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Competitive interactions in visual working memory drive access to awareness

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ABSTRACT

Models of biased competition assume that pre-activating a visual representation in visual working memory (VWM) biases perception towards memory-matching objects. Consistent with this, it has been shown that targets suppressed by interocular competition gain prioritized access to awareness when they match VWM content. Thus far, these VWM biases during interocular suppression have been investigated with minimal levels of competition, as there was always only one target stimulus and observers only held a single item in VWM. In the current study we investigated how VWM-based modulation of access to awareness is influenced by a) multiple-item competition within the stimulus display and b) multiple-item competition within VWM. Using the method of breaking continuous flash suppression (b-CFS), we replicated the finding that information matching the content of VWM is released from interocular suppression faster than non-matching information. This VWM-based facilitation was significantly reduced, though still present, when VWM load increased from one to two items, demonstrating a clear competitive constraint on the top-down modulation by VWM. Furthermore, we manipulated inter-stimulus competition by varying the presence of distractors. When distractors were present, VWM-based facilitation was no longer specific to interocular suppression, but also occurred for monocular displays. The results demonstrate that VWM-based visual biases occur in response to competition, whether between or within the eyes, and reconcile findings from different paradigms.

1. Introduction

The visual information available in a typical scene by far surpasses the processing capacity of the visual system. Consequently, many different objects compete for neural representation, leading to mutual suppression of visually evoked neural responses (Beck & Kastner, 2009). According to models of biased competition, this ongoing battle can be resolved by giving a particular stimulus a competitive

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advantage over others, through pre-activation of its representation in visual working memory (VWM; Desimone & Duncan, 1995). Consistent with this viewpoint, studies using the method of *breaking continuous flash suppression* (b-CFS; Jiang, Costello, & He, 2007; Stein, Hebart, & Sterzer, 2011; Gayet, Van der Stigchel, & Paffen, 2014) have shown that information matching the content of VWM has a competitive advantage in access to awareness (Gayet, Paffen, & Van der Stigchel, 2013; Gayet, van Maanen, Heilbron, Paffen, & Van der Stigchel, 2016; Pan, Lin, Zhao, & Soto, 2014).

The b-CFS paradigm inherently capitalizes on strong interocular competition, as a target stimulus presented to one eye is temporarily suppressed from awareness by a high contrast dynamic pattern presented to the other eye. The time it takes for the target to overcome this interocular suppression is taken as a measure to what degree a stimulus is prioritized for access to awareness. Gayet et al. (2013) and Pan et al. (2014) found that targets matching the content of VWM broke through interocular suppression more rapidly than items that were not in memory. Interestingly, no such advantage for VWM-matching stimuli was found when displays were presented monocularly, suggesting that the bias in access to awareness is specific to interocular competition. However, this would be at odds with many earlier findings showing prioritized processing for VWM-matching stimuli in paradigms that do not involve any interocular suppression, most notably visual search tasks (e.g., Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005), and would be surprising given the assumed functional role of VWM in biasing competition in general.

One major difference between the b-CFS paradigm and the visual search paradigm in investigating VWM-based biases is that the b-CFS paradigm typically involves strong interocular competition, but no inter-item competition, whereas visual search involves no interocular competition, but typically strong inter-item competition. Previous studies incorporating visual search paradigms have argued for stronger attentional biases the more competition there is from distracting stimuli (Hickey, Olivers, Meeter, & Theeuwes, 2011; Lamy, Zivony, & Yashar, 2011; Meeter & Olivers, 2006). This feeds the hypothesis that VWM-based biases are tied to competition in general also in b-CFS type tasks, and not specific to interocular suppression. Thus far, VWM-based facilitation in b-CFS paradigms has only been investigated with minimal levels of inter-item competition, as these studies have only used single-item target displays. In the present study we therefore combined b-CFS with different levels of competition in the stimulus displays to assess the role of competition in access to awareness. Specifically, we were interested to examine whether a) VWM-based biases during suppression are increased when interocular competition is combined with inter-item stimulus competition, and b) whether VWM-based facilitation is limited to interocular competition in this type of task, or generalizes to monocular conditions when the inter-item competition is increased.

