Behavioral and Computational Evidence for Simultaneous Guidance of Attention by Multiple Working Memory Items

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Abstract

During visual search, task-relevant representations in visual working memory (VWM), known as attentional templates, are assumed to guide attention. A main debate over this VWM-based guidance concerns whether only one (Single-Item-Template hypothesis, or SIT) or multiple (Multiple-Item-Template hypothesis, or MIT) items can serve as attentional templates simultaneously. The current study was designed to test these two hypotheses. Participants memorized two colors, prior to a visual-search task where the target and the distractor could match or not match the colors held in VWM. Robust attentional guidance was observed when one of the memory colors was presented as the target (reduced response times [RTs] on target-match trials) or the distractor (increased RTs on distractor-match trials). We then constructed two drift-diffusion models that implemented the MIT and SIT hypotheses, which are similar in their predictions about overall RTs, but differ in their predictions about RTs on individual trials. Critically, simulated RT distributions revealed a better match of the MIT hypothesis to the observed data. Taken together, our findings provide behavioral evidence for the concurrent guidance of attention by multiple items in VWM.

Keywords: visual working memory, attentional template, visual search, attentional guidance, attentional capture

Significance statement

Theories differ in how many items within visual working memory can guide attention at the same time. This question is difficult to address, because multiple- and single-item-template theories make very similar predictions about average response times. Here we model response times at an individual level. Crucially, we find that multiple-item-template theories predict human behavior much better than single-item-template theories; that is, we find behavioral and computational evidence for multiple attentional templates that are simultaneously active.

Simultaneous Guidance by Multiple Attentional Template

Internal representations of task-relevant information, or *attentional templates*, stored in visual working memory (VWM), guide attention in visual search (Bundesen, 1990; Bundesen, Habekost, & Kyllingsbæk, 2005). For example, when you are looking for a chocolate cake, all dark items in a bakery will be more likely to draw your attention. In other words, VWM contents guide attention towards memory-matching items in a top-down manner to optimize visual search (Chelazzi, Miller, Duncan, & Desimone, 1993; Chelazzi, Duncan, Miller, & Desimone, 1998).

Although multiple representations can be maintained in VWM simultaneously, there is debate about the number of VWM items that can simultaneously serve as attentional templates. The Single-Item-Template hypothesis (SIT; Houtkamp & Roelfsema, 2006; Olivers, Peters, Houtkamp, & Roelfsema, 2011) proposes a functional division within VWM: While one item actively interacts with visual processing to guide attentional selection towards matching items, other items are shielded from visual sensory input, and thus cannot guide attention.

Studies demonstrating a switch cost between templates are often interpreted as evidence for the SIT model. In a study by Dombrowe, Donk, and Olivers (2011), participants made a sequence of two eye movements towards two spatially separated target items which were indicated by arrows. In the switch condition, the two targets had different colors, and thus required a switch between two templates; in the no-switch condition, both targets had the same color, and thus required only one attentional template. Crucially, eye movements that were correctly aimed at the second target were delayed by about 250ms – 300ms in the switch condition, compared to the no-switch condition. This cost associated with switching between templates is in line with the SIT hypothesis, suggesting that only one template can be active at one time.

In contrast to the SIT hypothesis, other researchers propose that multiple VWM items can guide attention simultaneously (Beck, Hollingworth, & Luck, 2012). Although, according to this Multiple-Item-Template (MIT) hypothesis, holding multiple items in VWM reduces the memory quality of each item, thus reducing memory-driven guidance (Bays & Husain, 2008; Kristjánsson & Kristjánsson, 2018). But unlike the SIT hypothesis, the MIT hypothesis does not pose a strict limitation on the number of items that can serve as attentional templates simultaneously. Recent work by Hollingworth and Beck (2016) supported the MIT hypothesis. They asked participants to memorize one or two colors, followed by a visual-search task in which participants had to report the orientation of a target among distractors. The distractors were either unrelated to the VWM colors (Match 0); matched one of the VWM colors (Match 1); matched both of the VWM colors (Match 2); or were gray (i.e. no colored distractor). When two colors were held in VWM, stronger distraction was found on Match 2 trials, compared to Match 1 trials. This suggests that multiple items can guide attention at the same time.

