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How retaining objects containing multiple features in visual working memory regulates the priority for access to visual awareness

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ABSTRACT

The content of visual working memory influences the access to visual awareness. Thus far, research has focused on retention of a single feature, whereas memoranda in real life typically contain multiple features. Here, we intermixed a delayed match-to-sample task to manipulate VWM content, and a breaking Continuous Flash Suppression (b-CFS) task to measure prioritization for visual awareness. Observers memorized either the color (Exp. 1), the shape (Exp. 2) or both the features (Exp. 3) of an item and indicated the location of a suppressed target. We observed that color-matching targets broke suppression faster than color-mismatching targets both when color was memory relevant or irrelevant. Shape only impacted priority for visual awareness through an interaction with color. We conclude that: (1) VWM can regulate the priority of visual information to access visual awareness along a single feature dimension; (2) different features of a memorandum vary in their potency to impact access to visual awareness, and the more dominant feature may even suppress the effect of the less dominant feature; (3) even stimuli that match an irrelevant feature dimension of the memorandum can be prioritized for visual awareness.

1. Introduction

While reading this text, you might not be aware of other objects on your desk, even if they do project an image on your retinae. Because access to visual awareness is limited, we are not aware of the vast majority of the visual information that is readily available. Our visual system has evolved to prioritize relevant visual information over irrelevant visual information. For example, previous studies have suggested that a fearful face (Jiang, Costello, & He, 2007), a threatening symbol (Gayet, Paffen, Belopolsky, Theeuwes, & Van der Stigchel, 2016), or a salient item (Ding, Paffen, Naber, & der Stigchel, 2019; Stuit, Verstraten, & Paffen, 2010) gains preferential access to awareness.

Besides these intrinsically relevant stimuli, our current mental state also influences the priority of stimuli for access to visual awareness. For instance, by requiring observers to memorize a color for later recognition, Gayet, Paffen, and der Stigchel (2013, 2016, 2019) observed that memory congruent items break interocular suppression faster than memory incongruent items. This finding reveals that an item which is currently stored in visual working memory (hereafter: VWM) is prioritized to enter awareness compared to

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other items. A follow-up study showed that when two items (i.e., of two distinct colors) are memorized simultaneously, each of them will be prioritized for visual awareness, suggesting that multiple features in VWM can jointly regulate visual awareness (van Moorselaar et al., 2018). Furthermore, the same principle holds for more complex memoranda that are defined by multiple features, such as faces (Liu, Wang, Wang, & Jiang, 2016; Pan, Lin, Zhao, & Soto, 2014). Interestingly, Liu et al. (2016) observed that faces with threatening expressions are released from suppression faster when observers are memorizing threatening faces; an effect that was not observed for faces with happy or neutral expressions. As differences between emotional expressions are relatively subtle, this raises the question to what degree complex object representations in VWM interact with the dynamics of visual awareness. More generally, as visual items stored in VWM typically comprise multiple features, it is currently unknown whether and how these features jointly regulate access to awareness.

For the questions introduced above it is important to know how items are represented in VWM. A body of evidence suggests that multiple features of a single item can be maintained in VWM as a bound conjunction. For instance, Luck and Vogel (1997) reported that the number of items stored in memory was not different when only a single feature needed to be remembered (e.g., either their color or their orientation) or when multiple features needed to be remembered (e.g., their color as well as their orientation). Sequential studies replicated this finding thereby supporting this object-based theory of VWM (see Luria, Balaban, Awh, & Vogel, 2016 for a review; Luria & Vogel, 2011; Vogel, Woodman, & Luck, 2001). These studies suggest that the features of a memorized object in VWM are somehow linked together. Alternative to the object-based theory of VWM is the multiple-resources theory which assumes that there are separate pools of resources for maintaining features from different dimensions (Alvarez & Cavanagh, 2004; Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Parra, Cubelli, & Della Sala, 2011; Wheeler & Treisman, 2002). For instance, Alvarez and Cavanagh (2004) observed that the object-based theory cannot entirely explain the capacity of VWM. Instead, they argue that VWM load is not only determined by the number of objects, but also by the complexity of objects. Furthermore, Wheeler and Treisman (2002) observed that features from the same dimension (e.g., color) compete for storage capacity while features from different dimensions (e.g., color and orientation) are stored in parallel without competition. Delvenne and Bruyer (2004) replicated this finding, revealing that features from different dimensions can be stored without affecting capacity limits.

The discussion about the nature of VWM representations above, leads us to question whether VWM regulates the priority of an item for visual awareness along a single feature dimension and/or whether multiple features from different dimensions regulate access synergistically (i.e., as a bound entity). In this study, we opted for the feature dimensions ‘color’ and ‘shape’ to facilitate comparison with previous studies investigating the influences of VWM on perception using similar feature dimensions (e.g., Soto & Humphreys,