Inter-item competition is not limited to processing of new sensory input, but also occurs within VWM (Franconeri, Alvarez, & Cavanagh, 2013; Wei, Wang, & Wang, 2012). In the context of visual search such competition appears to attenuate VWM-based biases. Consistent with models of biased competition, during visual search selection is inadvertently biased towards memory-matching distractors (e.g., Olivers et al., 2006; Soto et al., 2005). However, loading VWM with two or more items significantly reduces VWM-based attentional capture, to the point that it is virtually abolished (Moorselaar, Battistoni, Theeuwes, & Olivers, 2015; van Moorselaar, Theeuwes, & Olivers, 2014). On the one hand, such a strict capacity limitation appears surprising, as holding two items in VWM is still well within traditional capacity limits (Zhang & Luck, 2008). On the other hand, it is directly in line with a single-item attentional template model proposed by Olivers, Peters, Houtkamp, and Roelfsema (2011). In that model, although VWM as a whole can maintain multiple items simultaneously, only a single item at a time can be kept in a state that has access to, and can thus bias, perception. The absence of any significant VWM-based biases at load 2 suggests that when multiple, equally relevant representations are maintained in VWM, none of these will bias perception. Here, we were interested to establish whether this load constraint is specific to attentional capture paradigms, where the content of VWM interferes with target selection, or also generalizes to the b-CFS paradigm where the content of VWM facilitates target selection. This would further bridge the findings on VWM-perception interactions from the two different paradigms.

To investigate the influence of the two forms of competition (inter-item stimulus competition and VWM load) on VWM-based facilitation, we adopted the procedure illustrated in Fig. 1. Each trial started with the presentation of either one or two colors, which had to be remembered for a subsequent test at the end of the trial. In between, participants switched to a b-CFS task, which required them to report the location of a target circle whose opacity gradually increased from 0 to 100%. This target circle was interocularly suppressed by a dynamic pattern. Importantly, the target circle could carry a color that matched one of the colors in VWM, or an unrelated color. Finally, the target was either the only item in the display or it was embedded in a display with three more distractor objects. These objects, two stars and one diamond, of various colors, never matched the color(s) maintained in VWM. We can make two main predictions. First, with regards to stimulus competition, we may observe larger behavioral benefits when the target stimulus is not only in competition with the dynamic pattern, but at the same time needs to be selected from a multiple-item display rather than being presented in isolation. Moreover, with added inter-stimulus competition, we should observe VWM-based facilitation for awareness during both suppression and monocular trials, in line with earlier studies showing biased competition without interocular suppression. Alternatively, VWM-based facilitation for awareness may remain specific to interocular competition, even with added inter-item competition. Second, concerning competition within VWM, if VWM-based perceptual biases are limited by VWM load, then we should see reduced b-CFS facilitation with increasing number of items held in VWM.

2. Experiment

The experiment tested to what extent the faster detection of VWM matching visual input depends on VWM load and