However, the results of Hollingworth and Beck (2016) (see also, Frătescu, Van Moorselaar, & Mathôt, in press) can also be explained by the SIT hypothesis. If only one of the two memorized colors served as an attentional template on any given trial, then this color will match a distractor color on all trials (100%) in the Match 2 condition, but only half of all trials (50%) in the Match 1 condition. Therefore, average distraction would be stronger in the Match 2 condition than in the Match 1 condition. In other words, even the SIT hypothesis would predict slower reaction times in the Match 2 condition, compared to the Match 1 condition. Put differently, because we generally look at averages across many trials when looking at behavioral data, it is difficult to make inferences about attentional guidance on individual trials. However, by modelling behavioral data at the level of individual trials, we can make such inferences, and doing so is one of the key contributions of the current study.

In the current study we investigate the attentional guidance of memory items in a visual-search task based on the additional-singleton paradigm (Theeuwes, 1992). Crucially, we compare not only the average RTs, but also the RT distributions of trials in different conditions. Moreover, we will extend our analyses by simulating individual trials based on the predictions of MIT and SIT hypotheses by means of a drift-diffusion model (Ratcliff & McKoon, 2008) and compare the simulated data to the obtained data. Participants first kept two colors in working memory, after which they searched for a colored target shape among a colored distractor shape and, in one experiment (Experiment 1), a grey distractor shape. The color of the target and the (colored) distractor was manipulated to match or not match the memorized colors.

Overall, both the SIT and MIT hypotheses predict faster reaction times (RTs) on target-match trials (i.e., only the target color matches one of the memory colors), and slower RTs on distractor-match trials (i.e., only the distractor color matches one of the memory colors). However, the SIT and MIT hypotheses make different predictions about what happens on individual trials. Specifically, when the target matches a VWM color, then the MIT hypothesis predicts that attention is always guided toward the target; in contrast, the SIT hypothesis predicts that attention is only guided toward the target on 50% of trials, because there's only a 50% chance that the target color serves as an attentional template.

Furthermore, we also manipulated the congruency between the target and the distractor to investigate whether both memory colors guide attention. Inside the target, the orientation of a line-segment was either congruent, or incongruent, with a line-segment inside the (colored) distractor. The MIT hypothesis predicts the strongest congruency effect on both-match trials (i.e., both the target and the distractor match the memory colors), because attention is simultaneously guided towards both the target and the distractor. Therefore, when the line-segment orientations of target and distractor are congruent, it is easier to report the orientation even though attention is partly drawn to the distractor, resulting in reduced RTs and error rates. In contrast, in the incongruent condition, there is more cognitive conflict caused by the different orientation of the matching distractor, resulting in increased RTs and error rates. The SIT hypothesis does not predict that attention is guided simultaneously towards the target and the distractor and therefore does not predict an especially strong congruency effect on both-match trials.

When it comes to the RT distribution of individual trials, the MIT hypothesis predicts that the distribution for both-match and non-match (i.e., neither the target nor the distractor match the memory colors) trials are the same, or at least very similar: On both-match trials, attention is guided toward both the target and the distractor, and the resulting facilitation and interference should cancel each other out, resulting in an RT distribution that is similar to the condition where no color matches the VWM items. In contrast, under the SIT hypothesis, on both-match trials, attention is guided either toward the target, resulting in fast RTs, or toward the distractor, resulting in slow RTs, but never to both at the same time. Thus, the distribution for both-match trials is expected to be wider than that for non-match trials. We built drift-diffusion models of individual trials to simulate the two hypotheses' predictions about RT distributions, and compared these with the collected data.

To foresee the results: The data by-and-large favor the predictions of the MIT hypothesis over the SIT hypothesis.

Experiment 1

Method

Participants

Thirty-five first-year psychology students (aged from 18 to 23 years old; 18 female, 17 male) from the University of Groningen participated in exchange for course credits. All participants had normal or corrected-to-normal acuity and color vision. We set our sample size to a minimum of thirty participants, so that our statistical power would be considerable higher than is standard in the field. The exact number of participants depended on how many participants signed up for our study. The study was approved by the local ethics review board of the University of Groningen (18123-S). Participants provided written informed consent.

