in Foerster and Schneider (2018). Their Cohen's d_z was larger than 2, which requires a sample size of five with an alpha of 0.05 and a power of 0.95. While we aimed for eight

participants (as in Foerster and Schneider (2018)), difficulties in the scheduling of participants sometimes led to larger sample sizes. Ten students participated in the saccade task (2 male, age: $M = 20.3$ years, $SD = 2.7$) and nine participated in the mouse task (2 male, age: $M = 20.4$ 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.

2.1.2. Apparatus

Stimuli were displayed on a 22.5-inch LCD monitor at 100 Hz with a resolution of 1920×1080 pixels (VIEWPixx Light, VPixx Technologies Inc., Canada), driven by an AMD Radeon HD 7470 graphics card with a color resolution of eight bits per channel. CIE1931 chromaticity coordinates and luminance (xyY) of the monitor primaries were $R = (0.6735, 0.3124, 25.7)$, $G = (0.0945, 0.7504, 56.3)$, and $B = (0.6734, 0.3124, 25.7)$. The white-point of CIELAB was xyY = (0.2856, 0.359, 90.1), which corresponds to chromatic adaptation and maximum lightness. Gamma corrections were applied based on the measured gamma curves of the monitor primaries. Colors were measured with a Cambridge Research Systems ColorCAL MKII colorimeter. Head position was stabilized with a chin/forehead rest at a viewing distance of 80 cm. Eye-movements were recorded at a sampling rate of 1000 Hz using the desktop-mounted EyeLink1000 (SR Research, Ontario, Canada). The standard EyeLink saccade criteria for cognitive research were used (i.e., velocity of $30^\circ/s$ and acceleration of $8000^\circ/sec^2$).

2.1.3. Stimuli

The pictures were taken from the collection presented in Brady, Konkle, Gill, Oliva, and Alvarez (2013), which can be downloaded at <https://bradylab.ucsd.edu/stimuli.html>. The objects were largely in a single color. Because natural objects are mostly composed of various colors (Witzel & Gegenfurtner, 2018), the images looked artificial. In other words, a match between one of the four selected colors and a natural color distribution was improbable. Thus, it was unlikely that an object would resemble its representation in semantic memory. We removed 30 shapes that were highly memorable (e.g., a bra) or contained letters, reducing the number of available shapes to 510. The shapes were rendered in CIELAB-space. CIELAB space was used because distances in CIELAB space approximate perceived color differences (Fairchild, 2005; Witzel & Gegenfurtner, 2015, 2018). The hue in the original images corresponded to brownish red. We calculated four versions of the originals by rotating the hue of the originals by -30° , 60° , 150° , and 240° without changing luminance. The resulting colors were purple, brown, green, and blue.

There were three display types besides a blank screen. In the memory display, a single shape was shown in the center of the display. In the choice display, two shapes were shown at 5.7° (center-to-center) to the left and right of the fixation cross in the center of the display. The size of each image was $1.4^\circ \times 1.4^\circ$, but the area covered by the shape varied from picture to picture. In the fixation display, only the fixation cross was shown. The size of the fixation cross was 0.4° . The stimuli were shown on a white background of 90.1 cd/m^2 .

2.1.4. Procedure

A trial started with the presentation of the fixation mark for 0.5 s (see Fig. 1A). Then, the memory display was shown for 0.5 s. After a blank interval of 0.5 s, the fixation cross reappeared for a randomly determined period between 0.5 and 1 s. Finally, the choice display was shown until a response was registered. The choice display contained the target shape from the memory display and a distractor shape. Participants were asked to select the target shape in the choice display while ignoring its color. They were instructed to respond as rapidly and accurately as possible. Two response modes were tested, saccadic selection and selection by mouse click. Each task was preceded by some practice trials.

2.1.5. Saccade task

In the interval before the onset of the choice display, eye fixation was checked. Eye gaze had to be within 1.4° of central fixation for 0.3 s or the choice display would not be shown. If eye gaze was not in the critical region around central fixation, the program waited for a maximum of 5 s to find a valid interval. Otherwise, the trial was aborted and recalibration was initiated. After successful fixation, the choice display was shown and participants were asked to look at the picture with the object they had seen in the memory display. The choice display disappeared once participants fixated the correct shape for at least 0.1 s. A saccade had to occur within 0.5 s after onset of the choice display. Otherwise, the trial was aborted. The eyetracker was calibrated at the beginning and after blocks of 96 trials.

2.1.6. Manual task

Participants were asked to press the mouse button (left or right) corresponding to the location of the target image. Eye fixation had to be maintained from the onset of the choice display until mouse click. The mouse click had to occur within 1 s and terminated the choice display. No feedback was given.

2.1.7. Design

There were three conditions relating to the match between the color in the memory display and the colors in the choice display (see Fig. 1B). In target-match and distractor-match conditions, the color in the memory display matched either the target (25%) or the distractor (25%), respectively. The color of the other object in the choice display was randomly selected from the three remaining colors. In the no-match condition (50%), the color in the memory display matched neither target nor distractor in the choice display. Colors in the choice display were selected from the three available colors without replacement.

Participants worked through two blocks of 192 trials. In each block, 192 target and 192 distractor objects were randomly drawn without replacement from the 510 shapes in the database. Thus, a different target-distractor pair was shown on each trial of a block. The four colors were equally likely to be drawn as target color in the memory display. Left and right target positions were balanced.

2.2. Results

The data for all experiments are available in the open science framework at https://osf.io/bfng8/?view_only=010b4df6aa5c4662a15309e048061456

2.2.1. Saccade task

Trials with the following error types were removed in the order of enumeration: trials with saccadic reaction times shorter than 0.1 s (4.6%) or longer than 0.35 s (1.8%), trials without a saccadic response (1.7%), trials with starting points of the first saccade outside the fixation window (1%), trials where it took longer than 2 s to find a 0.3 s fixation window (1.4%) and trials with saccadic amplitudes less than half the target eccentricity (2.7%). Overall, 13.2% ($SD = 7.3\%$) of trials were removed, ranging from 1% to 40%.

As shown in Fig. 2 (upper left panel), the proportion of first saccades landing on the target shape depended strongly on its color. When the color of the target shape in the choice display matched its irrelevant color in the memory display, 92.6% of first saccades landed on the correct shape. When the color of the distractor shape in the choice display matched the color from the memory display, the percentage of first saccades landing on the target dropped to 53.9%. When neither the target nor the distractor shape in the choice display matched the color in the memory display, the percentage of correct saccades was intermediate with 79.4%. A one-way ANOVA on the three conditions (color match: target match, distractor match, no match) showed a significant main effect, $F(2, 18) = 91.61, p < .001, \eta_p^2 = 0.911$. Follow-up t -tests