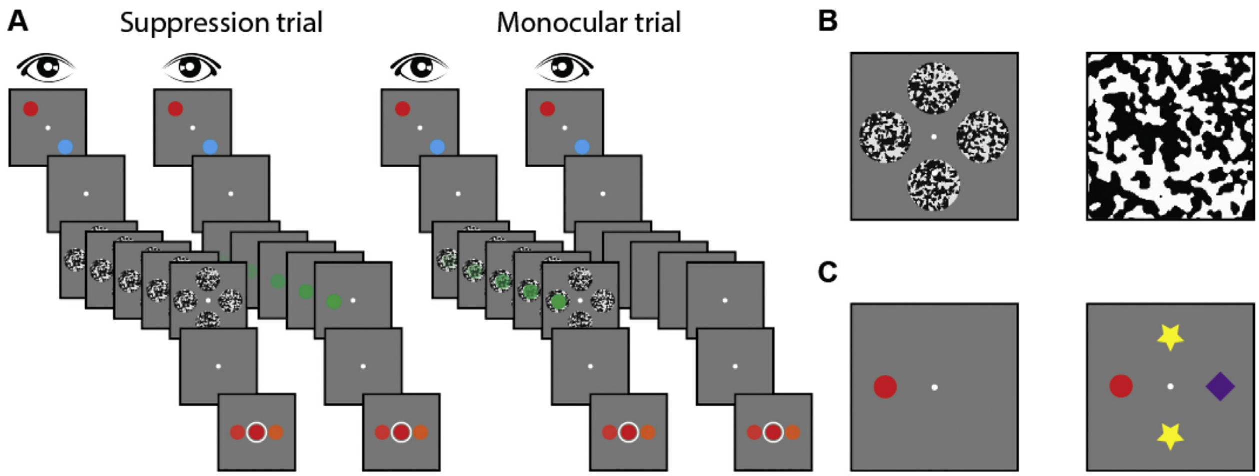

Fig. 1 – (A) Stimulus sequence of an incongruent trial with circular pattern masks. In all experiments, participants were instructed to report whether a colored circle appeared left, right, below or above fixation, during the presentation of the dynamic mask. Depending on the trial the color of this circle could be congruent or incongruent with a color that was presented before the visual detection task and which needed to be remembered for a later test. (B) Examples of different mask types (Experiment 1A top right; Experiment 1B top left). (C) Examples of single-item (left) and multiple-item (right) stimulus displays.

stimulus competition. One characteristic of binocular rivalry is that the perceptual transition from one percept to the other typically occurs in a spatially gradual manner, in which the suppressed stimuli first regain perceptual dominance in isolated spots, before it spreads throughout the entire image, through what has been labeled a traveling wave (Paffen, Naber, & Verstraten, 2008; Wilson, Blake, & Lee, 2001). When using multi-item displays, such traveling waves may cause one item to be revealed by the breakthrough of another item. To control for any potential confounds that these traveling waves might cause, we ran two versions of the experiments, each with a different type of mask. In Experiment 1A the whole stimulus area was filled with a single high-contrast dynamic pattern mask, as in Gayet et al. (2013). In Experiment 1B, the items were suppressed through four separate masks, one for each item (Fig. 1B). Such separate masks should prevent spreading of dominance from one stimulus location to another (for a similar approach, see Gayet et al., 2016).

2.1. *Methods*

2.1.1. *Participants*

A planned number of twenty participants (six males, age 19–33, $M = 25$ years) took part in Experiment 1A and another twenty participants (six males; age 18–34; $M = 24$ years) took part in Experiment 1B, in exchange for course credit or 8€ per hour. Participants reported normal or corrected-to-normal acuity. Additionally, each participant's eye dominance was determined off-line (see Gayet et al., 2013 for details). Procedures were approved by the Scientific and Ethical Review Committee (Faculty of Behavioral and Movement Sciences, VU University).

2.1.2. *Apparatus, stimuli, procedure, and design*

The experiment was modeled after experiments reported in Gayet et al. (2013). A Windows 7 PC running OpenSesame v0.28 (Mathôt, Schreij, & Theeuwes, 2012) generated the stimuli on a Samsung SyncMaster 2233 120 Hz screen, at 60 cm viewing distance. Participants sat in a dimly lit cubicle. Two half-images were presented dichoptically on a uniform gray background (29 cd/m^2) through a mirror stereoscope. The area presented to each eye was surrounded by a black frame (6.5° × 6.5°) to facilitate binocular fusion of the complementary images.

Each trial started with a white fixation dot for 500 msec followed by a 1000 msec memory display. After a 1250 msec delay the visual detection task was initiated. This task lasted until a response was given or until 20 sec elapsed. It ended with a 500 msec fixation display. Finally, a memory test was shown until response.