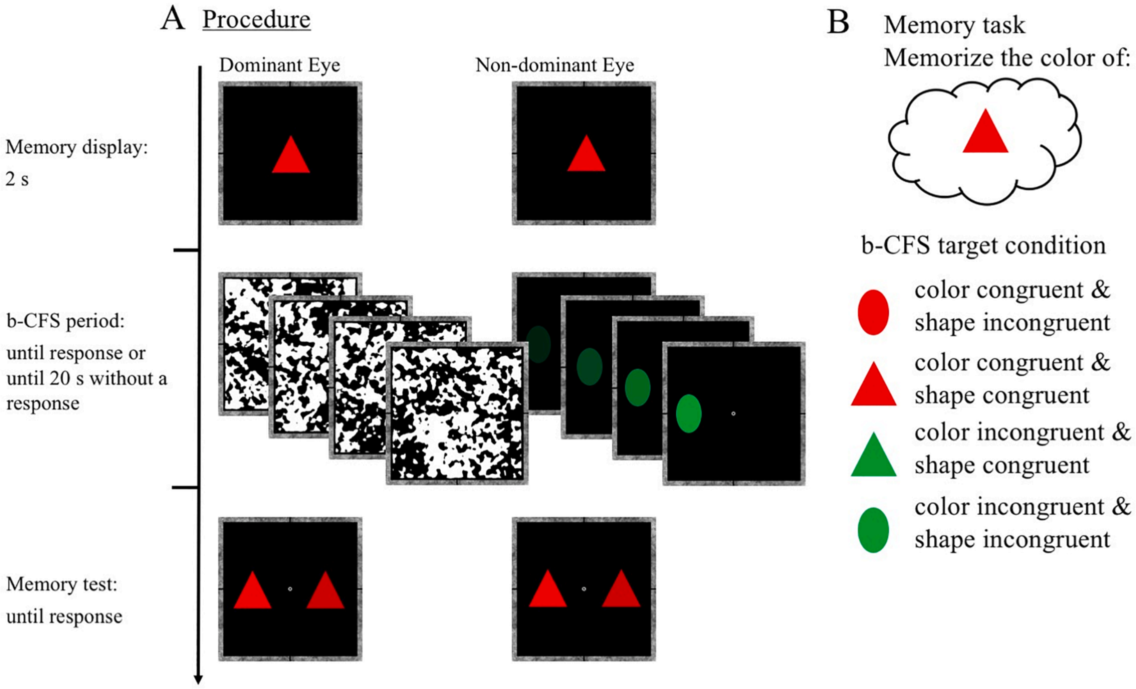

Fig. 1. (A) Schematic depiction of a trial sequence showing a shape and color incongruent trial in Experiment 1. Observers were instructed to memorize the color of the memory item in the memory encoding phase. In the b-CFS phase, the dynamic masks were presented to the dominant eye and the target was ramped up from zero to full intensity for the other eye. Observers were required to indicate whether the target appeared to the left or right of fixation as soon as they saw it. In the memory recognition phase, two items from the same shape and color categories were presented, one of which was identical to the memory item, while the other was of a slightly different hue. (B) Illustration of the four congruency conditions of the b-CFS target in case the memory item was a red triangle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2009; Olivers, Meijer, & Theeuwes, 2006; Gayet et al., 2013; Bahle et al., 2018; Soto, Heinke, Humphreys, & Blanco, 2005; Wheeler & Treisman, 2002). To quantify the priority to visual awareness, we used the so-called breaking continuous flash suppression paradigm (i.e., b-CFS; Jiang et al., 2007; Stein, Hebart & Sterzer, 2011; Gayet, Van der Stigchel, & Paffen, 2014; Stein, 2019). In a typical b-CFS task, a target stimulus is initially suppressed from awareness by presenting it to one eye while the other eye is presented with dynamic stimuli (i.e., masks). The duration for a b-CFS target to overcome interocular suppression is an index quantifying the priority of a target to access visual awareness. In the current study, we combined b-CFS and a VWM task. In the first two experiments, we will investigate whether VWM regulates visual awareness at a specific feature dimension. We will ask observers to memorize a single feature (specifically, the color or the shape, respectively) of a memory item that contains multiple features (specifically, both a color and a shape), and vary the congruency between the b-CFS target and the memory item. In the third experiment, we will research whether VWM regulates access to visual awareness of an object along multiple features dimensions (i.e., synergistically) when multiple features of an item are simultaneously maintained in VWM (specifically, as a conjunction of both color and shape).

2. Experiment 1 – Memorize color

2.1. Method

2.1.1. Observers

A planned number of twenty observers (age: M = 22.7, SD = 3.1; 7 males) participated in Experiment 1 after giving written informed consent. All observers reported normal or corrected-to-normal sight and having no epilepsy. The current study was approved by the local Ethical Committee of the Faculty of Social and Behavioral Sciences of Utrecht University and followed the general guidelines set out in the Declaration of Helsinki.

2.1.2. Design and procedure

The congruency between the memory item and the target during b-CFS defined four main experimental conditions (Fig. 1B). On color congruent and shape incongruent trials, the b-CFS target was of the same color category and of a different shape category than the memory item (hereafter: *color only match*). On color congruent and shape congruent trials, the b-CFS target shared both the color category and the shape category with the memory item (*whole object match*). On color incongruent and shape congruent trials, the b-CFS target was of the same shape category and of a different color category than the memory item (*shape only match*). On color incongruent and shape incongruent trials, the b-CFS target shared neither color category nor shape category with the memory item (*whole object mismatch*). The within-subject experimental design comprised a total of 4 congruency conditions (described above) × 3 color categories (a color from the red, green or blue category is memorized) × 3 shape categories (ellipse, triangle or rectangle shaped memory item) × 2 target horizontal locations (left or right of fixation) × 2 target vertical locations (above or below fixation). Every unique combination of conditions was presented once, resulting in 144 trials presented in randomized order to each observer (36 trials per congruency condition). In addition to these fully counterbalanced factors, a number of factors were not balanced, but chosen at random. First, on trials where the b-CFS target mismatched the shape (or color) category of the memory item, the shape (or color) of the b-CFS target was chosen at random from the remaining two categories. Second, the specific within-category color or shape variation for the memory item was chosen at random from the three existing options. Third, in mismatching trials, the specific within-category color or shape variation for the b-CFS target was chosen at random from the three existing options. Fourth, the correct response to the memory task was chosen at random from the left or the right response option.

Before the main experiment, we measured each observer's sensory eye dominance using a b-CFS task (this is important because eye-dominance is task-specific; Ding, Naber, Gayet, der Stigchel, & Paffen, 2018). As illustrated in Fig. 1, each trial in the main experiment started with a fixation dot presented for 500 ms. The memory item (i.e., a colored shape) then replaced the fixation dot for 2000 ms. Observers were instructed to memorize the color of the memory item for a memory recognition task at the end of each trial. After a blank screen (2000 ms), the b-CFS target detection task was initiated by presenting a colored shape (the b-CFS target) to the non-dominant eye and dynamic masks (refreshing at 10 Hz) to the dominant eye. The intensity (i.e., opacity) of the b-CFS target increased linearly within 1.5 s and retained the highest intensity until the end of the trial. Observers were instructed to respond as soon as they saw the target appearing to the left or the right of fixation (at an eccentricity of 1.8°), by pressing the left or right arrow button of the keyboard, respectively. The target detection task lasted until observers responded, or until 20 s without a response had passed. A blank screen was presented for 500 ms between the disappearance of the b-CFS stimuli and the onset of the memory recognition task. During the memory task, we presented two stimuli, left and right of fixation, until observers chose which of these two was identical to the memorized stimulus. One item was identical to the memory item, and the other had an identical shape and was chosen from the same color category but with a slightly different hue. It is important to make the hue difference sufficiently small to prevent ceiling effects and to prevent observers from encoding the memory stimuli verbally or categorically (Olivers et al., 2006). In case an incorrect response was given in either the b-CFS task or the memory recognition task, the text 'Incorrect' was presented on the screen directly after the incorrect response. Trials with a localization error or without a response in the b-CFS task were recycled and presented at the end of the experiment to preserve an equal number of trials in all conditions of interest.

