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The priority for access to awareness of information matching VWM is mirror-invariant

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ABSTRACT

Previous studies suggest that 1) storing a visual representation of an item in visual working memory (VWM) prioritizes access to visual awareness for this item and that 2) VWM can contain representations of bound items instead of separate features. It is currently unclear whether VWM affects access to visual awareness at the individual feature level, the conjunction of multiple features level or the object level. To investigate this question, we conducted a series of experiments in which we combined a delayed match to sample task with a breaking Continuous Flash Suppression (b-CFS) task. On each trial, subjects memorized an object consisting of a disk with two halves with different colors for the later recall test and, between them, had to detect the location of a target initially presented under suppression. We varied the congruence in colors between the memory representation and to-be-detected target. Our results show that memory congruent objects (consisting of a conjunction of features) break CFS faster than memory incongruent objects. Interestingly, we also observe this congruence effect when we presented the memorized object in a horizontally-mirrored configuration of colors. However, we do not observe a faster effect when the target shares only a single feature of a memorized object (semi-congruent) or when the memory congruent target is rotated by 90°. Our results suggest that VWM prioritizes access to visual awareness for complex visual memoranda for which the spatial lay-out of the individual features does not need to exactly match the lay-out of the memoranda.

1. Introduction

When we open our eyes, our visual system is bombarded with visual input. Our brain is not equipped to process all of this information to the same extent and most of the visual information that is presented to our retinae therefore does not give rise to conscious experience (B.J. Baars, 1997, B.J. Baars, and Baars, S. F. in T. N. B. J, 1997, Dennett, 1993). Because of the limited capacity of visual awareness, some of the visual information needs to be prioritized for access to visual awareness. For instance, previous studies observed that upright bodies enter visual awareness more rapidly than inverted bodies and that the same holds for recognizable versus scrambled words and fearful versus neutral stimuli (Costello, Jiang, Baartman, McGlennen, & He, 2009; S. Gayet, Paffen, Belopolsky, Theeuwes, & Van der Stigchel, 2016; Jiang, Costello, & He, 2007; T. Stein, Sterzer, & Peelen, 2012; Yang, Zald, & Blake, 2007). The visual system has evidently evolved to prioritize relevant information for access to visual awareness.

To what degree a stimulus receives priority for visual awareness is generally measured with a paradigm termed breaking continuous flash suppression (b-CFS). In b-CFS a target stimulus is rendered unaware by presenting it to one eye while the other eye is presented with strong dynamic stimuli (i.e., a mask). Because the mask suppresses the target, it takes some time until the target enters awareness. This breakthrough period typically lasts a couple of seconds, and the time it takes for a stimulus to be detected by the observer is an index of the degree to which the target received priority to access visual awareness. Importantly, not only stimulus properties impact visual processing and priority to access awareness. By combining b-CFS and a VWM task (Jiang et al., 2007; Mudrik, Breska, Lamy, & Deouell, 2011; Tsuchiya & Koch, 2005), Gayet, Paffen, and Stigchel (2013; S. Gayet, van Maanen, Heilbron, Paffen, & der Stigchel, 2016; S. Gayet, van Moorselaar, Olivers, Paffen, & der Stigchel, 2019) were able to find that a memory congruent target breaks into awareness more rapidly than a memory incongruent target. This means that if an object is held in working memory, it will enter awareness quicker than other objects. This phenomenon also applies when multiple objects are remembered: a later study showed that when two items (i.e., distinct in color) are memorized one by one, both items will receive priority (van Moorselaar et al., 2017). However, the question remains which aspects of the items are memorized and affect the prioritization for awareness. Previous

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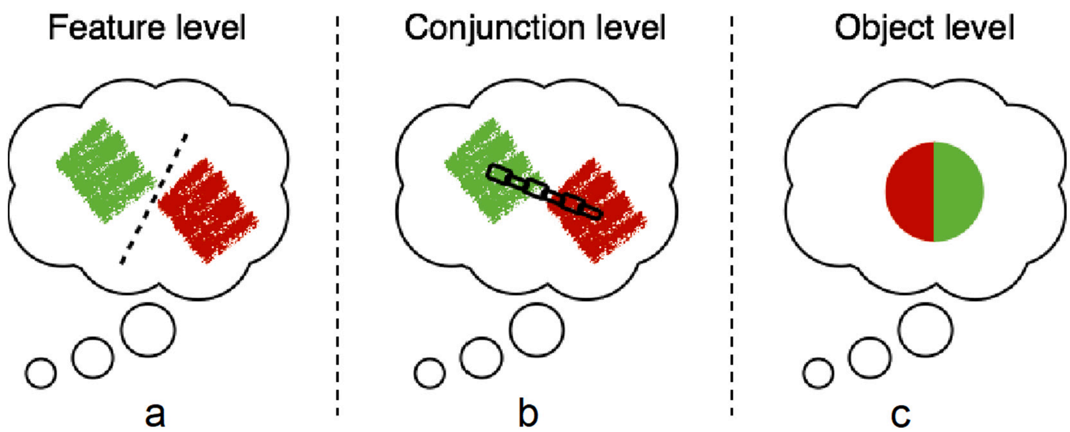