Memory displays contained one or two colored disks (radius .65°), randomly placed at two possible locations at 2.8° eccentricity on the northwest intercardinal axis. Each color was selected at random from the same color pool used in our previous work (Moorselaar, et al., 2015; van Moorselaar, et al., 2014). There were five different color categories (red, green, blue, yellow, purple). Within each color category, nine different exemplars were selected on basis of the Munsell color system (Munsell, 1929), such that the brightness of each color was kept constant (around 26 cd/m^2), except for yellow which was overall brighter (66 cd/m^2) to prevent it from appearing as brown (see Olivers et al., 2006 for more details about the selected colors).[1]

In the visual detection task, participants were instructed to report the location of the target (which was always a circle), by using the four arrow keys. The target appeared randomly on one of four locations at 2.0° eccentricity on the cardinal axes (i.e., left, right, below or above fixation). On half of the trials

[1] Although across conditions yellow targets were detected significantly faster than non-yellow targets, a separate analysis with only including non-yellow targets showed the same pattern of results (all F's > 9.94, all p's < .003).

the color of the target was identical to one of the memorized colors (*congruent* condition). In the other half of the trials the target color was unrelated to the memory content (*incongruent* condition). Note that the color of the target was irrelevant for the suppression task.

In *single-item* displays the target circle was the only item in the display. In the *multiple-item displays* this circle was surrounded by three colored objects, two stars and one diamond, randomly placed on the remaining three target locations. The colors of the two stars and the diamond never matched the memory content and were selected randomly from the remaining color categories. To further increase the saliency of (and therefore competition with) the distractors, both stars carried the same color.

During the b-CFS task a high-contrast dynamic pattern mask (10 Hz), specifically designed to evoke CFS (see Gayet et al., 2013 for details), was presented to the dominant eye. At the onset of the suppression task, the shape stimuli started to gradually increase in contrast. In the CFS condition stimuli were presented to the non-dominant eye and reached their maximum contrast after 1000 msec. In the monocular condition the stimuli were superimposed on the dominant pattern mask, and the ramp-up of the stimuli was lengthened such that they reached full contrast after 3000 msec to mimic the longer suppression durations of trials with dichoptic presentation (Gayet et al., 2014). This way we achieved similar RTs in the two conditions (see Results section).

Finally, the memory test was a forced choice recognition task in which participants had to select the exact color that was memorized at trial onset from three colored circles, all from the same color category. At load 2, one of the two possible color categories was selected randomly. Participants could select the memory matching circle by moving a white outline with the left and right arrow buttons and submit their response with the up arrow button.

In both versions of the experiment, participants completed 14 experimental blocks of 32 trials each. Each participant completed seven single-item blocks and then seven multiple-item blocks, each preceded by 18 practice trials, in counterbalanced order. Each block contained four congruent and four incongruent trials per load (1, 2) and viewing condition (CFS, monocular), which were randomly mixed. This resulted in 28 observations per cell in an ANOVA with factors congruency, load, display type and viewing condition per experiment. After each block, feedback was given on RTs (suppression) and accuracy (suppression and memory). Participants were encouraged to take a break in between blocks.

2.1.3. Data processing

Reaction time data were analyzed as in our previous work (Olivers et al., 2006; van Moorselaar, et al., 2014). Only trials with a correct response during the suppression task were included in the analysis. Then a two-step trimming procedure was applied. First, trials with RTs faster than 200 msec or slower than 5000 msec were excluded. Next, the RTs were trimmed on the basis of a cutoff value of 2.5 standard deviations from the mean per participant per condition. We also analyzed median RTs (as in Gayet et al., 2013), and this showed the same pattern of results.