Stimuli, design and procedure

Participants were seated in a dimly lit, sound-attenuated testing booth, behind a computer screen on which the stimuli appeared, at a viewing distance of approximately 62 cm. Each trial started with a 500ms fixation display, followed by a 1,000ms memory display, consisting of two color disks placed in the middle of the screen to the left and the right of the fixation dot (*Figure 1*). The memory colors were randomly drawn from a color circle with full brightness and saturation (luminance ranged between 49 cd/m² and 90 cd/m²), with the restriction that colors were at least 30° away from each other on the color circle. Participants were instructed to remember the exact colors of the items.

Following a 200ms fixation display, the search display was presented and remained visible until a response was given. The search display consisted of three shapes (1.3° visual angle): one diamond-shaped, colored target; one square-shaped, colored distractor and another square-shaped, gray distractor, all placed around the fixation dot, with a 200px radius (5.4°

visual angle). The colors of the target (diamond) and the colored distractor (square) either matched or did not match the remembered color depending on the *Target-Color-Match* (Match, Non-Match) and *Distractor-Color-Match* condition (Match, Non-Match), resulting in four types of trials: Non-Color-Match (short for: Target-Color-Match: Non-Match; Distractor-Color-Match: Non-Match), Target-Color-Match (short for: Target-Color-Match: Match; Distractor-Color-Match: Non-Match), Distractor-Color-Match (short for: Target-Color-Match: Non-Match; Distractor-Color-Match: Match), and Both-Color-Match (short for: Target-Color-Match: Match; Distractor-Color-Match: Match). All shapes in the search display contained a line segment (1.1° visual angle) that was tilted 22.5° clockwise or counterclockwise from a vertical orientation. The line segments in the target and the colored distractor were tilted in the same (Congruent) or a different (Incongruent) direction depending on the *Orientation-Congruency* condition. The line segment inside the grey distractor was chosen randomly, and will not be analyzed.

Participants indicated the left or right orientation of the line segment within the diamond by clicking either the left or right mouse button, respectively, as quickly and accurately as possible. Feedback was given for 500ms immediately following the response: a green dot for a correct response, or a red dot for an incorrect response. Each trial ended with a memory test, in which participants selected the exact color they memorized in the color circle. They did this twice, once for each memorized color. Visual feedback followed, comparing the colors they selected with those that they actually saw.

The three factors (*Target-Color-Match*, *Distractor-Color-Match, Orientation-Congruency)* were mixed randomly within blocks. Participants completed eight blocks of 32 trials each (256 trials in total), preceded by one practice block of 32 trials which was excluded from analysis. Stimulus presentation and response collection were controlled with OpenSesame version 3.2 (Mathôt, Schreij, & Theeuwes, 2012).

A detailed pre-registration of the experiment is available at https://osf.io/sy7n8/.