Fig. 1. VWM could regulate the priority for access to visual awareness at (a) the feature level, (b) the conjunction level, or (c) the object level. The disk with two colors in the object level (c) is an example of a stimulus used in the current study and here represents an exact copy (i.e., colors combination, orientation, and shape is preserved). Note that the feature level (a) contains only the unbound individual colors of the object while the intermediate, conjunction level (b) also contains spatially-bound colors.

evidence about the influence of visual memoranda on visual awareness is based on simple targets, typically consisting of a disk with a single specific color. As studies have suggested that even complex visual stimuli (multi-featured, e.g., faces) which are stored in VWM can also facilitate priority to visual awareness (Liu, Wang, Wang, & Jiang, 2016; Pan, Lin, Zhao, & Soto, 2014), this means that VWM could regulate the priority for visual awareness of items consisting of multiple features. However, these previous studies do not tell us whether VWM regulates the priority for access to visual awareness at 1) the individual feature level 2) the conjunction of multiple features level or 3) the object level (see Fig. 1). For instance, when holding a two-colored Pepsi logo in VWM, it could be that a product which shares one color of the logo enters awareness faster in a supermarket (i.e. at the individual feature level), or that objects share multiple features of the logo but the lay-out of the features does not need to exactly match the lay-out of the logo are prioritized (at the conjunction level). Alternatively, it could be that only an exact copy containing the colors in the same spatial arrangements as the memorized object is prioritized for conscious access (the object level). Our current study aims to answer this question.

Answering this question addresses one of the most heated debates in VWM literature, namely the extent to which VWM can store items as bound conjunctions or not. For instance, Luck and Vogel (1997) reported that VWM contains representations of conjunctions instead of separate features. They found that the accuracy to memorize multiple stimuli was about equal when the stimuli contained a single varying feature (a single color) or when stimuli consisted of multiple features. However, the debate whether WM stores bound object representation is still ongoing, mainly because a number of subsequent studies reported divergent evidence: some studies find results in favor of bound object representations in VWM (Luria & Vogel, 2011; Vogel, Woodman, & Luck, 2001), whereas other studies reported that memoranda are stored as single features (Alvarez & Cavanagh, 2004; Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Parra, Cubelli, & Della Sala, 2011; Wheeler & Treisman, 2002). For example, Alvarez et al. showed that the accuracy for remembering complex objects is less that than for simple objects. Knowing at which level VWM regulates the access to visual awareness helps us to understand how VWM content is represented.

Our main question is whether VWM affects access to awareness at the feature, conjunction or object level. To answer this question, we combined a VWM task with a b-CFS task in our experiments: on each trial subjects memorized an object which consisted of multiple features for the later recall phase and, between the memorization and recall, indicated the target location during the b-CFS period. We varied the congruency between the b-CFS targets and the memory probes at the single feature level, the conjunction level and the object level. By comparing the durations for the b-CFS targets to break into awareness, we could quantify how and at what level of processing VWM affects access to visual awareness.

2. Experiment 1

2.1. Method

2.1.1. Observers

After informed consent was obtained, 26 observers (5 males; mean age 24.00, SD = 4.02) participated in Experiment 1 for monetary reward. All observers reported having normal or corrected-to-normal sight and having no visual disorder or epilepsy. This study was approved by the Ethics Committee at the Faculty of Social and Behavioral Sciences of Utrecht University and was conducted in accordance with the Declaration of Helsinki.

2.1.2. Apparatus, stimuli, and procedure

A PC equipped with a linearized 27-inch LCD monitor (2560 by 1440 pixels, 144-Hz refresh rate) was used to conduct the experiments. A stereoscope with four mirrors (two per eye) was fixed on a chinrest to achieve dichoptic presentation for b-CFS. Stimuli were presented on a gray background and were viewed from approximately 61 cm. As illustrated in Fig. 2, the stimulus area presented to each eye was enclosed by a Brownian (i.e., 1/f2) noise square frame with a height and width of 7.5° and a thickness of 0.25°. The square was identical for both eyes and was used to promote binocular fusion. The colors used in the WM and b-CFS task (red, green, blue, and purple) were perceptually equal in luminance to prevent differences in luminance to (1) affect memory performance, and (2) to affect b-CFS breakthrough-times[1]. Two hundred different binary patterns (0 and 41.80 cd/m2 for black and white parts, respectively), that consisted of pink noise images filtered by a Gaussian low-pass filter (ó = 3.2), were generated before the experiment as the CFS masks.

Before the main experiment, we measured each observer's dominant eye with a b-CFS task because eye dominance is task specific (Y. Ding,

[1] The low-luminance blue color was best suited as the baseline luminance reference to which the other colors were subjectively matched with heterochromatic flicker photometry (Kaiser & Comerford, 1975; Wagner & Boynton, 1972). The hues of each color were slightly different but, about equal in luminance. We produced the hues using two selection steps: First, we identified the location of each of the five color categories into an equiluminant plane in CIE 1931 color space. Next, two more hues of each color category were chosen from this plane.