2.2. Results and discussion

RT analysis. Correct trials made up 98.3% of the data (Exp. 1A = 98.4%, Exp. 1B = 98.2%). Trimming resulted in an extra loss of 3.3% of the data (Exp. 1A = 3.0%, Exp. 1B = 3.5%). Remaining RTs were entered in a repeated-measures ANOVA with within-subjects factors *display type* (single-item, multiple-item), *viewing condition* (CFS, monocular), *load* (1, 2) and *target color* (congruent, incongruent). Experiment (1A, 1B) was added as a between subjects factor to assess the effect of mask type. As can been seen in Fig. 2, although overall response times were slower in Experiment 1B than in Experiment 1A [F (1, 38) = 9.38, $p < .01$], the pattern of results did not differ across experiments. There was a main effect of target display [F (1, 38) = 239.43, $p < .001$], with overall slower RTs in multiple-item than in single-item displays and a main effect of memory load [F (1, 38) = 24.04, $p < .001$], driven by slower RTs at load 2 relative to load 1. Furthermore, across experiments and all other factors, the memory content facilitated target detection, with congruent targets being detected faster than incongruent targets [F (1, 38) = 139.93, $p < .001$].

Importantly, there was a significant load by target color interaction, [F (1, 38) = 9.89, $p < .01$]: VWM-based facilitation was more pronounced at load 1 [F (1, 38) = 110.15, $p < .001$] than at load 2, where it was nevertheless still highly reliable [F (1, 38) = 60.64, $p < .001$]. Load interacted with none of the other factors, although the load by target display by viewing condition interaction was close to significant (F = 3.73, p = .06). However, the load by target color interaction was stable whether the analysis was split by target display [F (1, 38) = 4.69, p = .04 for single-item; F (1, 38) = 6.59, p = .01 for multiple-item] or by viewing condition [F (1, 38) = 4.50, p = .04 for CFS; F (1, 38) = 7.43, p = .01 for monocular]. Thus, across conditions, the benefits of having a representation active in VWM were reduced when the number of items in VWM was increased from one to two. At the same time, VWM-based facilitation was not completely eliminated. Numerically this reduction differed between single-item and multiple-item displays (see Table 1). In single-item displays the congruency effect was reduced by about half from load 1 to load 2, whereas this reduction was smaller – about one-third – in multiple-item displays.

Another important finding was that the target congruency effect was also modulated by display type, with overall larger effects in the multiple-item than in the single-item displays [F (1, 38) = 10.04, $p < .01$]. Within the CFS condition, however, the congruency effect did not differ between single-item and multiple-item displays [F = .57, p = .46]. A significant three-way interaction showed that the interaction between display type and target color differed across viewing conditions [CFS *vs* monocular; F (1, 38) = 25.75, $p < .001$]. In single-item displays, VWM-based facilitation reliably differed between CFS and monocular displays, but this was not the case in multiple item displays. In single-item displays, congruent targets broke through suppression faster than incongruent targets [F (1,38) = 33.85, $p < .001$], whereas this congruency effect was attenuated, although still significant, in the monocular displays [F (1,38) = 10.19, $p < .01$]. By contrast, in multiple-item displays, the size of the congruency effects did not differ