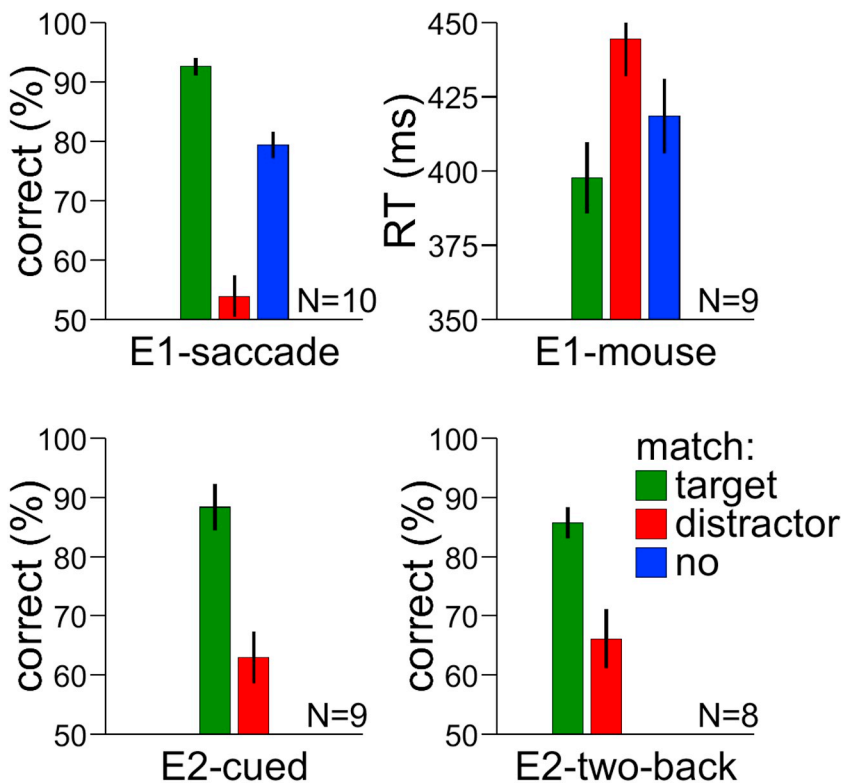


Fig. 2. Results from Experiments 1 and 2. In the saccade condition of Experiment 1 (E1-saccade), the main dependent variable was the percentage of saccades directed at the target shape (% correct). Means from the target-match, distractor-match and no-match conditions are shown. In the mouse condition of Experiment 1 (E1-mouse), reaction times of the mouse click were the main dependent variable (RTs in ms). In Experiment 2, the saccadic selection task was run on the target-match and distractor-match conditions. Results are shown for the group with cued recall (E2-cued) and two-back task (E2-two-back). Error bars show the standard error of the mean.

confirmed a significant difference between the target-match and distractor-match conditions (difference of 38.7%), $t(9) = 10.59$, $p < .001$, Cohen's $d_z = 3.35$.

We calculated individual medians of saccadic RTs. RTs were shorter when the color of the target shape matched its irrelevant color from the memory display (206 ms) than when the distractor color matched (211 ms) or no color matched (215 ms). The same one-way ANOVA as above revealed a significant main effect of color match, $F(2, 18) = 5.72$, $p = .012$, $\eta_p^2 = 0.389$. The difference between the target match and distractor match conditions approached significance (difference of 5 ms), $t(9) = 2$, $p = .076$, Cohen's $d_z = 0.63$.

2.2.2. Mouse task

Trials with breaks of fixation (9.7%) or late responses (slower than 1 s, 0.3%) were excluded. A one-way ANOVA (match to the color in the memory display: target-match, distractor-match, no-match) on individual median RTs revealed a significant effect, $F(2, 16) = 42.74$, $p < .001$, $\eta_p^2 = 0.842$. As shown in Fig. 2 (upper right panel), RTs were shortest in the target-match condition (398 ms), intermediate in the no-match condition (419 ms) and longest in the distractor-match condition (444 ms). The target-match and distractor-match conditions were significantly different (difference of 47 ms), $t(8) = 7.46$, $p < .001$, Cohen's $d_z = 2.49$. Running the same ANOVA on the percentage of choice errors also revealed a significant effect, $F(2, 16) = 5$, $p = .021$, $\eta_p^2 = 0.385$. Fewer choice errors occurred in the target-match (2.2%) than in the distractor-match (7.5%) condition. By paired t-test, this difference was significant, $t(8) = 2.51$, $p = .036$, Cohen's $d_z = 0.84$. The percentage of choice errors in the no-match condition was intermediate (3.3%).

2.3. Discussion

We replicated the results from Foerster and Schneider (2018) with our stimulus set. In the saccade task, correct target selection was facilitated when the target in the choice display appeared in the same color as in the memory display, although color was irrelevant.

Conversely, target selection was impaired when the target in the choice display was shown in a new color and the distractor was shown in the color from the memory display. These results are consistent with the notion that encoding of perceptual information in VWM is object-based (Foerster and Schneider, 2018, 2019a, 2019b; Gao et al., 2016; Soto & Humphreys, 2009). The design of the experiment provided no incentive to use color to find the target shape, yet color had a strong effect. Therefore, it is unlikely that participants made strategic use of color and the many control experiments by Foerster and Schneider (2018) corroborate this point. Rather, effects of color were automatic and involuntary. Further, we found a pattern of RTs in the mouse task that mirrored results from the saccadic selection task, showing that the mechanism underlying saccadic choice errors is attentional, and not specific to saccadic control. Consistent with this conclusion, Foerster and Schneider (2019b) found similar results with masked displays and the accuracy of letter identification as dependent measure. Finally, the current set of experiments was concerned with oculomotor capture when color was irrelevant while shape was relevant. The question arises whether similar effects may be obtained when the roles of color and shape are swapped. According to Foerster and Schneider (2019a), the answer to this question depends on the discriminability of target and distractor features, not on the choice of target and distractor features per se. Oculomotor capture occurs reliably when the irrelevant feature is highly discriminable, while the relevant feature is only moderately discriminable, regardless of feature.

3. Experiment 2

After having established that our methods yield large memory-based interference, we proceed to the main experiment where the task-relevant shape in the memory display of the saccadic selection task was shown in gray. That is, we loaded a colorless shape into VWM. The question was whether memory-based interference would result from the irrelevant color associated with the shape in episodic memory. If so, attention was guided by object features reinstated from episodic memory. To associate each shape with one of four possible colors in

episodic memory, two different learning procedures were employed. In the color-shape association task, participants viewed the 64 colored shapes once in the learning phase before being asked to indicate the color of each shape in the test phase. In the two-back task, participants viewed the 64 colored shapes (plus 10 repetitions) and indicated when a stimulus was repeated. The former task solicits explicit memory mechanisms, while the latter task promotes implicit learning of color-shape associations. The association task and the two-back task were repeated five times to ensure reliable transfer to episodic memory. In the following saccadic selection task, the target shape was shown in gray in the memory display, but both the target and the distractor shape were colored in the choice display. In the target-match condition (32 trials), the target shape was shown in the memorized color whereas the distractor object was shown in a random color. In the distractor-match condition (32 trials), the distractor shape was shown in the memorized color of the target shape whereas the target shape was shown in a random color. If the memorized color of the target shape was automatically reinstated into VWM to complement the attentional template, more correct saccades should be found in the target-match than in the distractor-match condition. However, there was no incentive to attend to (or inhibit) color because color was non-predictive. Effects of color therefore reflect involuntary or automatic processing.

3.1. Methods

3.1.1. Participants

Nine students participated in the color-shape learning task (1 male, age: $M = 19.8$ years, $SD = 1.4$) and eight participated in the two-back task (1 male, age: $M = 20.6$ years, $SD = 2.8$).