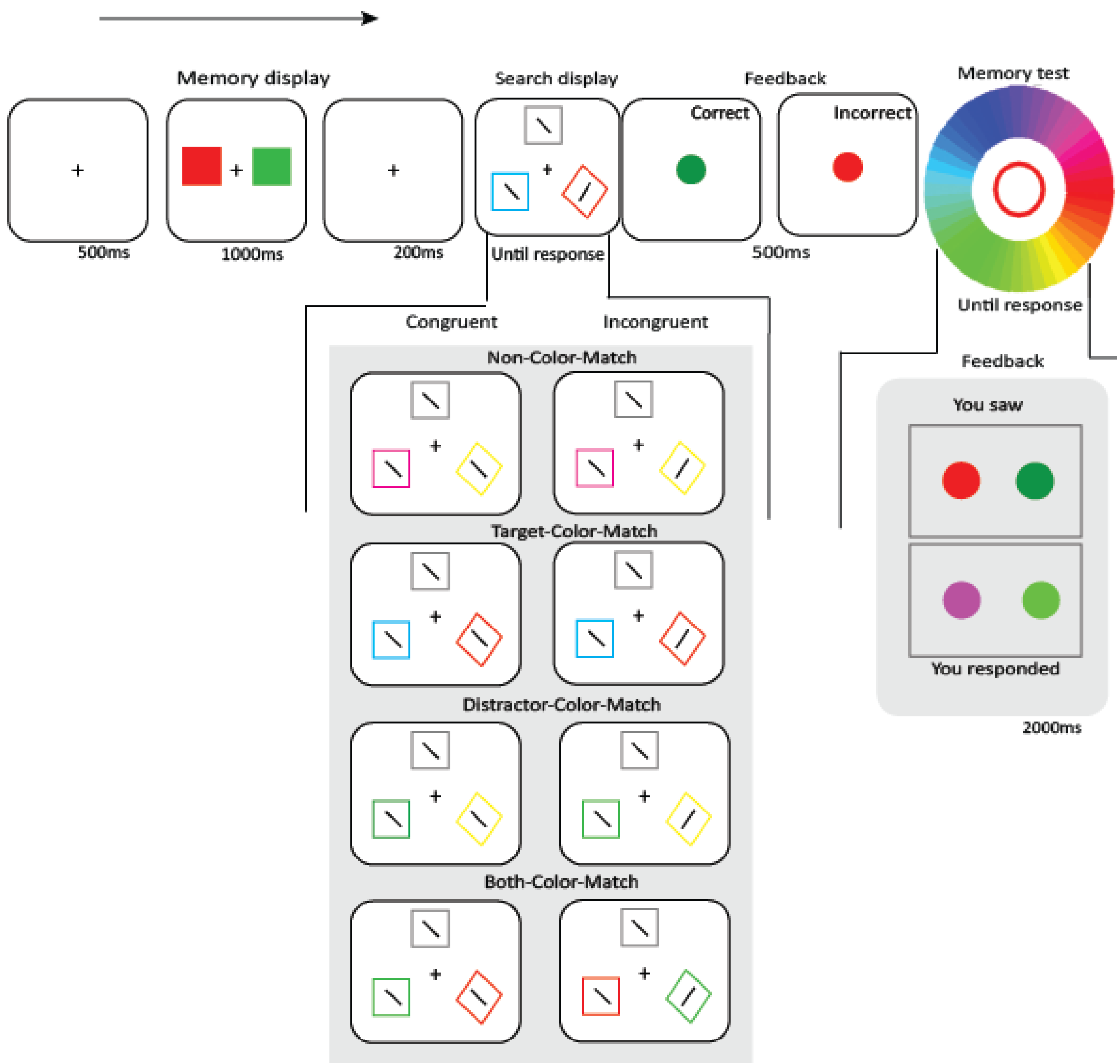

Figure 1. Sequence of events in a trial of *Experiment 1*. All Target-Color-Match and Distractor-Color-Match conditions in the search display for both Congruent and Incongruent trials are illustrated.

Data processing

Trials with RTs shorter than 200ms and longer than 2,000ms were excluded. Furthermore, participants were excluded from analysis if their mean RT for deviated more than 2.5 SD from the grand mean RT of all participants, or if his/her accuracy rate in the search task was less than 0.7. Only RT data of correct trials were analyzed. Thirty participants and 7478 trials (of 8960) remained for further analysis.

Data analysis

The data were analyzed using the JASP software package (version 0.9; JASP Team, 2018) with the default settings, with *Target-Color-Match* (Match, Non-Match), *Distractor-Color-Match* (Match, Non-Match), and *Orientation-Congruency* (Congruent, Incongruent) as factors. Inclusion Bayes Factor based on matched models were used to quantify evidence for effects (Rouder, Speckman, Sun, Morey, & Iverson, 2009).

Following Wetzels et al. (2011), we consider Bayes factors (*BFs*) between 3 and 10 or between .1 and .33 are indicators of "substantial" evidence in favor of the alternative (H_1) or the null hypothesis (H_0), respectively; *BFs* between 10 and 30 or between .03 and .1 are indicators of "strong" evidence; and *BFs* between 30 and 100 or between .01 and .03 are indicators of "very strong" evidence of H_1 or H_0.

Results and Discussion

Search RTs

A Bayesian Repeated-Measure ANOVA revealed very strong evidence for memory-based guidance in the Target-Color-Match ($BF_{10} = 3.301\times10^{24}$) and Distractor-Color-Match ($BF_{10} = 4.074 \times10^{15}$) conditions, suggesting that the overall search performance was faster when the target matched the memory color, and slower when the distractor matched the memory color (*Figure 2*). Moreover, the results showed substantial evidence for the effect of Orientation-Congruency on RTs (BF_{10} =7.187), indicating that RT were faster on congruent trials than incongruent trials. No interaction effect between the factors was found (all $BF_{10} < .06$).