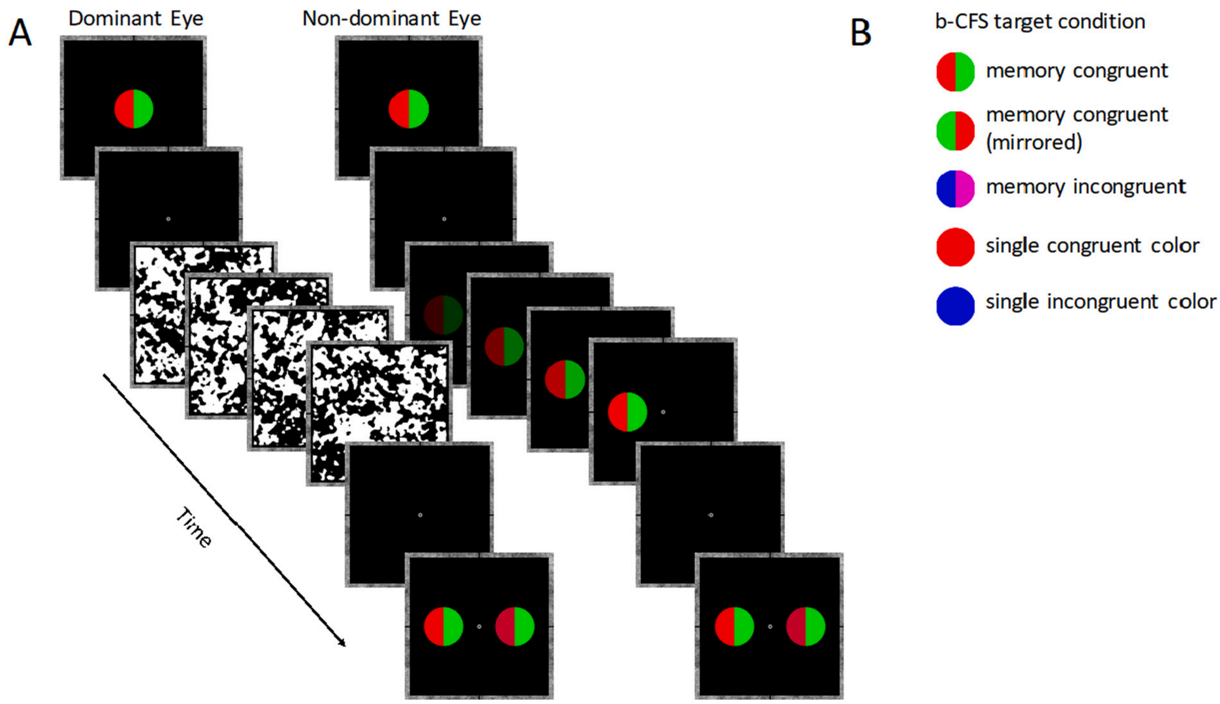

Fig. 2. (A) Example trial sequence showing a Memory Congruent trial. Subjects were instructed to memorize the item consisting of two colors in the memory phase. In the suppression phase, the dynamic masks were presented to the dominant eye and a target ramped up to full contrast in the other eye, and observers were required to indicate as soon as possible whether the target appeared to either left or right of the fixation. Trials ended with the recall phase, in which two colored items of same color category but one of the hues was not identical as the memory item, and the observers had to indicate the item which were identical to the memory one. (B) Examples of the b-CFS target conditions.

Naber, Gayet, der Stigchel, & Paffen, 2018). In the main experiment, the b-CFS masks were always presented to the dominant eye. As depicted in Fig. 2A, each trial in the main experiment started with a fixation point presented for 500 ms. The memory probe consisting of a disk with two halves with different colors (size of 1.2° visual angle (VA)) was presented at the fixation position for 2000 ms. The two colors were chosen from the color set (a pair from all possible combinations of red, green, blue and purple) and were to be memorized for later recall. After presenting a blank screen for 2000 ms, the b-CFS task started by presenting a disk of 1.2° VA (the b-CFS target) to the non-dominant eye and the CFS mask (refreshing at 10 Hz) to the dominant eye. The intensity (i.e., transparency) of the disk in the b-CFS task increased linearly within 1.5 s. Observers were instructed to respond by pressing the left or right arrow button as soon as they saw the target appearing either to the left or to the right of fixation, respectively. The b-CFS task lasted until observers responded or until 20 s without a response had passed. 500 ms after the disappearance of the b-CFS stimulus, the memory recall task started. During this phase, we presented two discs (size of 1.2° VA) left and right of fixation until observers chose which of the two options matched the memorized stimulus. Each disc consisted of two colors: one disc was identical to the probe disc, the other disc had one identical half and one half of which the color was of the same category, but of a slightly different hue. This small adjustment made the task difficult enough to prevent ceiling effects in the memory performance and to prevent that memory stimuli were encoded verbally or categorically. The colors with adjusted hues were equiluminant to that of the memory probe and b-CFS target colors. A trial was ended with feedback to the observers if an incorrect response was given in either the b-CFS and memory task.