3.1.2. Apparatus and stimuli

The same apparatus and stimuli were used as in Experiment 1 with the exception that a gray-scale version of each image was created. Gray differs from the other colors in saturation, whereas the other colors had the same saturation, but differed in hue. For each participant, 64 images were randomly selected from the database. The color of each image was randomly determined with the constraint that each color was equally represented.

3.1.3. Procedure

Participants were familiarized with the choice task in the same way as in Experiment 1 with the exception that the shapes in the memory and choice displays were gray. Then, participants performed five learning blocks. Finally, the saccadic selection task was performed with a gray memory display and a colored choice display where either the target shape or the distractor shape was shown in the learned color of the target shape. The procedure is illustrated in Fig. 3.

Two different learning tasks were administered to two different groups of participants. In both tasks, the 64 colored shapes were presented once in each of five learning blocks.

In the **color-shape association task**, each learning block consisted of a learning phase followed by a test phase. In the learning phase, the 64 colored shapes were presented in random order. Each shape was presented for 2 s in the center of the screen and separated by a blank 1-s interval from the following shape (Fig. 3A). Participants were asked to memorize the color-shape association. The learning phase was followed by a test phase, where each shape was shown in gray and participants were asked to select the associated color (Fig. 3B). To indicate the color, a panel with the four possible colors was shown 1.8° below the gray image. The panel consisted of 4 colored squares with 0.5° side length separated by 2.5° (center-to-center). The four colors were mapped onto the spatially corresponding keys j, k, l, and é on a Swiss-French keyboard. Participants responded with the fingers of their right hand. After pressing a key, the button corresponding to the selected color was highlighted by slightly increasing the size of the corresponding square (from 0.5° to 0.6°). At the same time, written feedback indicated

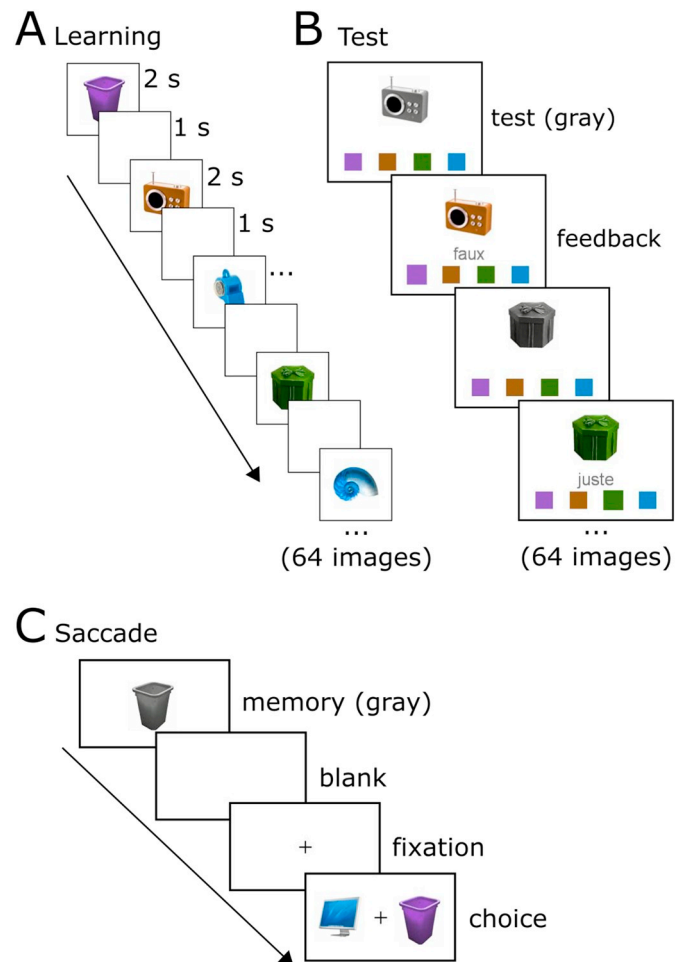


Fig. 3. Procedure in the cued recall task of Experiment 2. In the learning phase of each learning block, participants saw a series of 64 color-shape pairs (panel A). In the subsequent test phase (panel B), the learned shapes were shown in gray and participants indicated the memorized color. Feedback was given (wrong = “faux”, correct = “juste”) and the correct color was indicated. After five learning blocks, the saccade task from Experiment 1 was run, but with a gray memory display (panel C). Target-match and distractor-match conditions were determined with respect to the learned color of the target shape. Here, a target-match trial is shown because the color of the target corresponds to the learned color.

whether the answer was correct and the color of the shape turned from gray to the correct color. The feedback was presented for 1 s.

In the **two-back task**, participants were asked to indicate whether the current object matched the one from two steps earlier in the sequence. Each object was presented for 2 s in the center of the screen and separated by a blank 1-s interval from the following object. Participants had to respond while the stimulus was on the screen. Therefore, the maximal response latency was 2 s. There were ten repetitions per learning sequence. The order of presentation was random, but the order of repetitions was constrained. First, successive repetitions were separated by at least two images to avoid ambiguity. Second, the maximum number of presentations without repetition was limited to 14 to keep participants alert. Visual feedback was given for missed repetitions and false alarms.

The **saccadic choice task** was as in Experiment 1 with the exception that the target shape in the memory display was gray (see Fig. 3C). All 64 shapes from the learning phase were used as targets. Randomly selected new shapes served as distractors. While the target shape in the memory display was gray, both target and distractor shapes in the choice display were colored. Either the color of the target or distractor matched the color of the target shape from the learning phase. The

other color was randomly drawn from the remaining three colors. There were 32 target-match and 32 distractor-match trials. The no-match condition from Experiment 1 was omitted.

3.2. Results

3.2.1. Learning phase

By one-way ANOVA, performance on the color-shape association task increased from the first to the fifth block, $F(4, 32) = 73.38$, $p < .001$, $\eta_p^2 = 0.902$. The percentages of correct responses were 56.8%, 78.3%, 90.5%, 93.1% and 96.7%.

In the two-back task, we analyzed the percentage of false alarms and missed repetitions per block. Neither ANOVA yielded a significant effect of block ($ps > .104$). The mean percentage of false alarms per block was 1.4% and the mean percentage of missed repetitions per block was 7.3%.

3.2.2. Saccadic choice task

Trials with the following errors were successively removed. Trials with saccadic reaction times shorter than 0.1 s (association: 2.1%, two-back: 2%) or longer than 0.35 s (association: 4.5%, two-back: 1.8%), trials without a saccadic response (association: 2.1%, two-back: 1%), trials with starting points of the first saccade outside the fixation window (association: 0.2%, two-back: 0.4%), trials where it took longer than 2 s to find a 0.3 s fixation window (association: 0.2%, two-back: 0.4%) and trials with saccadic amplitudes less than half the target eccentricity (association: 3.1%, two-back: 7%). Overall, 12.2% ($SD = 8.6\%$) of trials were removed in the group with the association task (range: 5% to 30%) and 12.5% ($SD = 12.2\%$) in the group with the two-back task (range: 0% to 36%).