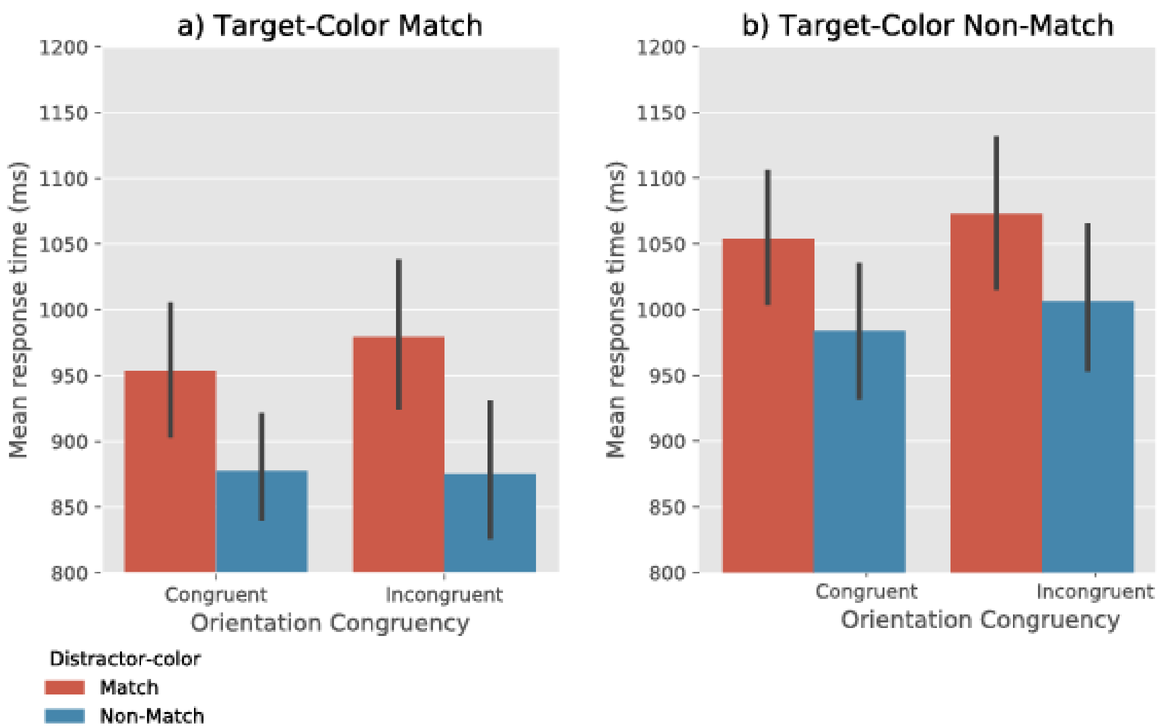

Figure 2. Mean response time as a function of Target-Color-Match, Distractor-Color-Match, and Orientation-Congruency.

RT distributions

To test whether only one of the color items maintained in working memory served as attentional template (i.e., SIT), or both of the two color items guided attention (i.e., MIT) in the visual search task, we analyzed the RT distributions for the Both-Color-Match and Non-Color-Match trials. According to the SIT hypothesis, on Both-Color-Match trials, attention is guided by the target on some trials, which leads to faster RTs, while on other trials attention is guided by the distractor which leads to slower RTs. Therefore, the Both-Color-Match trials should result in a bimodal distribution (i.e. wider than that of the Non-Color-Match trials) according to the SIT hypothesis. In contrast, the MIT hypothesis predicts that on Both-Color-Match trials, both the target and the distractor guide attention, thus resulting in a unimodal distribution (i.e. resembling that of the Non-Color-Match trials).

To test this, an Inverse Gaussian distribution was fit to the RTs per condition for each participant. The scale parameter, which reflects the width of the distributions was analyzed using a two-tailed Bayesian Repeated-Measure T-test. We found substantial evidence that the RT distributions for the Both-Color-Match and the Non-Color-Match trials were equally wide ($BF_{10} = 4.046$), as predicted by the MIT hypothesis.