The stimuli presented during the b-CFS phase defined five main conditions (Fig. 2B). On Memory Congruent trials (condition 1), the b-CFS target was identical to the probe disk. On Memory Congruent Mirrored trials (condition 2), the left and right halves of the disk matched the colors of the *right* and *left* halves of the probe disk, respectively. On Memory Incongruent trials (condition 3), both halves of the disk were of different color categories than the probe disk. On Single Memory Congruent trials (condition 4), the disk contained only one color which was one of the two colors of the probe disk. On Single Memory Incongruent color trials (condition 5), the disk contained only one color category which was different from either one of the probe disks. A total of 5 (main conditions) × 4 (number of probed colors) × 3 (number of hues) conditions was used. As each unique combination was presented for 4 times, each observer performed in 240 trials.

By comparing b-CFS durations on the first three conditions, we investigated whether VWM content affects access to visual awareness at the conjunction level; by comparing the b-CFS durations on the last two conditions, we investigated whether VWM content affects access to visual awareness at the feature level.

2.2. Data analysis and results

One observer was excluded from the analysis because the accuracy on the memory task was lower than the 50% chance level (for the rest subjects, M = 73.91% correct, SD = 7.27%). Only trials in which observers indicated the correct target location were included in the response-time (RT) analysis of the b-CFS task (fewer than 3% (SD = 1.86%) of the trials were incorrect). We determined observers' median RTs for each memory condition. No trials were lost because of RT outliers. The extent to which observers exhibit different effects in b-CFS varies extensively (in the range of hundreds of milliseconds) which might result in a large difference in RTs between observers. Since the within-subject comparison does not remove the variability between subjects, we transformed the RTs with a latency-normalization method[2] (S. Gayet & Stein, 2017) for the analyses to remove the between-subject

[2] The formula here depicts how to transform the RT of condition A with latency-normalization method: $RT_{A\ TRANSFORMED} = 100 * \frac{RT_A}{mean(RT_{OVERALL})}$

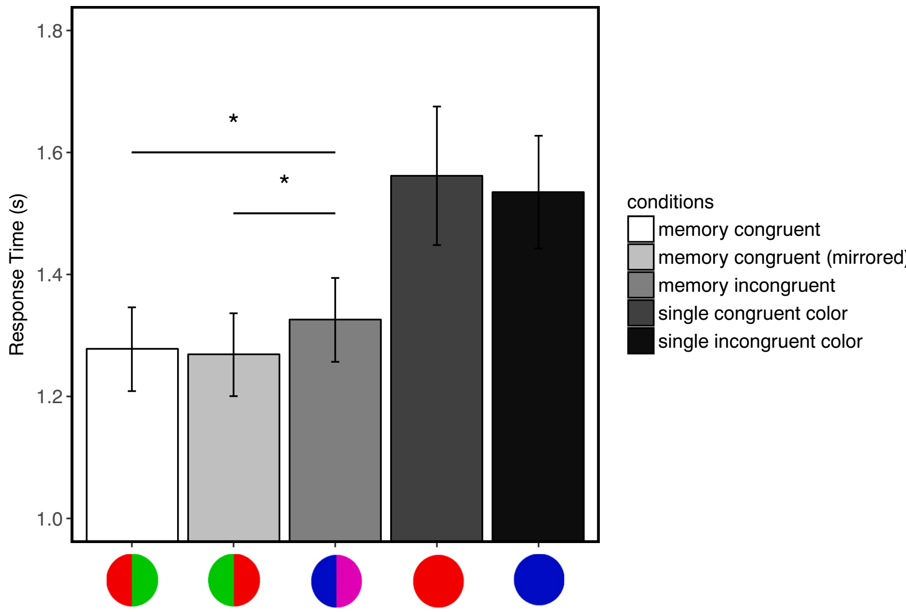

Fig. 3. Response times as a function of different b-CFS conditions for the main experiment (*$p < 0.05$). Error bars denote ± 1 SEM.

variability in suppression duration from the effect of interest. To facilitate the interpretation for the reader, however, the RTs reported in the text and depicted in the figures express the raw RTs.

The effects of VWM on RTs in the b-CFS task were analyzed with a repeated-measures ANOVA. As depicted in Fig. 3, we observed significant main effects of b-CFS condition ($F(4, 96) = 25.08, p < 0.001$). The subsequent paired-sample two-tailed *t*-tests show that: 1) observers detected memory congruent targets and left-right mirrored memory congruent targets faster than memory incongruent targets (Memory Congruent vs. Memory Incongruent: 1277 ms vs. 1326 ms, $t(24) = 2.67, p < 0.02, \eta_G^2 = 0.30$; Memory Congruent Mirrored vs. Memory Incongruent: 1268 ms vs. 1326 ms, $t(24) = 2.66, p < 0.02, \eta_G^2 = 0.33$); 2) there was no difference between detecting memory congruent targets as and the left-right mirrored memory congruent targets ($t(24) = 0.19, p = 0.85, \eta_G^2 = 0.02$); 3) there was no significant difference between RTs of single memory congruent color targets and single memory incongruent color targets ($t(24) = 0.47, p = 0.64, \eta_G^2 = 0.10$). The t-tests were not corrected since we designed the comparisons in the experiments beforehand and we only focused on these comparisons.