Results from the saccadic choice task are shown in Fig. 2. In the group with the color-shape association task (lower left panel of Fig. 2), the percentage of saccades to the correct shape was higher when the target shape was in the learned color than when the distractor was in the learned color (target-match vs. distractor-match: 88.3% vs. 62.9%, difference of 25.5%), $t(8) = 4.94$, $p = .001$, Cohen's $d_z = 1.65$. Saccadic latencies tended to be shorter in the target-match than in the distractor-match condition (224 vs. 233 ms), $t(8) = 2.04$, $p = .075$, Cohen's $d_z = 0.68$.

In the group with the two-back task (lower right panel of Fig. 2), results were similar. The percentage of saccades to the correct shape was higher in the target-match than in the distractor-match condition (85.7% vs. 66.1%, difference of 19.6%), $t(7) = 4.92$, $p = .002$, Cohen's $d = 1.74$. Saccadic latencies tended to be shorter in the target-match than in the distractor-match condition (191 vs. 197 ms), $t(7) = 2.27$, $p = .057$, Cohen's $d_z = 0.80$.

3.3. Discussion

We associated shapes with colors in the learning phase and tested whether the memorized color would interfere with saccadic selection. Importantly, only the target shape was loaded into VWM immediately before the selection task. We found that saccadic selection was strongly biased by the remembered color, regardless of whether transfer to episodic memory was explicit (cued-recall procedure) or implicit (two-back task). Saccades went more frequently to the distractor when it was shown in the remembered target color, suggesting that the attentional template of the target was not confined to the gray-scale image presented before the selection task. Rather, the learned color from episodic memory was involuntarily or automatically reinstated into VWM and guided search.

4. Experiment 3

In natural environments, the target features are sometimes distinct from other objects, but sometimes they are not. In Experiments 1 and 2,

the target colors were highly distinct. It has been demonstrated that stimulus similarity is a major determinant of attentional capture (Ansorge & Becker, 2014; Barras & Kerzel, 2017; Gaspelin, Ruthruff, & Lien, 2016; Theeuwes, 1991) and we therefore investigated whether memory-based capture would occur with less distinct colors. Accurate memory of similar colors without attentional capture by those colors is consistent with earlier claims that the precision of attentional selection is worse than the precision of memory (Kerzel, 2019).

4.1. Methods

The methods were as in the color-shape association task of Experiment 2, with the exception that the colors were more similar. The colors varied between green and blue in steps of 30° in CIELAB space, which resulted in four colors: green, bluish-green, greenish-blue and blue (see Fig. 4A). Thirteen students participated (age: $M = 18.7$, $SD = 1.6$). We increased the sample size to 13 because this allowed us to find significant effects with a Cohen's d_z of 0.85 (assuming $p = .05$ and power = 0.8), which is about half of what was observed in Experiment 2, where Cohen's d_z was around 1.7.

4.2. Results

One dataset had to be removed because only 30% of the trials in the saccadic choice task could be retained. By one-way ANOVA, performance on the color-shape association task increased from the first to the fifth block, $F(4, 44) = 211.64$, $p < .001$, $\eta_p^2 = 0.951$. The percentages of correct responses were 38.5%, 60.2%, 77.6%, 86.2%, and 92.7%. To confirm that the similar colors were more difficult to remember than distinct colors, we performed a mixed 2 (Experiment: E2-association, E3) \times 5 (learning block) ANOVA. There was an effect of block, $F(4, 80) = 270.23$, $p < .001$, $\eta_p^2 = 0.931$, and a significant interaction, $F(4, 80) = 7.79$, $p < .001$, $\eta_p^2 = 0.28$. The interaction showed that performance with similar colors was worse at the beginning, but approached performance with distinct colors as learning progressed. The performance from block 1 to 5 with distinct colors was better by 18.9%, 19.3%, 13.6%, 7.6%, and 5.1% than performance with similar colors. The difference between experiments in the first block (18.9%) was significant by independent-samples t -test, $t(20) = 3.94$, $p = .001$, Cohen's $d = 1.62$, while the difference in the last block (5.1%) was not, $t(20) = 1.71$, $p = .102$, Cohen's $d = 0.76$.

For the saccadic choice task, we removed the following trials: Trials with saccadic reaction times shorter than 0.1 s (2.2%) or longer than 0.35 s (5%), trials without a saccadic response (1.7%), trials with starting points of the first saccade outside the fixation window (6.4%), trials where it took longer than 2 s to find a 0.3 s fixation window (2%) and trials with saccadic amplitudes less than half the target eccentricity (1%). Overall, 12.4% ($SD = 8.2\%$) of trials were removed (range: 5% to 34%).

As shown in Fig. 4B, the percentage of saccades to the correct shape was higher when the target shape was in the learned target color than

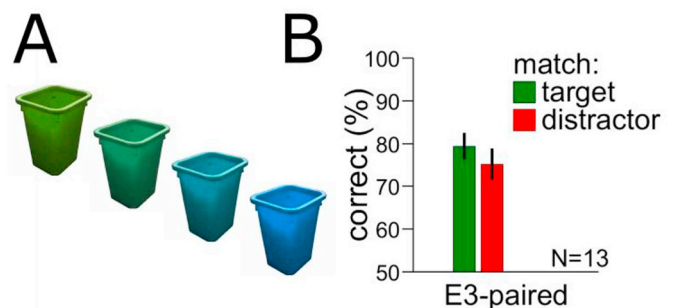


Fig. 4. Colors (panel A) and results (panel B) from Experiment 3.

when the distractor was in the learned target color (target-match vs. distractor-match: 78.9% vs. 73.8%, difference of 5.1%), but this difference only approached significance, $t(11) = 1.81$, $p = .098$, Cohen's $d_z = 0.52$. Saccadic latencies were slightly shorter in the target-match than in the distractor-match condition (212 vs. 217 ms), but this difference was not significant, $t(11) = 0.93$, $p = .375$, Cohen's $d_z = 0.27$.

The effect of color match was strongly reduced in Experiment 3 compared to Experiment 2. To provide statistical evidence for this conclusion, we performed a mixed 2 (Experiment: E2, E3) \times 2 (match: target-match, distractor match) ANOVA. We collapsed across the two groups in Experiment 2 because the effect of color match did not differ between the association and two-back tasks, $p = .392$. The ANOVA showed an effect of color match, $F(1, 28) = 36.43$, $p < .001$, $\eta_p^2 = 0.57$, and the expected interaction between experiment and color match, $F(1, 28) = 17$, $p < .001$, $\eta_p^2 = 0.378$, which confirmed that the effect of color match was smaller with similar than distinct colors.

4.3. Discussion

We evaluated whether memory-based interference would change with less distinct colors. Learning less distinct colors was more difficult than learning distinct colors, but in the last learning block, the same level of performance was reached. Thus, the final transfer into episodic memory was comparable between distinct and less distinct colors. However, we found interference from the memorized color to be strongly reduced with less distinct colors. Thus, the relatively precise color information in episodic memory did not affect attentional selectivity. A simple explanation of this pattern is that the precision of memory is better than the precision of attention (see Kerzel, 2019) so that fine discriminations are possible in memory, but not in attentional selection.