Accuracy

The same analysis for RTs was conducted on mean accuracy. We found substantial evidence for the effect of Target-Color-Match ($BF_{10} = 3.022$) and Distractor-Color-Match ($BF_{10} = 6.577$), revealing that the overall search accuracy was higher when the target matches the memory color, and lower when the distractor matches the memory color (*Figure 3*). Moreover, a strong overall Orientation-Congruency effect was found ($BF_{10} = 4.496\times10^{13}$), showing that search performance was more accurate when the orientation of the line-segment in a target was congruent with that in a distractor than when they were incongruent. No evidence for any interaction effect between the factors was found (all $BF_{10} < 2.0$).

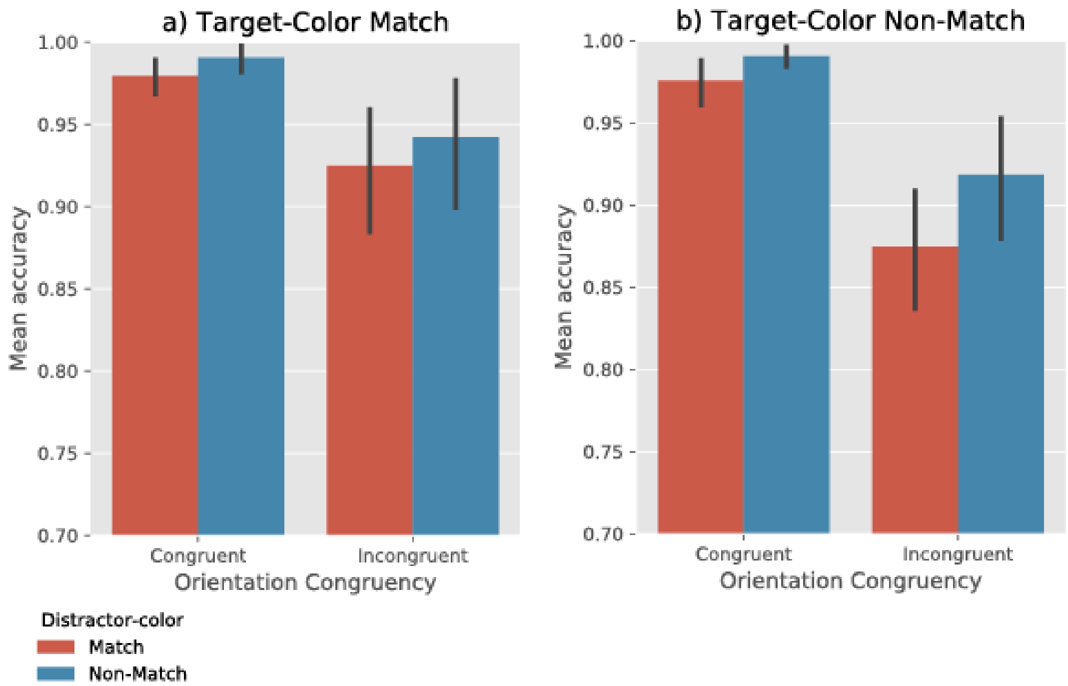

Figure 3. Mean accuracy rate as a function of Target-Color-Match, Distractor-Color-Match, and Orientation-Congruency.

In summary, we found that the search performance increased (i.e. became faster and more accurate) when the target matched one of the colors held in VWM, but decreased when the distractor matched the VWM item. Moreover, the RT distribution for both-match trials and no-match trials are similar, which suggests that both color items that were maintained in the VWM draw attention. These results are consistent with the assumptions of the MIT hypothesis. Unlike we predicted, however, we did not find evidence that the effect of Orientation-Congruency is larger when both the target and the distractor matched, compared to other conditions. We suspected that the presence of the grey (unrelated) color might affected the processing of the target and the distractor in visual search. Therefore, in the follow-up experiment, we removed the grey color in the search display.