2.1.3. Apparatus and stimuli

We showed stimuli to the observers in a dark room using a desktop computer and a linearized 27-inch LCD monitor (2560 × 1440 pixels, 144-Hz refresh rate). All stimuli were created and presented with MATLAB 2016 (The Math Works, Inc) and its PsychToolbox extension software (Brainard, 1997; Pelli, 1997). The viewing distance was maintained at around 61 cm with a chin and forehead rest.

A stereoscope with four mirrors (two per eye) was fixed on the chinrest to allow for separately stimulating the two eyes of the observer.

In the main experiment, the masks were always presented to the dominant eye to avoid large differences within participants in suppression duration in b-CFS. To promote binocular fusion of the complementary images, the stimulus area presented to each eye was enclosed by a Brownian (i.e., $1/f^2$) noise quadrate frame with a width of 7.5° and a thickness of 0.25° (see Fig. 1). The colors (red, green, and blue) used in the memory display, memory recognition task and b-CFS task were subjectively equal in luminance to prevent observers from memorizing the item based on the luminance instead of hue in the memory task (Olivers et al., 2006), and to prevent the difference in luminance between colors to create variance in break-through times in the b-CFS task. Three shape categories (triangle, ellipse, and rectangle) were used in the VWM task and the b-CFS task, and each shape category included three shape variations that slightly differed in terms of height-to-width ratio (i.e., elongation). The CFS masks consisted of two hundred different binary images that were generated by filtering pink (1/f) noise using a circular Gaussian low-pass filter (sigma = 3.2), and rounding the resulting images to black (~0 Cd/m^2) and white (41.8 Cd/m^2).

2.2. *Data analysis, results, and discussion*

Trials without a response (5.17%) or with incorrect localization (2.40%) in the b-CFS task were recycled at the end of the experiment, and the original ones were excluded from further analysis. The accuracy on the memory task was well above the 50% chance level but not at ceiling ($M = 84.31\%$ correct, $SD = 8.04\%$).

The observer's median response-times (RT) to the b-CFS target were determined for each memory-relevant feature condition (i.e., color; congruent and incongruent) and each memory-irrelevant feature condition (i.e., shape; congruent and incongruent). A 2 × 2 repeated-measures analysis of variance (ANOVA) was conducted on these median RTs per condition, to investigate the effects of color and shape congruence on RTs in the b-CFS task. As depicted in Fig. 2, we observed a significant main effect of color congruency ($F(1, 19) = 14.04$, $p = 0.001$), but neither a significant main effect of shape congruency ($F(1, 19) = 0.27$, $p = 0.61$), nor an interaction between color and shape ($F(1, 19) = 0.73$, $p = 0.40$). In summary, we observed faster response times for b-CFS targets when they matched compared to when they mismatched the memorized color (1523 ms vs. 1632 ms).

The results of Experiment 1 show that a suppressed target stimulus was detected faster when the color matched rather than mismatched the color of the memory item. Shape congruency, however, did not impact RTs. These results indicate that VWM can regulate the access of visual information to visual awareness along the color feature dimension, at least when color is relevant for the upcoming recognition task.

2.3. *Experiment 2 – Memorize shape*

To investigate whether VWM modulates visual awareness along the shape feature dimension, in Experiment 2, observers were only required to memorize the shape of the memory item for the upcoming recognition task, and not its color. We expected two possible outcomes: first, if b-CFS targets that match the shape of the memory items are detected faster than those with a mismatching shape while color does not affect detection times, this indicates that (1) VWM content can regulate visual awareness along the shape feature dimension, and that (2) only the feature dimension that is relevant for the upcoming memory task can regulate access to visual awareness. A second outcome, however, is also feasible, namely that b-CFS targets with matching colors (i.e., the incidental, non-

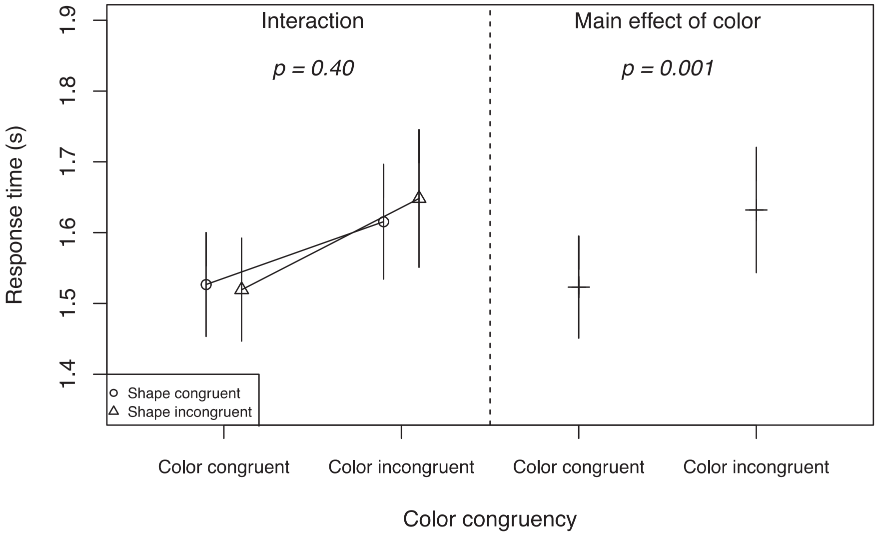

Fig. 2. Mean response times across observers as a function of color congruency and shape congruency for Experiment 1. On each trial, participants were required to memorize the color (but not the shape) of the memory item for the subsequent recognition task. Error bars denote ± 1 SEM across observers. The results show a main effect of color congruency.

memorized feature) will be detected faster than targets with mismatching colors. This would indicate that (1) even incidentally stored features in VWM can regulate access to visual awareness but that (2) this effect is restricted to cases in which color is the incidental feature (as no effect of the incidental feature 'shape' was observed in Experiment 1).

2.4. Method

2.4.1. Observers and procedure

Twenty new observers participated in Experiment 2 (7 males; mean age 24.8, SD = 4.5). All reported having (corrected to) normal sight and having no epilepsy. The method was the same as Experiment 1 except that observers were instructed to only memorize the shape of the memory item, and only the shape would be tested at the end of each trial.