5. General discussion

We investigated memory-based interference by features reinstated from episodic memory into VWM. Our investigation used a paradigm developed by Foerster and Schneider (2018, 2019a, 2019b) who loaded both the relevant shape and the irrelevant color of an object into VWM and found that fewer saccades went to the correct shape when the irrelevant color appeared in a distractor shape. Experiment 1 replicated this finding. In Experiment 2, we only loaded the relevant shape into VWM. The irrelevant color of the target shape was not shown, but color-shape associations were stored in episodic memory at the beginning of the experiment. We found that the learned color-shape associations strongly biased saccadic selection. Fewer saccades found the correct target shape when the memorized color of the target shape was presented in the distractor shape. A manipulation of the learning protocol showed that explicit and implicit transfer of color-shape associations into episodic memory was equally effective. In Experiment 3, we reduced the distinctiveness of the colors. Memory-based interference was strongly reduced with similar colors while recall of these colors was comparable (at least at the end of the learning phase), suggesting that the precision of memory was better than the precision of attention.

Functionally, the automatic reinstatement of object attributes from memory may increase search efficiency. More precise attentional templates result in shorter search times (Castelano et al., 2008; Hout & Goldinger, 2015; Jenkins et al., 2018; Malcolm & Henderson, 2009; Nako et al., 2014; Schmidt & Zelinsky, 2009; Vickery et al., 2005; Wolfe et al., 2004; Yang & Zelinsky, 2009). Therefore, it makes sense to add object features stored in long-term memory to the attentional template in VWM. In this sense, the attentional template in real-world situations may be less static than laboratory experiments suggest. Returning to the example of the key on a cluttered desk, one may first constitute an attentional template based on the typical shape of the key ("Where is my key?"). Subsequently, the attentional template may be complemented as specific features of the object are retrieved. For instance,

its color or size may be added to facilitate search ("I remember the key being red and small."). Thus, the precision of the attentional template may increase over time as additional features of the target become available from long-term memory.

5.1. Automatic reinstatement in the memory literature

Because there was no incentive to attend to color in our experiments, our results suggest that reinstatement in VWM and subsequent guidance of attention were involuntary and automatic. While automatic reinstatement of object attributes in VWM may make visual search more efficient, automatic reinstatement is unlikely to be a search-specific mechanism. Rather, it is consistent with previous studies from the memory literature showing that irrelevant object attributes are automatically recalled (Bornstein & Norman, 2017; Ecker, Maybery, & Zimmer, 2013; Geukes, Vorberg, & Zwitterlood, 2019; Hoskin, Bornstein, Norman, & Cohen, 2019; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Shen, Tang, Wu, Shui, & Gao, 2013; Yin et al., 2012). For instance, Ecker et al. (2013) asked participants to store geometrical shapes in VWM. The color of the shapes was irrelevant, but memory performance was improved when the color from the study display was repeated in the test display. Further, better performance with repeated colors occurred only when the shape was colored, but not when the background was colored, suggesting that only intrinsic object attributes are recalled automatically. Similarly, Shen et al. (2013) showed that change detection of a relevant feature in multi-item displays was impaired when an irrelevant attribute changed. While all of these studies support automatic object-based encoding in memory, there is also evidence for feature-based encoding that is controlled by top-down intentions (McCants, Katus, & Eimer, 2020; Woodman & Vogel, 2008). While the current results support object-based encoding in perception and memory, future research will have to clarify the boundary conditions for object-based encoding in memory-tasks.

5.2. Object files

In their seminal paper, Kahneman, Treisman, and Gibbs (1992) write that "the context within which a stimulus is processed is frequently evoked by the stimulus itself" (p. 176). Because the automatic reinstatement of an object's context resembles the reinstatement of features from episodic memory, we will highlight some similarities and differences between research on object files and the current study. In one exemplary experiment, Kahneman et al. (1992) presented a preview display with several boxes, two of which contained a letter. In the subsequent test display, a single letter was shown in one of the boxes and participants had to name the letter. Kahneman et al. noted that RTs were shorter when an occupied box from the preview display contained the same letter as in the preview display compared to when it contained a different letter from the preview display. Thus, repeating the location (i.e., box) of a previewed letter resulted in an object-specific preview benefit, suggesting that location and identity of the letter are integrated in an object file, which facilitated responses when it was re-encountered. However, subsequent research showed that repetition benefits do not increase linearly with the sum of repeated features. For instance, repeating the irrelevant shape of an object only facilitates performance if the object color is also repeated, otherwise, repetition may harm performance (e.g., Giesen & Rothermund, 2014; see also Frings & Rothermund, 2011; Hommel, 1998; van Dam & Hommel, 2010). While the repetition benefit with a single feature may be similar between research on object files and the current paradigm, the main difference concerns the experimental task. We investigated a search task where the shape from the memory display had to be located in the choice display. Therefore, the response-relevant shape could not be changed between memory and choice display. Otherwise, it would be impossible to perform the task. In contrast, work on object files only had a single object in the target display and a categorization task was

used. For instance, observers had to indicate whether the color of the target was red or green by pressing a designated button (Giesen & Rothermund, 2014). No internal representation of the target object was necessary, only the stimulus-response translation had to be retained (e.g., green > left response, red > right response). Thus, the memory representation of the previewed attributes in research on object-files was incidental, whereas memory of the task-relevant shape in our search task was explicit. Despite these fundamentally different types of memory representation, the results converge on the broad notion that the original features of a stimulus may be evoked by a subset of the original features, arguing for object-based representations in memory.

5.3. Semantic memory

The current experiments investigated the relation between episodic memory and the attentional template. We found that contents from long-term episodic memory automatically guide attention. Some previous work focused on semantic memory and came to similar conclusions. For instance, Huettig and Altmann (2011) presented observers with spoken words that were associated with a prototypical color. Participants were asked to look at the screen where four objects were displayed, but no specific instructions were given other than to listen to the spoken words. The results showed that participants looked more frequently at objects sharing the prototypical color associated with the spoken word. For instance, upon hearing the word “pea”, participants had a tendency to look at an unrelated object sharing the prototypical green color of a pea (e.g., a green blouse). These results suggest that semantic memory created an attentional template for a particular color, which resulted in overt shifts of attention to the corresponding objects (see also Dahan & Tanenhaus, 2005; Nuthmann, de Groot, Huettig, & Olivers, 2019). In addition, search for an object may be impeded by a distractor sharing the typical color associated with the target object (Olivers, 2011). For instance, during search for a grayscale image of a sign that is red in the real world, a single red distractor sign in an otherwise grayscale search display interfered more than a single blue distractor sign, showing that participants activated the real-world color of the target sign. While these results are suggestive, they also reveal the difficulty of disentangling object attributes in semantic memory. For instance, only the red signs in Olivers' (2011) study had thick colored outline contours (e.g., “speed limit 50” or “pedestrian crossing”, see Fig. 2 in Olivers, 2011). Thus, shape and color may be partially correlated. In contrast, our work on episodic memory used arbitrary associations between shape and color, which eliminates existing correlations between features.