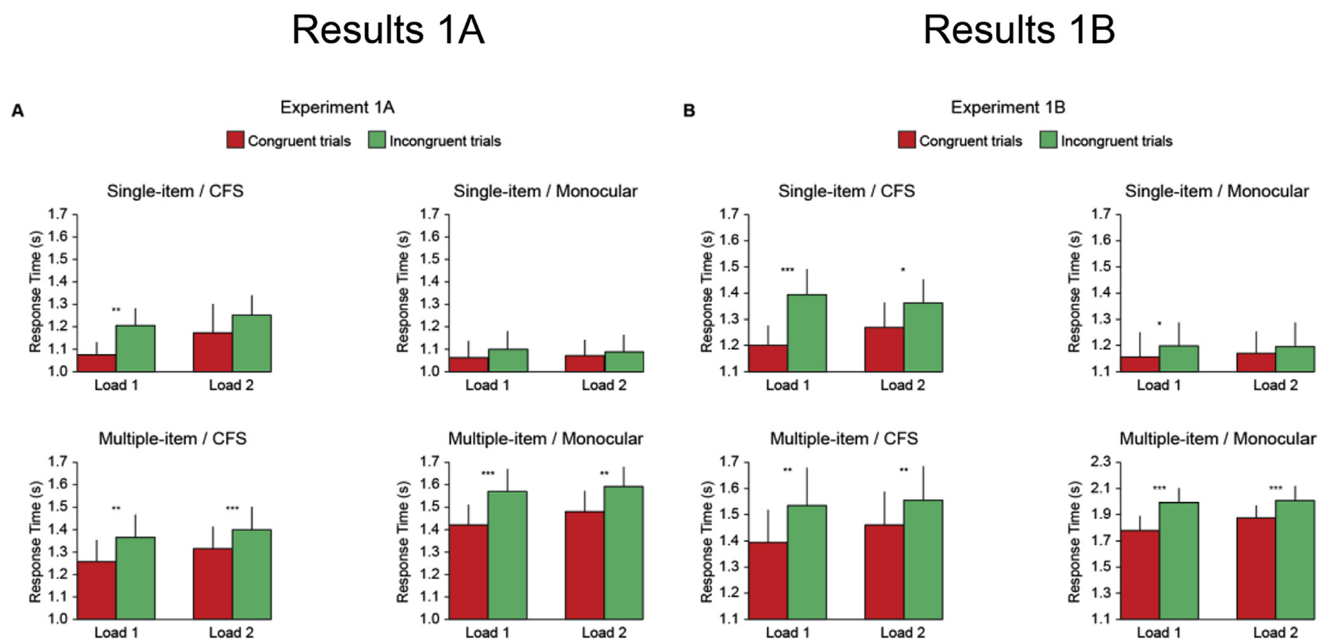

Fig. 2 – Experiment 1: Reaction times as a function of display type, viewing condition, memory load and congruency for Experiment 1A (A) and 1B (B). Note that the y-axis is shifted for the multiple-item/monocular display condition in Experiment 1B. Error bars in all figures represent condition-specific, within-subject 95% confidence intervals (Morey, 2008).

between CFS [F (1,38) = 46.11, $p < .001$] and monocular displays [F (1,38) = 95.30, $p < .001$]. This pattern was observed in both experiments, although it was more pronounced in Experiment 1B resulting in a significant interaction with experiment [F (1,38) = 12.98, $p < .001$]. The same pattern also held when these analyses were split up by load (all F's > 6.93, all p's < .01), again demonstrating that the effects were less pronounced at load 2 than at load 1, but still reliable.

The overall pattern of results is clear. One noteworthy aspect, however, is that overall response times were slower in the monocular displays with stimulus competition relative to the other conditions. Based on previous studies we lengthened the ramp-up of the suppressed stimuli in monocular conditions relative to CFS conditions to obtain similar reaction time distributions across conditions (Gayet et al., 2013; Stein et al., 2011; see Methods section here). In contrast to CFS, where there is a sudden shift in percept when the suppressed stimuli breaks through the pattern mask, the percept appears more gradually in monocular conditions. Although speculative, this perceptual difference might explain the increased response times in monocular multiple-item displays. Whereas a vague representation is sufficient for a relatively "quick" response in single-item displays where location is the only relevant information, it is probably insufficient in multiple-item displays where target localization also requires shape identification. To control for any differences in reaction time distribution between different display types and viewing conditions, we repeated the analysis on normalized response times. We normalized the data as follows:

$$\text{Normalized RT difference}: \frac{RT\ unrelated - RT\ related}{RT\ unrelated} \times 100$$

The resulting measure reflects the difference brought about by the manipulation and controls for between-subject variability in absolute response speed (i.e., sensitivity to CFS; Gayet et al., 2016). This analysis showed the same pattern of results with a significant overall load effect [F (1, 38) = 9.32, $p < .01$] and a significant display type by viewing condition interaction [F (1, 38) = 15.764, $p < .001$]. The latter again reflected that the congruency effect only differed between CFS and monocular displays in the single-item displays [F (1, 38) = 13.13, $p < .001$], but not in the multiple-item displays (F = 1.08, $p = .31$). A one sampled t-test testing against zero replicated the absence of a reliable congruency effect in monocular displays without competition in Experiment 1A ($t = 1.90$, $p = .03$). However, in Experiment 1B this effect was still not large but significant [t (20) = 2.32, $p = .03$].