2.5. Results and discussion

Observers performed well in both the b-CFS task (only 2.19% trials were recycled because of incorrect localization responses, SD = 1.83%) and the memory recognition task (accuracy for the shape test, $M = 79.58\%$, $SD = 8.25\%$).

Akin to Experiment 1, the median localization RTs of the b-CFS task were analyzed with a repeated-measures ANOVA. As illustrated in Fig. 3, the results showed a significant main effect of color congruency ($F(1, 19) = 4.57, p = 0.046$) but again no main effect of shape congruency ($F(1, 19) = 0.41, p = 0.53$). Interestingly, we now observed a significant interaction between color congruency and shape congruency ($F(1, 19) = 7.01, p = 0.016$). To investigate the nature of the interaction, subsequent pairwise *t–test comparisons* were conducted among different congruency conditions (i.e., color congruent only, shape congruent only, both shape and color congruent, and neither shape nor color congruent – see Table 1). This analysis revealed that two pairs of conditions differed significantly from each other: color congruent/shape incongruent versus color incongruent/shape incongruent (the left versus the right triangle of Fig. 3; $p = 0.007$), and color incongruent/shape congruent versus color incongruent/shape incongruent (the right circle versus the right triangle of Fig. 3; $p = 0.033$). The other comparisons did not reveal significant differences. The overall pattern of post-hoc comparisons suggests that the condition that involved two features that were incongruent with the memory item, lead to *slower* breakthrough times than the other three conditions (which had similar breakthrough times). Therefore, to test whether, generally, a target is prioritized for awareness when it matches *any* feature with the memory item (i.e., color, shape, or both), we collapsed RTs across the three congruent conditions and compared this to the RTs in the color and shape incongruent condition. This analysis revealed that observers detected targets faster when they matched the color, the shape or the color as well as the shape of the memory item, as compared to targets that matched neither feature (1714 ms vs. 1802 ms, $t(19) = 2.88$, $p = 0.010$).

We can conclude that VWM content can prioritize stimuli for visual awareness along the color feature dimension, even when the color dimension is irrelevant to the VWM task. This goes against the hypothesis that only the memory-relevant feature dimension impacts access to visual awareness. However, the interpretation of the results of Experiment 2 is more complex than we initially expected. The post-hoc comparisons also hint at the possibility that color dominates over shape in the potency of VWM to regulate access to visual awareness, even when shape is relevant for the upcoming memory task and color is not. Also, these results suggest that VWM content can prioritize stimuli along the shape dimension as well, albeit subtly: shape congruency gates the influence of color

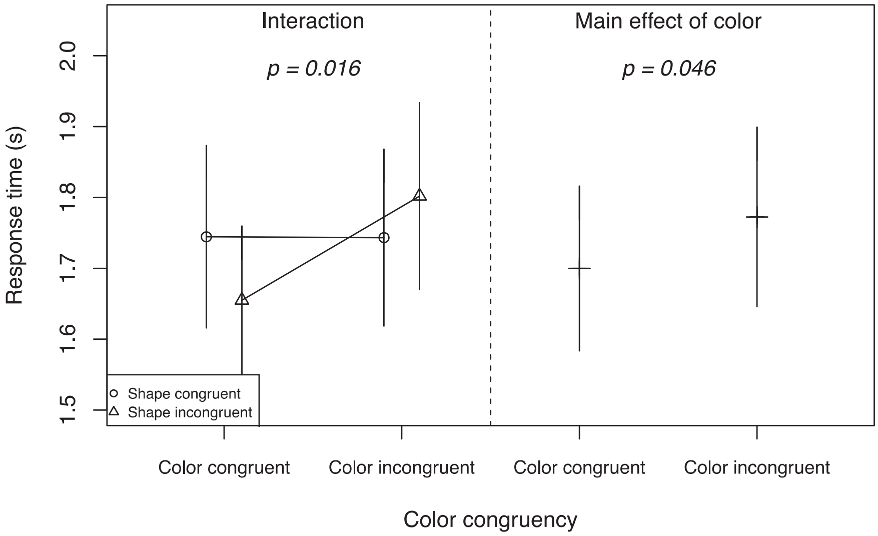

Fig. 3. Response times as a function of congruency condition in the b-CFS task of Experiment 2. In this experiment, participants were only required to memorize the shape (but not the color) of each memory item for the upcoming memory recognition task. Error bars denote ± 1 SEM across participants. The results show a main effect of color congruency (right panel) and an interaction between shape congruency and color congruency (left panel).

Table 1
RT differences between all the different congruent conditions in the b-CFS task.

Condition 1		Condition 2			
Color	Shape	Color	Shape	*t(19)*	*p*
Congruent	Congruent	Incongruent	Incongruent	1.44	0.166
Congruent	Incongruent	Incongruent	Incongruent	3.01	0.007
Incongruent	Congruent	Incongruent	Incongruent	2.31	0.033
Congruent	Congruent	Congruent	Incongruent	1.96	0.065
Congruent	Congruent	Incongruent	Congruent	0.03	0.975
Congruent	Incongruent	Incongruent	Congruent	2.02	0.058

congruency on visual awareness, but (perhaps only) when shape is relevant for the VWM task and color is not.

3. Experiment 3 – Memorize color and shape

In daily life, when memorizing an object, we typically don’t memorize only a single feature dimension (i.e., an orientation or color) but multiple feature dimensions at once (resulting in a face, or a car, etc.). As such, we questioned whether the content of VWM would regulate access to visual awareness of a concurrently presented object along multiple features dimensions (i.e., synergistically) when multiple features of an item are simultaneously maintained in VWM (i.e., as a bound object). To this end, in Experiment 3, we made both features relevant for the upcoming memory task by requiring observers to memorize the shape and the color of the memory item simultaneously. We expected one of three possible outcomes: (1) If b-CFS targets that match either the color or the shape of the memorized item are detected faster than targets that do not, this indicates that VWM content can regulate visual awareness of a multi-feature object at either memory feature dimension; (2) If only the b-CFS targets that match both the color and the shape of the memory item are detected faster, this indicates that VWM content regulates visual awareness at the conjunction level, as long as the bound feature dimensions are both relevant; 3) Considering that the results of Experiments 1 and 2 suggest that color information in VWM is more dominant than shape information in VWM in regulating access to visual awareness, we also considered the possibility that only color congruent targets are detected faster, and shape congruent targets are not. This would indicate that certain feature dimensions in VWM (e.g., color) can null or suppress the effect of other (e.g., shape) in regulating access to visual awareness, even when both features are memorized.