5.4. The role of priming

One possible objection to research on memory-based interference is that the memorized, but search-irrelevant feature is primed because it was presented shortly before the search display and had to be attentionally selected because it was merged with the relevant attribute (for reviews on priming and attention, see Lamy & Kristjánsson, 2013; Theeuwes, 2013). Thereby, the search-irrelevant feature may attract attention and interfere with search. An obvious way to rule out this explanation is to compare a condition with retention of the search-irrelevant feature to a condition where the feature is passively viewed (Olivers et al., 2006). However, effects of cueing may be complex (Schoeberl, Goller, & Ansorge, 2019). For instance, Wilschut, Theeuwes, and Olivers (2014) demonstrated that better performance with visual compared to verbal cues might be accounted for by priming that occurs with visual cues, but not with word cues. When priming was eliminated by retro-cueing one of two possible target features, performance was comparable with visual and word cues. Similarly, one may argue that presentation and selection of colored shapes in the memory display in Experiment 1 primed the respective color, which may explain why attention was subsequently attracted to this color. The present

experiments provide strong evidence against the involvement of priming in memory-based interference. Only the target shape was loaded into VWM briefly before the choice task in Experiment 2, such that color priming was effectively ruled out. In addition, the interval between memory and choice display was long in the current experiments (between 1 and 1.5 s), which makes it unlikely that any perceptual priming took place. Further, the temporal separation of learning and saccadic choice trials in Experiment 2 is outside the range of priming effects (estimated at 30 s, Maljkovic & Nakayama, 1994), because the saccadic selection task was preceded by calibration of the eye tracker, which took about 1 min and involved different sets of stimuli.

5.5. Variable and fixed templates

A final consideration concerns the variable target in our study. Because the target changed from trial to trial, it had to be stored in VWM. In previous experiments, memory-based interference was absent with variable targets (Kerzel & Witzel, 2019; Olivers, 2009). According to Olivers et al. (2011) only a single item can act as attentional template. As a variable target fills this slot, a second item in VWM cannot act as attentional template and is deprioritized, as visible in its less precise memory representation (Kerzel & Witzel, 2019). However, the idea of a one-slot attentional template is disputed because attentional selectivity for two targets is comparable to a single target, even when the targets are variable (Ansorge, Horstmann, & Carbone, 2005; Beck, Hollingworth, & Luck, 2012; Goldstein & Beck, 2018; Grubert, Carlisle, & Eimer, 2016; Irons, Folk, & Remington, 2012; Kerzel & Witzel, 2019; Roper & Vecera, 2012) (but see Biderman, Biderman, Zivony, & Lamy, 2017). Possibly, the discrepancy between previous experiments with variable targets and the current investigation is explained by the presentation of color-shape associations as integrated objects. Studies where no memory-based interference was observed with variable targets presented two features from the same dimension (Kerzel & Witzel, 2019; Olivers, 2009). That is, participant had to memorize one color for later recall while another color specified the target. Two separate features from the same dimension make it difficult to create a unified representation. It would be interesting to know whether our results would change if the color information were spatially separated from the shape to prevent the formation of an integrated object. According to the idea of object-based encoding, color was encoded and retrieved together with the shape because the two features formed an object. If this was true, the effect of color should disappear when the color information was separated from the shape, for instance by showing a colorless shape inside a colored frame. In support of this idea, Ecker et al. (2013) observed that effects of color in a memory task disappeared when color surrounded the object instead of filling it.

In sum, the present study investigated the interactions between short-term and long-term memory in the creation of the attentional template. Consistent with previous research, we demonstrated that irrelevant features of an object are integrated into the attentional template. The novel finding is that irrelevant features do not have to be loaded into visual working memory, but may be automatically reinstated from long-term memory. Functionally, automatic reinstatement of object features makes the attentional template more precise, which is known to increase the efficiency of visual search.

Author contributions

DK and MKSA designed research. DK programed experimental protocol and analyzed data. MKSA ran experimental subjects. DK wrote article.