The results of Experiment 1 show that 1) a disc containing two colors was detected faster than a disc of one color and we reason that the former is more dominant to break interocular suppression because of a higher spatial frequency, which is not relevant to our current question; 2) a two-color disc was detected faster when the colors matched rather than mismatched the colors of the probe disc.[3] Interestingly, there was no difference in RTs between the identical and mirrored colors disc. One potential explanation for this result is that in Experiment 1, only the colors of the memory disk were tested in the recall task but not the left-right order of the colors. Thus, it is reasonable to query whether the lack of requiring subjects to memorize the left-right order of the disk could result in specific memory strategy (e.g., subjects memorizing the color combination of the memory disk and ignoring the color sequence). Experiment 2 was dedicated to tackle this possible confound.

3. Experiment 2

3.1. Method

3.1.1. Observers

To retain the statistical power, we recruited more subjects in Experiment 1 which had five conditions and fewer subjects in Experiment 2 which had three conditions. Sixteen observers participated in Experiment 2, one of them was replaced by a new observer because the memory accuracy was lower than 50% chance level (2 males; mean age 24.13, SD = 4.30). All reported having normal or corrected-to-normal sight and having no epilepsy or visual disorder.

3.1.2. Apparatus, stimuli, and procedure

The method was the same as in the first experiment except for the following changes: Three of the main conditions of Experiment 1 were included in Experiment 2 (the Memory Congruent condition, Memory Incongruent condition, and Memory Congruent Mirrored condition). In the memory recall task, per trial either hue or the left-right order of the colors were tested with equal chance (50% of the trials randomly occurring for each) to assess whether the memorization of order made the spatial layout relevant for the b-CFS task. When order was tested, observers had to indicate which of the two stimuli, one of which was horizontally mirrored, was the memory probe.

4. Results

The data were analyzed in the same way as for Experiment 1. Observers performed well in both the b-CFS task (fewer than 2% responses were incorrect, SD = 2.40%) and the memory task (accuracy for the color test, $M = 74.48\%$, $SD = 11.68\%$; accuracy for the order test, $M = 90.89\%$, $SD = 11.39\%$).

The transformed RTs were analyzed with a repeated-measures ANOVA, and the results show marginally significant effects of VWM on RTs ($F(2,30) = 2.69, p = 0.08$). Next, post hoc tests were conducted with

[3] To exclude a potential priming effect, we, as previous studies did (Ding et al., 2019; Gayet et al., 2013), conducted a control experiment in which observers were required to passively view the probe before the b-CFS task. We also removed the recall phase on each trial. The b-CFS target could be either congruent or incongruent with the probe. For 12 observers, our results show that there was no effect of priming ($t(11) = 0.17, p = 0.87, \eta G^2 = 0.01$): WM-matching targets were not detected faster than WM-mismatching targets when observers passively viewed the probe. These results indicate that the memory congruent facilitation in our experiments cannot be explained by bottom-up priming.

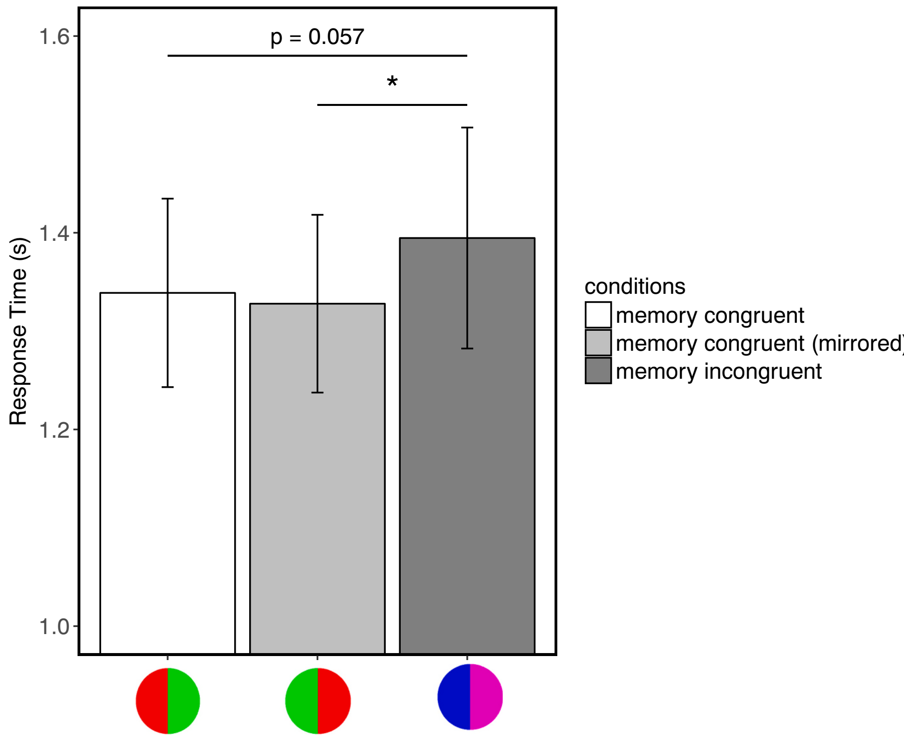

Fig. 4. Response times as a function of different b-CFS conditions for the main experiment (*$p < 0.05$). Error bars denote ± 1 SEM.

one-sided *t*-tests since Experiment 2 involved a replication of Experiment 1. As illustrated in Fig. 4, the results show that: 1) a marginally significant difference between the RTs on the memory congruent trials and the memory incongruent trials was observed (Memory Congruent vs. Memory Incongruent: 1339 ms vs. 1395 ms; $t(15) = 1.68$, $p = 0.057$, $\eta_G^2 = 0.73$); 2) observers detected left-right mirrored memory congruent targets faster than memory incongruent targets (Memory Congruent Mirrored vs. Memory Incongruent: 1329 ms vs. 1395 ms; $t(15) = 2.30$, $p = 0.026$, $\eta_G^2 = 0.89$); 3) there was no difference between RTs on memory congruent targets and left-right mirrored memory congruent targets ($t(15) = 0.43$, $p = 0.34$, $\eta_G^2 = 0.16$).