3.1. Method

3.1.1. Observers and procedure

To keep the statistical power equal between experiments, we recruited a new group of 20 observers in Experiment 3 (5 males; mean age 23.41, SD = 3.28). The observers were instructed to memorize both the color and the shape of each memory item, and the feature dimension that was probed during the memory recognition task was determined at random with equal probability (50% color memory

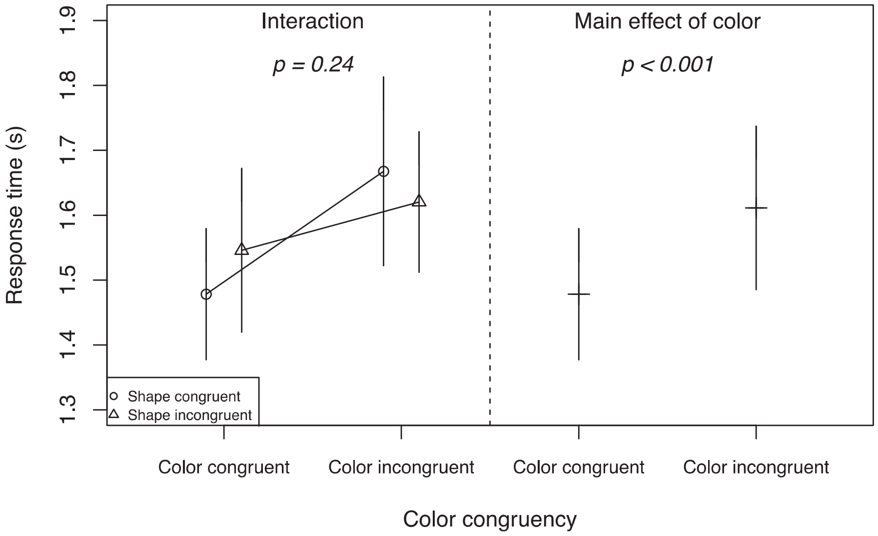

Fig. 4. RTs as a function of different congruency conditions of the b-CFS task in Experiment 3. On each trial, participants were required to memorize both the color and the shape of the memory item for the upcoming memory recognition task. Error bars denote ± 1 SEM across participants. The results show a main effect of color congruency.

recognition, 50% shape memory recognition). This motivated observers to memorize both the color and the shape of the memory item on each trial. When shape was tested, observers had to indicate which of the two stimuli, which were slightly different in shape, was the memory item. All other aspects were identical to Experiment 1.

3.2. Results and discussion

Observers performed well in the b-CFS task (only 2.02% trials were recycled because of incorrect localization responses, SD = 1.68%). The accuracy on the memory recognition task was again above chance and below ceiling, and accuracy was higher on the color-memory than on the shape-memory recognition task (82.41% (7.76%) vs. 73.58% (8.75%), respectively; $t(19) = 4.03$, $p = 0.0007$).

As illustrated in Fig. 4, we observed a main effect of color congruency ($F(1, 19) = 38.79, p < 0.001$), which means that the observers again detected the memory color-congruent targets faster than memory color-incongruent targets (1512 ms vs. 1644 ms). However, neither the main effect of shape congruency ($F(1, 19) = 0.20$, $p = 0.66$) nor the interaction between color congruency and shape congruency ($F(1, 19) = 1.48$, $p = 0.24$) was significant. Unlike the present results, the interaction between shape and color was significant in Experiment 2, where only shape was relevant for the memory task (F(1, 19) = 7.01, p = 0.016). To test whether the difference in task requirements between Experiments 2 and 3 reliably modulated this interaction, we conducted an additional omnibus ANOVA including the within-subject factors shape and color, and the between-subject factor Experiment. This revealed a three-way interaction between shape, color, and experiment on breakthrough times, F(1,38) = 5.75, p = 0.02, confirming the finding of the separate ANOVAs: the shape of the memorandum only influenced breakthrough times (through an interaction with color) when the color of the memorandum was irrelevant for the upcoming memory task.

The results of Experiment 3 show that VWM only accelerates access to visual awareness along the color feature dimension, even though both color information and shape information were made relevant for the VWM task. One potential caveat, however, is that the different features of our stimuli (color and shape) were not equally suppressed. Because interocular competition is stronger when the two competing stimuli are more similar (Stuit, Paffen, van der Smagt, & Verstraten, 2011), it is possible that the color of the target was less deeply suppressed by the achromatic mask than the shape of the target. In this scenario, participants first perceived the target color, and provided a localization response accordingly, while the shape of the target remained so deeply suppressed that it could not interact with the content of working memory. This possibility can easily be tested, because it implies that breakthrough times were fully governed by stimulus color, and not by stimulus shape. Thus, we conducted a new analysis, in which we tested whether the different shapes would elicit different breakthrough times in Experiment 3. Our results revealed a main effect of shape category (F(2, 648) = 5.13, p < 0.01, absolute effect size = 99 ms), suggesting that the current shapes robustly affected the breakthrough time. As such, given that (1) participants demonstrably maintained shape information in working memory, and that (2) shape information in the target stimuli governed breakthrough times, it can be inferred that (3) shape information in working memory had all the potential to impact breakthrough times. Yet, this was not the case (in fact, no memory congruency effect of shape was observed in Experiment 3; p = 0.66). Taken together, while the magnitude of the memory congruency effect for color and shape could depend on inherent differences in masking strength, such a difference in masking strength between the color and shape attributes of our target stimuli is unlikely to explain (A) the absence of a shape congruency effect in Experiment 3, and (B) the interaction between shape and color in Experiment 2. Rather, such a qualitative difference in results between the color and shape attributes clearly demonstrates that a more dominant feature (here, color) may even suppress the effect of the less dominant feature in working memory-based regulation of access to awareness.