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References

- Ansorge, U., & Becker, S. I. (2014). Contingent capture in cueing: The role of color search templates and cue-target color relations. *Psychological Research*, 78(2), 209–221. <https://doi.org/10.1007/s00426-013-0497-5>.
- Ansorge, U., Horstmann, G., & Carbone, E. (2005). Top-down contingent capture by color: Evidence from RT distribution analyses in a manual choice reaction task. *Acta Psychologica*, 120(3), 243–266. <https://doi.org/10.1016/j.actpsy.2005.04.004>.
- Baddeley, A. (2010). Working memory. *Current Biology*, 20(4), R136–R140. <https://doi.org/10.1016/j.cub.2009.12.014>.
- Bahle, B., Beck, V. M., & Hollingworth, A. (2018). The architecture of interaction between visual working memory and visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, 44(7), 992–1011. <https://doi.org/10.1037/xhp0000509>.
- Barras, C., & Kerzel, D. (2017). Target-nontarget similarity decreases search efficiency and increases stimulus-driven control in visual search. *Attention, Perception, & Psychophysics*, 79(7), 2037–2043. <https://doi.org/10.3758/s13414-017-1367-9>.
- Beck, V. M., Hollingworth, A., & Luck, S. J. (2012). Simultaneous control of attention by multiple working memory representations. *Psychological Science*, 23(8), 887–898. <https://doi.org/10.1177/0956797612439068>.
- Biderman, D., Biderman, N., Zivony, A., & Lamy, D. (2017). Contingent capture is weakened in search for multiple features from different dimensions. *Journal of Experimental Psychology: Human Perception and Performance*, 43(12), 1974–1992. <https://doi.org/10.1037/xhp0000422>.
- Bornstein, A. M., & Norman, K. A. (2017). Reinstated episodic context guides sampling-based decisions for reward. *Nature Neuroscience*, 20, 997. <https://doi.org/10.1038/nn.4573>.
- Brady, T. F., Konkle, T., Gill, J., Oliva, A., & Alvarez, G. A. (2013). Visual long-term memory has the same limit on fidelity as visual working memory. *Psychological Science*, 24(6), 981–990. <https://doi.org/10.1177/0956797612465439>.
- Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, 97(4), 523–547. <https://doi.org/10.1037/0033-295x.97.4.523>.
- Büsel, C., Voracek, M., & Ansorge, U. (2018). A meta-analysis of contingent-capture effects. *Psychological Research Psychologische Forschung*. <https://doi.org/10.1007/s00426-018-1087-3>.
- Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional templates in visual working memory. *The Journal of Neuroscience*, 31(25), 9315–9322. <https://doi.org/10.1523/jneurosci.1097-11.2011>.
- Castelhano, M. S., Pollatsek, A., & Cave, K. R. (2008). Typicality aids search for an unspecified target, but only in identification and not in attentional guidance. *Psychonomic Bulletin & Review*, 15(4), 795–801. <https://doi.org/10.3758/pbr.15.4.795>.
- Dahan, D., & Tanenhaus, M. K. (2005). Looking at the rope when looking for the snake: Conceptually mediated eye movements during spoken-word recognition. *Psychonomic Bulletin & Review*, 12(3), 453–459. <https://doi.org/10.3758/bf03193787>.
- Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, 36(12), 1827–1837.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, 96, 433–458. <https://doi.org/10.1037/0033-295x.96.3.433>.
- Ecker, U. K. H., Maybery, M., & Zimmer, H. D. (2013). Binding of intrinsic and extrinsic features in working memory. *Journal of Experimental Psychology: General*, 142(1), 218–234. <https://doi.org/10.1037/a0028732>.
- Fairchild, M. D. (2005). *Colour appearance models*. Hoboken, NJ: Wiley.
- Foerster, R. M., & Schneider, W. X. (2018). Involuntary top-down control by search-irrelevant features: Visual working memory biases attention in an object-based manner. *Cognition*, 172, 37–45. <https://doi.org/10.1016/j.cognition.2017.12.002>.
- Foerster, R. M., & Schneider, W. X. (2019a). Involuntarily attentional biases by visual working memory: Target-distractor similarity of search-irrelevant features matters. *Perception*, 48(Suppl. 1), 95.
- Foerster, R. M., & Schneider, W. X. (2019b). Task-irrelevant features in visual working memory influence covert attention: Evidence from a partial report task. *Vision*, 3(3), 42.
- Frings, C., & Rothermund, K. (2011). To be or not to be...Included in an event file: Integration and retrieval of distractors in stimulus-response episodes is influenced by perceptual grouping. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37(5), 1209–1227. <https://doi.org/10.1037/a0023915>.
- Gao, Z., Yu, S., Zhu, C., Shui, R., Weng, X., Li, P., & Shen, M. (2016). Object-based encoding in visual working memory: Evidence from memory-driven Attentional capture. *Scientific Reports*, 6, 22822. <https://doi.org/10.1038/srep22822>.
- Gaspin, N., & Luck, S. J. (2018). The role of inhibition in avoiding distraction by salient stimuli. *Trends in Cognitive Sciences*, 22(1), 79–92. <https://doi.org/10.1016/j.tics.2017.11.001>.
- Gaspin, N., Ruthruff, E., & Lien, M.-C. (2016). The problem of latent Attentional capture: Easy visual search conceals capture by task-irrelevant abrupt onsets. *Journal of Experimental Psychology: Human Perception and Performance*, 42(8), 1104–1120. <https://doi.org/10.1037/xhp0000214>.
- Geng, J. J., & Witkowski, P. (2019). Template-to-distractor distinctiveness regulates visual search efficiency. *Current Opinion in Psychology*, 29, 119–125. <https://doi.org/10.1016/j.copsyc.2019.01.003>.
- Geukes, S., Vorberg, D., & Zwitserlood, P. (2019). Disentangling semantic and response learning effects in color-word contingency learning. *PLoS One*, 14(5), e0212714. <https://doi.org/10.1371/journal.pone.0212714>.
- Giesen, C., & Rothermund, K. (2014). Distractor repetitions retrieve previous responses and previous targets: Experimental dissociations of distractor-response and distractor-target bindings. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 40(3), 645–659. <https://doi.org/10.1037/a0035278>.
- Goldstein, R. R., & Beck, M. R. (2018). Visual search with varying versus consistent attentional templates: Effects on target template establishment, comparison, and guidance. *Journal of Experimental Psychology: Human Perception and Performance*, 44(7), 1086–1102. <https://doi.org/10.1037/xhp0000520>.
- Grubert, A., Carlisle, N. B., & Eimer, M. (2016). The control of single-color and multiple-color visual search by attentional templates in working memory and in long-term memory. *Journal of Cognitive Neuroscience*, 28(12), 1947–1963. https://doi.org/10.1162/jocn_a_01020.
- Hollingworth, A., & Beck, V. M. (2016). Memory-based attention capture when multiple items are maintained in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, 42(7), 911–917. <https://doi.org/10.1037/xhp0000230>.
- Hommel, B. (1998). Event files: Evidence for automatic integration of stimulus-response episodes. *Visual Cognition*, 5(1–2), 183–216. <https://doi.org/10.1080/713756773>.
- Hoskin, A. N., Bornstein, A. M., Norman, K. A., & Cohen, J. D. (2019). Refresh my memory: Episodic memory reinstatements intrude on working memory maintenance. *Cognitive, Affective, & Behavioral Neuroscience*, 19(2), 338–354. <https://doi.org/10.3758/s13415-018-00674-z>.
- Hout, M. C., & Goldinger, S. D. (2015). Target templates: The precision of mental representations affects attentional guidance and decision-making in visual search. *Attention, Perception, & Psychophysics*, 77(1), 128–149. <https://doi.org/10.3758/s13414-014-0764-6>.
- Huetig, F., & Altmann, G. T. M. (2011). Looking at anything that is green when hearing “frog”: How object surface colour and stored object colour knowledge influence language-mediated overt attention. *Quarterly Journal of Experimental Psychology*, 64(1), 122–145. <https://doi.org/10.1080/17470218.2010.481474>.
- Hyun, J.-s., Woodman, G. F., Vogel, E. K., Hollingworth, A., & Luck, S. J. (2009). The comparison of visual working memory representations with perceptual inputs. *Journal of Experimental Psychology: Human Perception and Performance*, 35(4), 1140–1160. <https://doi.org/10.1037/a0015019>.
- Irons, J. L., Folk, C. L., & Remington, R. W. (2012). All set! Evidence of simultaneous attentional control settings for multiple target colors. *Journal of Experimental Psychology: Human Perception and Performance*, 38(3), 758–775. <https://doi.org/10.1037/a0026578>.
- Jenkins, M., Grubert, A., & Eimer, M. (2018). Category-based attentional guidance can operate in parallel for multiple target objects. *Biological Psychology*, 135, 211–219. <https://doi.org/10.1016/j.biopsycho.2018.04.006>.
- Jung, K., Han, S. W., & Min, Y. (2019). Opposing effects of stimulus-driven and memory-driven attention in visual search. *Psychonomic Bulletin & Review*. <https://doi.org/10.3758/s13423-019-01630-9>.
- Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, 24(2), 175–219.
- Kerzel, D. (2019). The precision of attentional selection is far worse than the precision of the underlying memory representation. *Cognition*, 186, 20–31. <https://doi.org/10.1016/j.cognition.2019.02.001>.
- Kerzel, D., & Witzel, C. (2019). The allocation of resources in visual working memory and multiple attentional templates. *Journal of Experimental Psychology: Human Perception and Performance*, 45(5), 645–658. <https://doi.org/10.1037/xhp0000637>.
- Kim, S., & Cho, Y. S. (2016). Memory-based attentional capture by colour and shape contents in visual working memory. *Visual Cognition*, 24(1), 51–62. <https://doi.org/10.1080/13506285.2016.1184734>.
- Kowler, E., Anderson, E., Doshier, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research*, 35(13), 1897–1916. [https://doi.org/10.1016/0042-6989\(94\)00279-U](https://doi.org/10.1016/0042-6989(94)00279-U).
- Lamy, D. F., & Kristjánsson, A. (2013). Is goal-directed attentional guidance just intertrial priming? A review. *Journal of Vision*, 13(3), 1–19. <https://doi.org/10.1167/13.3.14>.
- Lamy, D., Leber, A. B., & Egeth, H. E. (2012). Selective attention. In A. F. Healy, & R. W. Proctor (Vol. Eds.), *Comprehensive handbook of psychology*. Vol. 4. *Comprehensive handbook of psychology* (pp. 265–294). New York: Wiley.
- Liesefeld, H. R., & Müller, H. J. (2019). Distractor handling via dimension weighting. *Current Opinion in Psychology*, 29, 160–167. <https://doi.org/10.1016/j.copsyc.2019.03.003>.
- Malcolm, G. L., & Henderson, J. M. (2009). The effects of target template specificity on visual search in real-world scenes: Evidence from eye movements. *Journal of Vision*, 9(11), 1–13. <https://doi.org/10.1167/9.11.8>.
- Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. role of features. *Memory and Cognition*, 22(6), 657–672. <https://doi.org/10.3758/BF03209251>.
- McCants, C. W., Katus, T., & Eimer, M. (2020). Task goals modulate the activation of part-based versus object-based representations in visual working memory. *Cognitive Neuroscience*, 11(1–2), 92–100. <https://doi.org/10.1080/17588928.2019.1642864>.
- Nako, R., Wu, R., Smith, T. J., & Eimer, M. (2014). Item and category-based attentional control during search for real-world objects: Can you find the pants among the pants? *Journal of Experimental Psychology: Human Perception and Performance*. <https://doi.org/10.1037/a0036885>.
- Nuthmann, A., de Groot, F., Huetig, F., & Olivers, C. N. L. (2019). Extrafoveal attentional capture by object semantics. *PLoS One*, 14(5), e0217051. <https://doi.org/10.1371/journal.pone.0217051>.
- Olivers, C. N. L. (2009). What drives memory-driven attentional capture? The effects of memory type, display type, and search type. *Journal of Experimental Psychology: Human Perception and Performance*, 35(5), 1275–1291. <https://doi.org/10.1037/a0013896>.
- Olivers, C. N. L. (2011). Long-term visual associations affect attentional guidance. *Acta Psychologica*, 137(2), 243–247. <https://doi.org/10.1016/j.actpsy.2010.07.001>.
- Olivers, C. N. L., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of*