The replicated facilitated response for both the identical and left-right mirrored memory congruent targets suggests that configuration of the two colors is mirror-invariant for VWM content prioritizing access to visual awareness of matching visual input. However, it is still too preliminary to conclude that VWM prioritizes access to visual awareness at the conjunction level. This is because, in the memory congruent (mirrored) trials, the targets always consisted of two halves with the same colors (and perhaps different spatial layout), and either of the halves could be a memory feature which resulted in the facilitated response in the b-CFS task. That is to say: perhaps the facilitated response can be observed whenever a single color of a two-color disc matches a color of the memory probe. Experiment 3 was conducted to test whether the combination of two matching colors is necessary for the facilitated response to occur.

5. Experiment 3

5.1. Method

5.1.1. Observers

Sixteen observers participated in Experiment 3, one of them was removed and replaced by a new observer since the individual failed to keep stable binocular vision (6 males; mean age 23.47, SD = 1.84). All observers reported having normal or corrected-to-normal sight and having no epilepsy or visual disorder.

5.1.2. Apparatus, stimuli, and procedure

The current method was identical to the methods of the previous experiments except that the memory congruent mirrored condition was replaced by a one color memory congruent condition in which the b-CFS target was composed of two colors and where one of the halves was of the same color category as the memory probe (see x-axis of Fig. 5).

5.2. Results

All observers performed well in both the b-CFS task (fewer than 2% trials were incorrect (SD = 2.32%)) and the memory task (accuracy for the color test, $M = 76.61\%$, $SD = 10.16\%$; accuracy for the order test, $M = 95.72\%$, $SD = 10.16\%$).

The transformed RTs were entered in an analysis consisting of a repeated-measures ANOVA. As Fig. 5 illustrates, the results showed that VWM affected RTs in the b-CFS task ($F(2, 30) = 3.65$, $p < 0.04$). The post hoc two-tailed *t*-tests showed that: 1) observers detected memory congruent targets faster than memory incongruent targets and one color memory congruent targets (Memory Congruent vs. Memory Incongruent: 1219 ms vs. 1263 ms; $t(15) = 2.39$, $p = 0.03$, $\eta_G^2 = 0.95$; Memory Congruent vs. One Color Memory Congruent: 1219 ms vs. 1266 ms; $t(15) = 2.21$, $p = 0.04$, $\eta_G^2 = 0.91$); 2) There was no difference between the RTs on detecting memory incongruent trials and one color memory congruent trials ($t(15) = 0.12$, $p = 0.91$, $\eta_G^2 = 0.05$).

The results of Experiment 3 show that only when both colors of the disc match the memory probe, access to visual awareness is prioritized. This indicates that VWM regulates the access to visual awareness for the objects at the conjunction level. However, it is still not possible to conclude that the spatial lay-out of the individual features is irrelevant. Such a conclusion would be strengthened when matching probes are also prioritized when probe and b-CFS target are oriented differently. In Experiment 4, we manipulated the orientation of the b-CFS targets to investigate whether the spatial lay-out of a VWM conjunction affects the priority to access visual awareness.