4. General discussion

Recent studies have shown that VWM can regulate the access of visual information to visual awareness, by favoring VWM-matching stimuli compared to VWM-mismatching stimuli (Ding et al., 2019; Gayet et al., 2013, 2019; Gayet et al., 2016; Liu et al., 2016; Pan et al., 2014; van Moorselaar et al., 2018). In our current study, we combined a VWM task and a b-CFS task to examine whether items in VWM (comprising multiple feature dimensions) exert this regulation along a single or multi-feature dimension, and whether multiple feature dimensions regulate access to visual awareness synergistically. In Experiment 1, when observers were instructed to memorize the color of an item (but not its shape), we observed that stimuli matching the color of the memorandum enter visual awareness faster than stimuli mismatching the color of the memorandum. These results confirm previous findings in showing that VWM can regulate access to visual awareness along the color feature dimension (Gayet et al., 2013). The shape of the memorandum, which observers were not required to remember for the upcoming memory task (i.e., a so-called incidental feature) did not affect access to visual awareness. In Experiment 2, when observers were instructed to memorize the shape of those same items (but not their color), we observed that the color of a memorandum can affect access to awareness, even when it is an irrelevant feature dimension for the upcoming memory task (unlike shape). Strikingly, these findings also reveal that the shape of the memorandum only impacted priority for visual awareness through an interaction with color, selectively when shape was relevant but color was not.

In Experiment 3, observers were required to memorize both the color and the shape of the items for the upcoming memory recognition task. Under these circumstances, we observed that access to visual awareness of concurrently presented stimuli was only affected by the color feature dimension of the memorandum. Combining the results of Experiments 2 and 3, our findings suggest that when multiple features are maintained, the more dominant feature dimension (here, color) can suppress the influence of the less dominant feature dimension on access to visual awareness.

In line with our current finding that VWM can regulate access to visual awareness along a single feature dimension, previous studies have investigated whether VWM affects conscious processes (e.g., visual attention to unmasked stimuli) at a single feature dimension (Carlisle & Woodman, 2011; Olivers et al., 2006; Bahle, Beck, & Hollingworth, 2018). For instance, Olivers and colleagues (Experiment 4, 2006) required observers to memorize a single feature of an item before a visual search task. In the search task, observers needed longer time to find a target in an array comprising memory-task congruent distractors than in an array with memory-task incongruent distractors, suggesting that attentional capture occurs mostly for items that carried the memory relevant feature. Taking together these findings and our current observations suggests that VWM can regulate visual processing at a single, memory-relevant, feature dimension.

Interestingly, when only the shape of the memorandum was relevant for the upcoming recognition task, we did not observe a main effect of shape congruency, but we still observed a main effect of color congruency. Considering that, across all three experiments, color produced a congruency effect irrespective of whether observers were required to memorize it or not, the observed color congruency effect could be interpreted as a priming effect: repeated presentation (rather than memorization) of a color yields faster access to visual awareness. This interpretation is highly unlikely, however, based on previous studies showing that the color congruency effect disappeared when the color was presented but either not memorized (so-called passive viewing conditions) or dropped from memory (following a retro-cue) (Costello, Jiang, Baartman, McGlennen, & He, 2009; Pan et al., 2014; Ding et al., 2019; Gayet et al., 2013; Jiang et al., 2007). These studies, with paradigms very similar to ours, observed no effect of priming, indicating that the color congruency effect observed here is unlikely to be explained by bottom-up priming, but requires the colored item to be maintained in VWM.

In an experiment with an almost identical design as our current Experiment 2, Gayet et al. (2013; Experiment 5) required observers to memorize the shape of a colored memory item but, intriguingly, they did not observe the color congruency effect in b-CFS. This finding is inconsistent with our current results. It should be noted that, although our Experiment 2 used a very similar experimental paradigm and the same statistical tests as the study of Gayet et al. (2013; Experiment 5), the current study included more participants (20 instead of 10) and more trials per observers (144 instead of 108) than the study of Gayet et al. (2013; Experiment 5). Although tentative, this difference could explain why we observed an effect of color congruency that was not observed in this earlier study. As such, this previous study might have missed out on the color congruency effect, which appears less statistically reliable when color is an incidental feature in our findings as well.

In agreement with our current finding, previous studies also observed that the color of a memorandum influenced conscious processes (of unmasked stimuli), even when it was irrelevant for the upcoming memory task (Pratt & Hommel, 2003; Soto & Humphreys, 2009). For instance, in Experiment 4 of Pratt and Hommel (2003), observers were required to search an array of items for a target that matched the shape of the memory item. The memory item varied in color, which was irrelevant for the search target. Akin to our Experiment 2, it is reasonable to assume that observers did not memorize the color of the memory item voluntarily. However, their results showed that search performance improved when the target also matched the (incidental) color of the search target. Considering the qualitative similarities between memoranda following search instructions and memorization instructions (Bundesen, Habekost, & Kyllingsbaek, 2005; de Fockert, Rees, Frith, & Lavie, 2001; Gunseli, Meeter, & Olivers, 2014), their findings suggest that memory task irrelevant features can also affect the prioritization of concurrently presented stimuli (Pratt & Hommel, 2003), at least when consciously perceived. In the current study, we go beyond that finding, by showing that a memory task irrelevant feature can affect the prioritization of stimuli that are perceptually suppressed, thus accelerating conscious access. Furthermore, previous studies have shown that memory task irrelevant features could be actively maintained in VWM. For instance, O'Craven, Downing, and Kanwisher (1999) conducted a functional magnetic resonance imaging (fMRI) study and observed that attending to one feature of an item would result in both the task relevant feature and the task irrelevant feature of the item to be actively maintained. As such, it is possible that when observers memorized the shape of an item in our current study, the color of the memory item was also maintained in VWM. On the other hand, there is both behavioral and neuroimaging evidence suggesting that only the feature dimension that is relevant for the memory task is maintained in working memory (Sala & Courtney, 2009; Serences, Ester, Vogel, & Awh, 2009). For example, Serences and colleagues showed that color and orientation of a memory item could be decoded from fMRI BOLD activity during the memory delay only when they were relevant for the upcoming memory task, but not when they were irrelevant (Serences et al., 2009). In line with these latter findings, our data also show that memory representations depend on task requirements, as inferred from the potency of memory representations to modulate the access of information to visual awareness. Taken together, whether or not incidental features are maintained in VWM (and thus affect concurrent visual processing) appears to vary from study to study, and could depend on subtle differences in stimulus properties and task instructions. For instance, different feature dimensions will inherently differ in terms of processing efficiency and discriminability, and it has been shown before that more discriminable features will be processed irrespective of task relevance, whereas less discriminable features will be processed only when they are task relevant (e.g., Gao, Li, Yin, & Shen, 2010). In this view, one interpretation of our results is that shape was less discriminable than color, and therefore only processed (to some extent) when it was task relevant, whereas color was processed regardless of task relevance. Conversely, because color was more discriminable than shape, the instruction to memorize the shape of an item yielded incidental maintenance of its color, so that color congruent stimuli were prioritized for visual awareness, even when color was an irrelevant feature dimension.