- Experimental Psychology: Human Perception and Performance*, 32(5), 1243–1265. <https://doi.org/10.1037/0096-1523.32.5.1243>.
- Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, 15(7), 327–334. <https://doi.org/10.1016/j.tics.2011.05.004>.
- Roper, Z. J. J., & Vecera, S. P. (2012). Searching for two things at once: Establishment of multiple attentional control settings on a trial-by-trial basis. *Psychonomic Bulletin & Review*, 19(6), 1114–1121. <https://doi.org/10.3758/s13423-012-0297-8>.
- Sala, J. B., & Courtney, S. M. (2009). Flexible working memory representation of the relationship between an object and its location as revealed by interactions with attention. *Attention, Perception, & Psychophysics*, 71(7), 1525–1533. <https://doi.org/10.3758/APP.71.7.1525>.
- Schmidt, J., & Zelinsky, G. J. (2009). Search guidance is proportional to the categorical specificity of a target cue. *Quarterly Journal of Experimental Psychology*, 62(10), 1904–1914. <https://doi.org/10.1080/17470210902853530>.
- Schneider, W. X. (1995). VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition and space-based motor action. *Visual Cognition*, 2(2/3), 331–376.
- Schneider, W. X. (2013). Selective visual processing across competition episodes: A theory of task-driven visual attention and working memory. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1628), <https://doi.org/10.1098/rstb.2013.0060>.
- Schoeberl, T., Goller, F., & Ansorge, U. (2019). Testing a priming account of the contingent-capture effect. *Attention, Perception, & Psychophysics*, 81(5), 1262–1282. <https://doi.org/10.3758/s13414-019-01672-0>.
- Shen, M., Tang, N., Wu, F., Shui, R., & Gao, Z. (2013). Robust object-based encoding in visual working memory. *Journal of Vision*, 13(2), 1–11. <https://doi.org/10.1167/13.2.1>.
- Soto, D., Hodsoll, J., Rotshtein, P., & Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends in Cognitive Sciences*, 12(9), 342–348. <https://doi.org/10.1016/j.tics.2008.05.007>.
- Soto, D., & Humphreys, G. W. (2009). Automatic selection of irrelevant object features through working memory: Evidence for top-down attentional capture. *Experimental Psychology*, 56(3), 165–172. <https://doi.org/10.1027/1618-3169.56.3.165>.
- Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics*, 50(2), 184–193. <https://doi.org/10.3758/Bf03212219>.
- Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, 135(2), 77–99. <https://doi.org/10.1016/j.actpsy.2010.02.006>.
- Theeuwes, J. (2013). Feature-based attention: It is all bottom-up priming. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 368(1628), <https://doi.org/10.1098/rstb.2013.0055>.
- Tulving, E. (2002). Episodic memory: From mind to brain. *Annual Review of Psychology*, 53(1), 1–25. <https://doi.org/10.1146/annurev.psych.53.100901.135114>.
- van Dam, W. O., & Hommel, B. (2010). How object-specific are object files? Evidence for integration by location. *Journal of Experimental Psychology: Human Perception and Performance*, 36(5), 1184–1192. <https://doi.org/10.1037/a0019955>.
- van Moorselaar, D., Theeuwes, J., & Olivers, C. N. L. (2014). In competition for the attentional template: Can multiple items within visual working memory guide attention? *Journal of Experimental Psychology: Human Perception and Performance*, 40(4), 1450–1464. <https://doi.org/10.1037/a0036229>.
- Vickery, T. J., King, L. W., & Jiang, Y. (2005). Setting up the target template in visual search. *Journal of Vision*, 5(1), 81–92. <https://doi.org/10.1167/5.1.8>.
- Whitehead, P. S., Ooi, M. M., Egner, T., & Woldorff, M. G. (2019). Neural dynamics of cognitive control over working memory capture of attention. *Journal of Cognitive Neuroscience*, 31(7), 1079–1090. https://doi.org/10.1162/jocn_a_01409.
- Wilschut, A., Theeuwes, J., & Olivers, C. N. (2014). Priming and the guidance by visual and categorical templates in visual search. *Frontiers in Psychology*, 5, 148. <https://doi.org/10.3389/fpsyg.2014.00148>.
- Witzel, C., & Gegenfurtner, K. R. (2015). Chromatic contrast sensitivity. In R. Luo (Ed.), *Encyclopedia of color science and technology* (pp. 1–7). Heidelberg: Springer.
- Witzel, C., & Gegenfurtner, K. R. (2018). Color perception: Objects, Constancy, and categories. *Annual Review of Vision Science*, 4, 475–499. <https://doi.org/10.1146/annurev-vision-091517-034231>.
- Wolfe, J. M., Horowitz, T. S., Kenner, N., Hyle, M., & Vasan, N. (2004). How fast can you change your mind? The speed of top-down guidance in visual search. *Vision Research*, 44(12), 1411–1426. <https://doi.org/10.1016/j.visres.2003.11.024>.
- Woodman, G. F., & Vogel, E. K. (2008). Selective storage and maintenance of an object's features in visual working memory. *Psychonomic Bulletin & Review*, 15(1), 223–229.
- Yang, H., & Zelinsky, G. J. (2009). Visual search is guided to categorically-defined targets. *Vision Research*, 49(16), 2095–2103. <https://doi.org/10.1016/j.visres.2009.05.017>.
- Yin, J., Gao, Z., Jin, X., Ding, X., Liang, J., & Shen, M. (2012). The neural mechanisms of percept–memory comparison in visual working memory. *Biological Psychology*, 90(1), 71–79. <https://doi.org/10.1016/j.biopsycho.2012.02.023>.