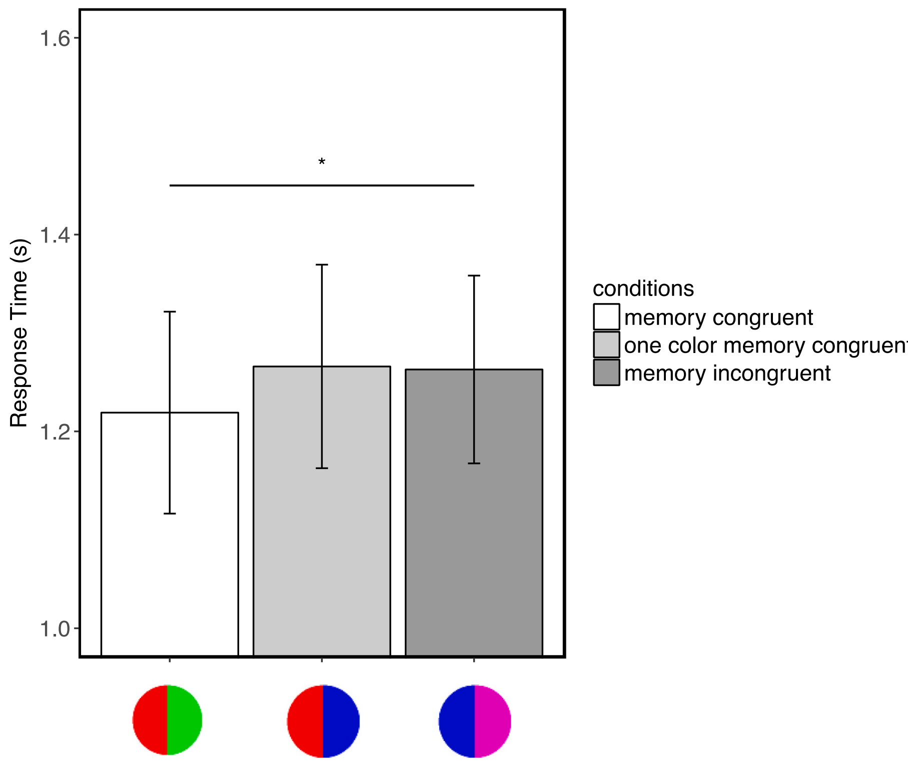

Fig. 5. Response times as a function of different b-CFS conditions for the main experiment (*$p < 0.05$). Error bars denote ± 1 SEM.

6. Experiment 4

6.1. Method

6.1.1. Observers

Eleven observers (4 males; mean age 24.36, SD = 5.41) participated in this experiment and all observers reported having (corrected to) normal sight and having no epilepsy or visual disorder.

6.1.2. Apparatus, stimuli, and procedure

The current method was identical to the methods of the previous experiment except that we replaced the b-CFS conditions with a horizontally oriented memory congruent condition and a horizontally oriented memory incongruent condition. In these conditions the b-CFS targets were the same as the memory congruent target and memory incongruent target of Experiment 3, except for the fact that they were flipped 90° clockwise or counterclockwise for each trial (see x-axis of Fig. 6).

6.2. Results

All observers performed well in both the b-CFS task (fewer than 2% responses were incorrect on average; SD = 1.02%) and the memory task (accuracy for the color test: M = 77.46%, SD = 4.82%; accuracy for the order test: M = 92.42%, SD = 6.80%).

As illustrated in Fig. 6, the results showed no difference between the RTs on detecting horizontally oriented memory congruent targets (1050 ms) and horizontally oriented memory incongruent targets (1060 ms); $t(10) = 0.39$, $p = 0.71$, $\eta_G^2 = 0.19$).

The results of Experiment 4 show that a disc is not prioritized to visual awareness when it matches the memory probe with respect to its colors but not with respect to its spatial orientation, suggesting that the spatial information of the VWM content, to some extent, regulates the visual awareness access. Combing these results with those of the first three experiments, objects that share multiple but not all features (e.g., the colors and spatial orientation but not the exact lay-out) of the memory object are prioritized, suggesting that VWM prioritizes the access to visual awareness for objects at the conjunction level but not at the object level.

6.3. Discussion

Recent research suggests that VWM can regulate access to visual awareness of incoming visual information (Gayet et al., 2013; S. Gayet, Paffen, et al., 2016; S. Gayet et al., 2019; van Moorselaar et al., 2017; Liu et al., 2016; Pan et al., 2014; Y. Ding, Paffen, Naber, & der Stigchel, 2019). Here we have examined whether VWM exerts this influence at the individual feature level, the conjunction level or the object level (see Fig. 1). We have combined a unique version of the VWM and b-CFS task to find that a target consisting of two color categories matching the content of VWM probe broke CFS faster than memory mismatching objects. Interestingly, we observe that this congruency effect was preserved when we presented the matching object in a configuration that mirrored the probe colors. Additionally, we did not observe the congruency effect when the object shared only a single feature or when the object did not share the spatial orientation of the memorized probe. It could be argued that the lack of a facilitation effect for a congruent single color target in Experiment 1 was due to observers' shift in post-conscious response criterion instead of conscious access (e.g., response strategy). A monocular control experiment which includes the presentation of the b-CFS target superimposed on the dynamic masks and together presented to the same eye has been used by previous studies to investigate this possibility. Importantly, these studies (Gayet et al., 2013; Y. Ding et al., 2019) observed no facilitation effect of the memory congruent target in monocular control experiments, suggesting that the memory congruent facilitation effect is not due to response strategy. In sum, the results show that VWM prioritizes the access to visual awareness for targets at the conjunction level but not at the individual feature level or at the object level. The priority for access to awareness of the information matching VWM is mirror-invariant.

van Moorselaar et al. (2017) have observed that multiple memorized colors receive priority to access visual awareness (van Moorselaar