An even more complex picture emerges when considering Experiment 3, in which color and shape were both relevant for the upcoming memory task. When the color and shape were simultaneously maintained, only the color of the memorandum influenced access to awareness. The relative dominance of one feature dimension over the other (i.e., color over shape) when both features are memorized might also be explained by differences in discriminability or processing efficiency. There is some support for the view that color is more dominant than shape for visual processing (Soto et al., 2005; Williams, 1966; Fan et al., 2019; Soto et al., 2006; Wolfe & Horowitz, 2004). For instance, Williams (1966) reported that, when observers are instructed to search for a target number presented within objects of a pre-specified color and shape, observers would mostly fixate objects of the specified color, not of the specified shape. Similarly, requiring observers to memorize both the color and the shape of an item, Soto et al. (2005) observed that a color-congruent stimulus captures more attention than a color-incongruent stimulus, whereas shape congruency did not affect attentional capture. When only the shape was required for the memory task, Soto and Humphreys (2009) observed that only a distractor that matched both the color and the shape of the memory cue captures attention more strongly than a memory incongruent distractor. However, there is also evidence showing that shape information in VWM can affect visual processing of stimuli that are consciously perceived (i.e., attentional processes; Egly, Driver, & Rafal, 1994; Ghirardelli & Egeth, 1998; Olivers et al., 2006; Bahle et al., 2018; Fan et al., 2019), and even prioritize access to visual awareness in a b-CFS task (Gayet et al., 2020; behavioral experiment). As we presented stimuli that were initially not consciously perceived, it is difficult to compare these latter findings with the current findings. It could be argued that shape information (which relies on perceptual integration) affects visual processing more strongly if perceived consciously as compared to when not. Interestingly, in the study of Gayet and colleagues, shape stimuli were prioritized for awareness when they matched a shape maintained in VWM. This shows that, in principle, shape information can influence access to awareness of concurrently presented stimuli. It should be noted, however, that although the shape stimuli used by Gayet et al. were very similar to the shapes used in the current study, the current shapes were colored, whereas those of Gayet et al. were presented in grayscale. This adds to the evidence that the influence of shape information in VWM on access to awareness, can be negated by the presence of a more dominant feature (such as color). Taken together, the interaction between VWM and perception is subject to an intricate interplay of the different feature dimensions of multi-feature objects. While the relative dominance of the different feature dimensions of a memorandum might depend on experiment-specific stimulus characteristics, our current study does show that the influence of a memorandum on access to visual awareness can dramatically vary for the different feature dimensions of that memorandum. Moreover, the more dominant feature can strongly suppress the influence of the less dominant feature.

In sum, our current results suggest that (1) VWM can regulate the priority of visual information to access visual awareness along a single feature dimension; (2) features from different dimensions can impact the competition for awareness to a variable degree, and the more dominant feature may even suppress the effect of the less dominant feature; (3) even stimuli that match an irrelevant feature dimension of the memorandum can be prioritized for visual awareness.

CRediT authorship contribution statement

Yun Ding: Conceptualization, Methodology, Software, Investigation, Formal analysis. **Marnix Naber:** Conceptualization, Methodology, Supervision. **Chris Paffen:** Conceptualization, Methodology, Supervision. **Surya Gayet:** Conceptualization, Methodology. **Stefan Van der Stigchel:** Conceptualization, Methodology, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2020.103057.

References

Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science, 15*(2), 106–111. https://doi.org/10.1111/j.0963-7214.2004.01502006.x.

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.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.

Bundesen, C., Habekost, T., & Kyllingsbaek, S. (2005). A neural theory of visual attention: Bridging cognition and neurophysiology. *Psychological Review, 112*(2), 291–328. https://doi.org/10.1037/0033-295X.112.2.291.

Carlisle, N. B., & Woodman, G. F. (2011). Automatic and strategic effects in the guidance of attention by working memory representations. *Acta Psychologica, 137*(2), 217–225. https://doi.org/10.1016/j.actpsy.2010.06.012.

Costello, P., Jiang, Y., Baartman, B., McGlennen, K., & He, S. (2009). Semantic and subword priming during binocular suppression. *Consciousness and Cognition, 18*(2), 375–382. https://doi.org/10.1016/j.concog.2009.02.003.

Delvenne, J., & Bruyer, R. (2004). Does visual short-term memory store bound features? *Visual Cognition, 11*(1), 1–27. https://doi.org/10.1080/13506280344000167.

Ding, Y., Naber, M., Gayet, S., der Stigchel, S. V., & Paffen, C. L. E. (2018). Assessing the generalizability of eye dominance across binocular rivalry, onset rivalry, and continuous flash suppression, 6–6 *Journal of Vision, 18*(6). https://doi.org/10.1167/18.6.6.

Ding, Y., Paffen, C. L. E., Naber, M., & der Stigchel, S. V. (2019). Visual working memory and saliency independently influence the priority for access to visual awareness, 9–9 *Journal of Vision, 19*(11). https://doi.org/10.1167/19.11.9.

Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: Evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General, 123*(2), 161–177. https://doi.org/10.1037/0096-3445.123.2.161.

Fan, L., Sun, M., Xu, M., Li, Z., Diao, L., & Zhang, X. (2019). Multiple representations in visual working memory simultaneously guide attention: The type of memory-matching representation matters. *Acta psychologica, 192*, 126–137.

de Fockert, J. W., Rees, G., Frith, C. D., & Lavie, N. (2001). The role of working memory in visual selective attention. *Science, 291*(5509), 1803–1806. https://doi.org/10.1126/science.1056496.

Gao, Z., Li, J., Yin, J., & Shen, M. (2010). Dissociated mechanisms of extracting perceptual information into visual working memory. *PloS one, 5*(12).

Gayet, S., Van der Stigchel, S., & Paffen, C. L. E. (2014). Breaking continuous flash suppression: Competing for consciousness on the pre-semantic battlefield. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00460.

Gayet, S., van Maanen, L., Heilbron, M., Paffen, C. L. E., & der Stigchel, S. V. (2016). Visual input that matches the content of visual working memory requires less (not faster) evidence sampling to reach conscious access, 26–26 *Journal of Vision, 16*(11). https://doi.org/10.1167/16.11.26.

Gayet, S., van Moorselaar, D., Olivers, C. N. L., Paffen, C. L. E., & der Stigchel, S. V. (2019). Prospectively reinstated memory drives conscious access of matching visual input. *Scientific Reports, 9*(1), 1–12. https://doi.org/10.1038/s41598-019-41350-7.