3. General discussion

Previous studies have demonstrated that information matching the content of VWM is prioritized by the visual system, so that it is released from suppression faster than non-matching information (Gayet et al., 2013; Pan et al., 2014). These studies made use of the b-CFS paradigm, in which a target stimulus presented to one eye is temporarily rendered invisible by presenting dynamic input to the other eye. Here, we used this method to investigate how memory load (i.e., competition within VWM) and competition within the visual input influence VWM modulation of perceptual selection. Replicating previous findings, it was found that information matching the content of VWM broke through interocular suppression faster than non-matching information. Consistent with the idea that the number of memory representations that can simultaneously interact with perception is limited, this VWM-based facilitation was significantly reduced when

Table 1 – Data columns represent the congruency effect and its reduction (Δ, in %) going from VWM load 1 (L1) to VWM load 2 (L2) for each condition (CFS or monocular for single and multiple-item displays).

	Single-item						Multiple-item					
	CFS			Monocular			CFS			Monocular		
	L1	L2	Δ%	L1	L2	Δ%	L1	L2	Δ%	L1	L2	Δ%
1A	131	79	40	37^{ns}	17^{ns}	54	108	84	23	149	112	25
1B	194	94	52	42	26^{ns}	38	141	94	34	216	132	39
Total	163	87	47	40	22	45	125	89	29	183	122	34

memory load increased from one to two items. Also, it was found that the level of competition modulates the interaction between VWM and perceptual selection. In single-item displays the VWM-based facilitation was largely specific to interocular competition. By contrast, for multiple-item displays, where there was also inter-stimulus competition within an eye, the level of facilitation no longer differed between CFS and monocular displays.

Across conditions there was a clear load constraint on the VWM-based facilitation. In single-item target displays loading VWM with two items reduced VWM-based facilitation by about half. Such a reduction is in line with a single-item template account, in which only a single memory representation at a time has direct access to perception (Olivers et al., 2011). If only a single memory representation at a time functions as attentional template, facilitation will only occur on those trials where the target color happens to match the active color in VWM, which by random selection should be about half of the trials. However, other aspects of the data do not support a hard architectural constraint on the number of template representations. In multiple-item displays the load-induced reduction of the congruency effect was only about one-third, a reduction that appears to be more in line with a multiple-item template account in which more than one target representation can be activated to at least some extent (Beck, Hollingworth, & Luck, 2012; Hollingworth & Beck, 2016). Related to this, the VWM-based bias did not completely disappear for load 2, in contrast to our previous findings that loading VWM with more than one item is by itself sufficient to eliminate the attentional bias towards memory-matching distractors (Moorselaar, et al., 2015; van Moorselaar, et al., 2014). It is not clear what is driving the difference in load reduction between single-item and multiple-item displays, and between the b-CFS and attentional capture tasks. One notable difference is that attentional capture paradigms have been designed such that VWM interferes with target detection, whereas in the typical b-CFS task it facilitates target detection.[2] Another important aspect could be that overall longer response times provide more opportunity for the memory representations to each bias selection, potentially in turn, leading to preserved biases. Consistent with this, a recent study found that VWM-based attentional capture could also be observed at load 2 when the efficient singleton-shape search was replaced by a more inefficient search task (Hollingworth & Beck, 2016). Note, however, that Hollingworth and Beck did not observer a reliable reduction with increasing memory load, although numerically the pattern went in the same direction. Thus, although the sensitivity of the paradigm seems to be an important factor, future studies are necessary to further investigate the role of competition within memory on VWM-based biases during perceptual selection.