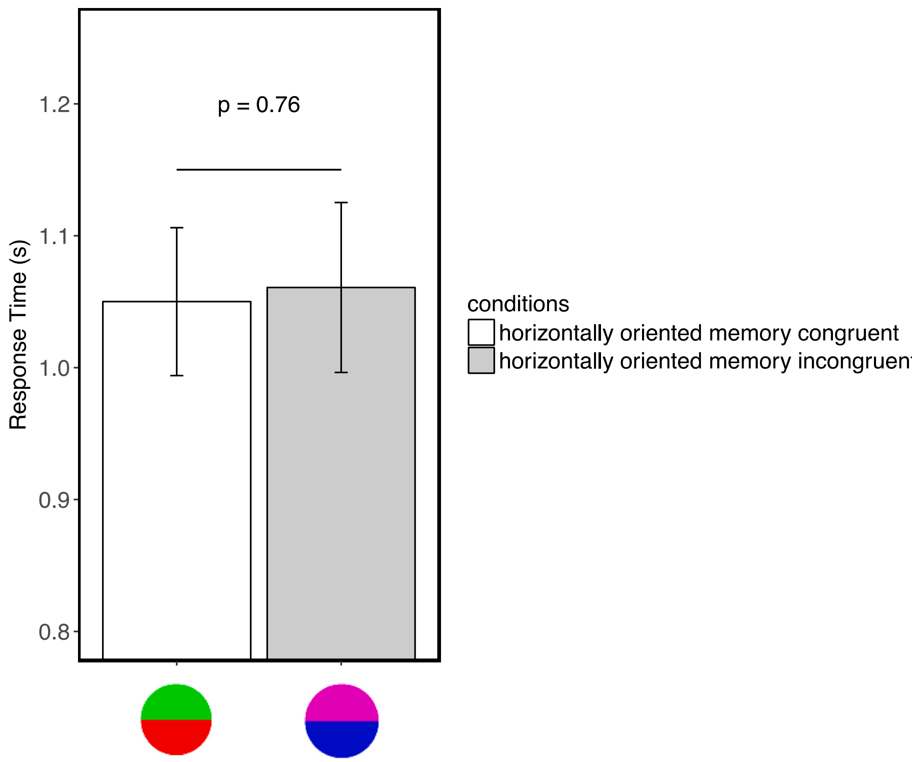

Fig. 6. Response times as a function of different b-CFS conditions for the main experiment (*$p < 0.05$). Error bars denote ± 1 SEM.

et al., 2017). We extend this observation with the finding that also multiple, spatially-bound colors are prioritized to access visual awareness, and we additionally find evidence that this process operates at an intermediate, conjunction level at which the spatial layout of the object does not need to exactly match the lay-out of the memoranda. That the content of VWM interacts with visual awareness at this level is not trivial. To clarify, let us use the search for the logo of a Pepsi can or bottle, as described earlier in the Introduction, as an analogy. When searching for a Pepsi can in a filled fridge, looking for the exact red-blue color combination through tolerating some variation of the spatial layout (e.g., the left-right sequence) of the logo would be the most efficient strategy, because the can might lie upside down. In contrast, using a search (or prioritization) template of the exact Pepsi logo with a specific color arrangement and spatial lay-out will limit search performance. Therefore, a prioritization strategy at the object level will fail to help observers to become aware of relevant objects mismatching any spatial layout. On the other side of the spectrum lies the use of multiple search templates of each individual aspects of the Pepsi logo; a strategy that is too liberal and will prioritize many irrelevant objects in the fridge (e.g., a red Babybel cheese package will cause false alarms and will cause inefficient search). At least within the realm of the current study, and the examples of real-life search mentioned above, it thus most useful to have VWM operate at an intermediate, conjunction level. It will be interesting, though, to investigate in future studies whether the level at which VWM and visual awareness interact can be (in)voluntarily changed depending on the task.

How do our findings relate to previous studies that examined how VWM retains several features? A large body of studies have not yet reached consensus on this topic, withholding us from choosing between the options that VWM representations operate as either the bound conjunctions or independent features level (Luck & Vogel, 1997; Vogel et al., 2001; Luria & Vogel, 2011; c.f., Wheeler & Treisman, 2002; Olson & Jiang, 2002; Parra et al., 2011; Awh, Barton, & Vogel, 2007; Alvarez & Cavanagh, 2004). We can conclude from the current results that the interaction between VWM and visual awareness can be best described by a process that lies in between the two theoretical viewpoints: when two colors are to be encoded simultaneously, the colors are stored as conjunctions and not as independent features (Brady & Alvarez, 2011).

Another interesting line of research to pursue is to use combinations of features from different domains, for example features that define what an object is (i.e., contour and shape; Lamme & Roelfsema, 2000). Instead of using two different colors, follow-up experiments may try to combine colors and shapes to see whether both a b-CFS should share both features with the memory probe in order to be prioritized. For example, a previous study suggests that an object's shape may have different effects on visual processing than colors (Soto, Heinke, Humphreys, & Blanco, 2005). These authors observed that objects matching memorized representations at both color and shape can speed observers' search performance but not when only the shape is matched. As more studies are needed to generalize these findings to other features, we leave the possibility open that not all features can be bound to regulate visual processing.

To conclude, previous studies have repeatedly reported that VWM can modulate the access to visual awareness (Gayet et al., 2013; Pan et al., 2014; Liu et al., 2016; van Moorselaar et al., 2017). Our present experiments provide clear evidence this process can operate at the conjunction level, which is an intermediate stage of the visual hierarchy (Alvarez & Cavanagh, 2004) preceding the stage of binding features into coherent objects.

CRediT authorship contribution statement

Yun Ding: conceptualization, methodology, software, investigation, formal analysis, writing and editing

Marnix Naber: conceptualization, methodology, editing, supervision

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Stefan Van der Stigchel: conceptualization, methodology, editing, supervision

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Appendix A. Supplementary data

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