Gayet, S., Paffen, C. L. E., Belopolsky, A. V., Theeuwes, J., & Van der Stigchel, S. (2016). Visual input signaling threat gains preferential access to awareness in a breaking continuous flash suppression paradigm. *Cognition, 149*, 77–83. https://doi.org/10.1016/j.cognition.2016.01.009.

Gayet, S., Paffen, C. L. E., & der Stigchel, S. V. (2013). Information matching the content of visual working memory is prioritized for conscious access. *Psychological Science*. https://doi.org/10.1177/0956797613495882, 0956797613495882.

Gayet, S., Guggenmos, M., Christophel, T. B., Haynes, J. D., Paffen, C. L., Sterzer, P., & Van der Stigchel, S. (2020). No evidence for mnemonic modulation of interocularly suppressed visual input. *NeuroImage*.

Ghirardelli, T. G., & Egeth, H. E. (1998). Goal-directed and stimulus-driven attention in cross-dimensional texture segregation. *Perception & Psychophysics, 60*(5), 826–838. https://doi.org/10.3758/BF03206066.

Gunseli, E., Meeter, M., & Olivers, C. N. (2014). Is a search template an ordinary working memory? Comparing electrophysiological markers of working memory maintenance for visual search and recognition. *Neuropsychologia, 60*, 29–38. https://doi.org/10.1016/j.neuropsychologia.2014.05.012.

Jiang, Y., Costello, P., & He, S. (2007). Processing of invisible stimuli: advantage of upright faces and recognizable words in overcoming interocular suppression. *Psychological Science, 18*(4), 349–355. https://doi.org/10.1111/j.1467-9280.2007.01902.x.

Liu, D., Wang, L., Wang, Y., & Jiang, Y. (2016). Conscious access to suppressed threatening information is modulated by working memory. *Psychological Science, 27*(11), 1419–1427. https://doi.org/10.1177/0956797616660680.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279–281. https://doi.org/10.1038/36846.

Luria, R., Balaban, H., Awh, E., & Vogel, E. K. (2016). The contralateral delay activity as a neural measure of visual working memory. *Neuroscience & Biobehavioral Reviews, 62*, 100–108. https://doi.org/10.1016/j.neubiorev.2016.01.003.

Luria, R., & Vogel, E. K. (2011). Shape and color conjunction stimuli are represented as bound objects in visual working memory. *Neuropsychologia, 49*(6), 1632–1639. https://doi.org/10.1016/j.neuropsychologia.2010.11.031.

O'Craven, K. M., Downing, P. E., & Kanwisher, N. (1999). FMRI evidence for objects as the units of attentional selection. *Nature, 401*(6753), 584–587. https://doi.org/10.1038/44134.

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.

Olson, I. R., & Jiang, Y. (2002). Is visual short-term memory object based? Rejection of the "strong-object" hypothesis. *Perception & Psychophysics, 64*(7), 1055–1067.

Pan, Y., Lin, B., Zhao, Y., & Soto, D. (2014). Working memory biasing of visual perception without awareness. *Attention, Perception, & Psychophysics, 76*(7), 2051–2062. https://doi.org/10.3758/s13414-013-0566-2.

Parra, M. A., Cubelli, R., & Della Sala, S. (2011). Lack of color integration in visual short-term memory binding. *Memory & Cognition, 39*(7), 1187–1197. https://doi.org/10.3758/s13421-011-0107-y.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*(4), 437–442. https://doi.org/10.1163/156856897X00366.

Pratt, J., & Hommel, B. (2003). Symbolic control of visual attention: The role of working memory and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 29*(5), 835–845. https://doi.org/10.1037/0096-1523.29.5.835.

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.

Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human primary visual cortex. *Psychological Science, 20*(2), 207–214. https://doi.org/10.1111/j.1467-9280.2009.02276.x.

Soto, D., Humphreys, G. W., & Heinke, D. (2006). Working memory can guide pop-out search. *Vision Research, 46*(6), 1010–1018. https://doi.org/10.1016/j.visres.2005.09.008.

Soto, D., & Humphreys, G. W. (2009). Automatic Selection of Irrelevant Object Features Through Working Memory. *Experimental Psychology, 56*(3), 165–172. https://doi.org/10.1027/1618-3169.56.3.165.

Soto, D., Heinke, D., Humphreys, G. W., & Blanco, M. J. (2005). Early, involuntary top-down guidance of attention from working memory. *Journal of Experimental Psychology. Human Perception and Performance, 31*(2), 248–261. https://doi.org/10.1037/0096-1523.31.2.248.

Stein, T., Hebart, M. N., & Sterzer, P. (2011). Breaking Continuous Flash Suppression: A New Measure of Unconscious Processing during Interocular Suppression? *Frontiers in Human Neuroscience, 5*. https://doi.org/10.3389/fnhum.2011.00167.

Stein, T. (2019). The breaking continuous flash suppression paradigm: Review, evaluation, and outlook. *Transitions Between Consciousness and Unconsciousness*. https://doi.org/10.4324/9780429469688-1.

Stuit, S. M., Verstraten, F. A. J., & Paffen, C. L. E. (2010). Saliency in a suppressed image affects the spatial origin of perceptual alternations during binocular rivalry. *Vision Research, 50*(19), 1913–1921. https://doi.org/10.1016/j.visres.2010.06.014.

Stuit, S. M., Paffen, C. L. E., van der Smagt, M. J., & Verstraten, F. A. J. (2011). Suppressed images selectively affect the dominant percept during binocular rivalry. *Journal of Vision, 11*(10), 7–7.

van Moorselaar, D., Gayet, S., Paffen, C. L. E., Theeuwes, J., Van der Stigchel, S., & Olivers, C. N. L. (2017). Competitive interactions in visual working memory drive access to awareness. *Cortex*. https://doi.org/10.1016/j.cortex.2017.03.026.

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance, 27*(1), 92–114. https://doi.org/10.1037/0096-1523.27.1.92.

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*(1), 48–64. https://doi.org/10.1037//0096-3445.131.1.48.

Williams, L. G. (1966). The effect of target specification on objects fixated during visual search. *Perception & Psychophysics, 1*(5), 315–318. https://doi.org/10.3758/BF03207398.

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience, 5*(6), 495–501. https://doi.org/10.1038/nrn1411.