The other central aspect of our data is that VWM-based facilitation no longer differed between monocular and CFS displays when the target was embedded in a multi-item display. In previous studies, using single-item target displays, the prioritization of memory matching information was specific to CFS (Gayet et al., 2013; Pan et al., 2014). Here, we largely confirm these findings, as facilitation was reliably more pronounced in CFS than monocular displays. By contrast, in multiple-item displays VWM facilitated target selection to the same extent in CFS as in monocular displays. We believe that this dissociation should be attributed to the level of competition within the visual system (Hickey et al., 2011; Luck, Girelli, McDermott, & Ford, 1997; Meeter & Olivers, 2006). In single-item displays, any sense of a stimulus breaking through suffices for a correct response and a response can thus be selected based solely on the first feedforward sweep of information that enters the visual system (Lamme & Roelfsema, 2000). The competition within this feedforward sweep is largely driven by the different input from both eyes during CFS. Such crude processing, however, is insufficient in multiple-item displays as target localization now also requires recurrent processing to identify the shape of the perceived colors (Treisman & Gelade, 1980). Consequently, competition is no longer limited to interocular competition, which gives VWM the opportunity to exert its effect in both CFS and monocular displays.

Although the results are in line with the idea that competition, be it interocular or inter-stimulus, strengthens VWM-based biases, we found no evidence for increased biases when combining these forms of competition. On the one hand this might indicate that if a VWM matching representation gains a representational benefit during one level of competition, there is little additional advantage to be gained at the other level of competition. Assuming that inter-ocular competition precedes the inter-item competition, in such a scenario inter-item competition will be significantly reduced

[2] There is evidence that the attentional capture by memory-matching distractors is partly, but not fully, malleable by cognitive control (Carlisle & Woodman, 2011; Kiyonaga, Egner, & Soto, 2012; Olivers & Eimer, 2011), suggesting that the memory content can be suppressed when it is known to be irrelevant for the current task. Thus paradigms where the memory content interferes rather than facilitates target selection might be less sensitive to VWM-based biases. Consistent with this, in a separate experiment with multiple-item displays, where only the distractor diamond instead of the target could match the memory content, we observed no VWM-based biases, not even at load 1.

as the target already gained a head start. Alternatively, there is the possibility that the two forms of competition were in fact additive, but this addition was obscured by a limit on the size of the congruency effect. Arguably the size of the congruency effect is constrained by the minimal values of the RT distribution, such that in the present paradigm there is little to no room for increased congruency effects.

The VWM-based facilitation was weak (Experiment 1B) to absent (Experiment 1A) for single item monocular displays. We believe that this is the case because in this condition the competition is weak to absent, as these conditions contained no competition within the target display, nor competition based on the interocular conflict that arises due to dichoptic presentation of incompatible images. However, since the monocular displays contained a dynamic high contrast background, one could argue that there actually was competition also in this condition. Yet, we would argue that the background pattern is competing rather weakly in these conditions, as it is highly dissimilar to the targets in both color and pattern, allowing for relatively easy and unambiguous segmentation. It is in the dichoptic conditions where the background pattern is competing strongly with the target, because background and target are presented to overlapping retinal locations stemming from ocular dominance columns (Tong & Engel, 2001). Such strong competition is clearly absent in the monocular condition. Interestingly, the emergence of the weak but reliable congruence effect in the single item monocular condition of Experiment 1B suggests that the smaller, individual and round background patterns were competing more strongly than the global background of Experiment 1A, consistent with the background patterns becoming more similar to the target and therefore arguably imposing more competition.

To conclude, we show that both stimulus competition and competition within VWM affect memory-driven biases of visual awareness. The findings allow for reconciliation of the discrepant findings from two different paradigms (visual search and b-CFS) by demonstrating that VWM-based biases emerge under conditions of competition. The specific type of competition may vary, and can be either inter-ocular or inter-item in nature. Furthermore, as in search, VWM-based facilitation is reduced when memory load is increased. Thus, while competition within VWM reduces memory-driven biases, competition between stimuli in a visual scene accentuates them.

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