Experiment 2

In Experiment 2, we removed the grey color item (the unrelated item) from the search display. We reasoned that this would increase the strength of the Orientation-Congruency effect, because there were now only two line segments in the display, thus providing a stronger test of our prediction that the effect of Orientation-Congruency should be strongest when both the distractor and the target matched the VWM colors. Furthermore, we wanted to replicate the main results of Experiment 1.

Method

Participants

Thirty-six first-year psychology students (aged from 18 to 25 years old; 20 female, 16 male) from the University of Groningen participated in exchange for course credits. All participants had normal or corrected-to-normal acuity and color vision.

Stimuli, design and procedure

The method was the same as in Experiment 1 except for the following. The search display consists of one diamond-shaped, colored target, and one square-shaped, colored distractor, placed on an imaginary circle around the fixation with equal space between them (see *Figure 4*).

Data processing

The same trimming criteria and analyses were used as in Experiment 1. Thirty participants and 7548 trials (of 9216) remained for further analysis. A detailed pre-registration of the experiment is available at https://osf.io/xpzhy/.

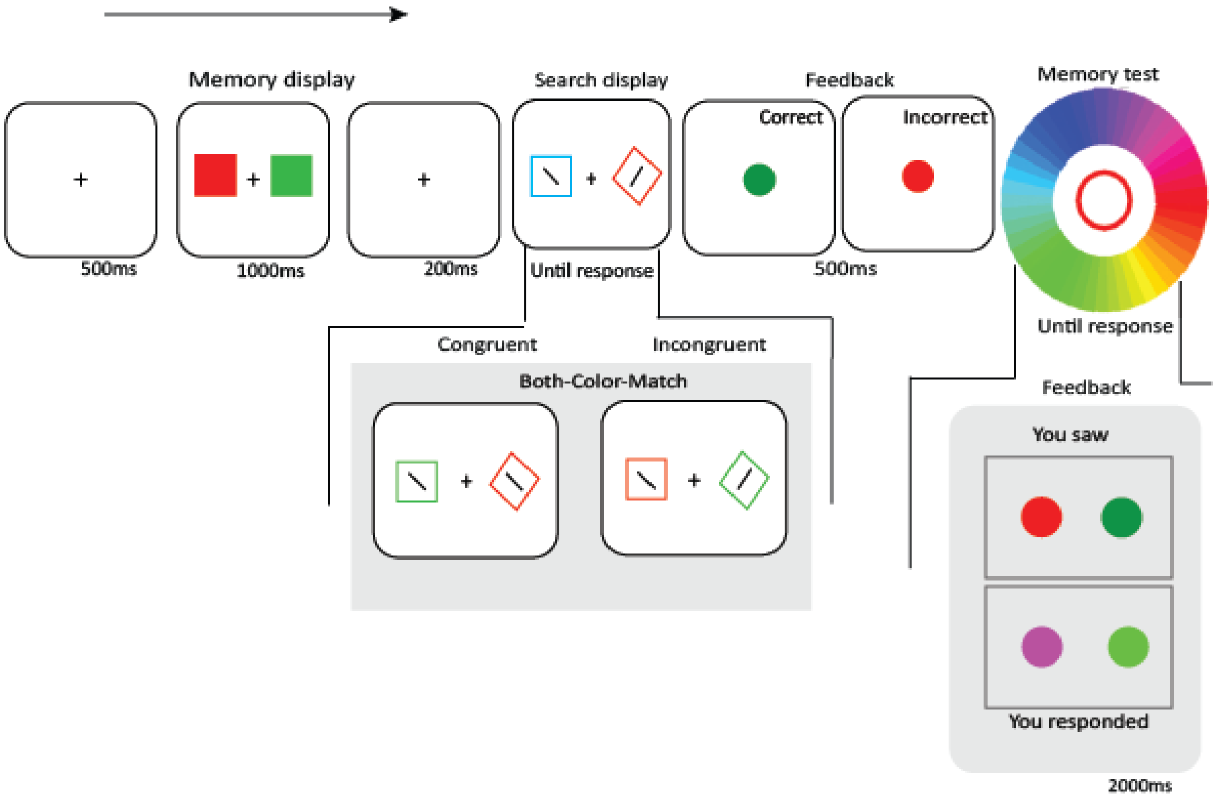

Figure 4. Sequence of events in a Distractor-Color-Match trial of *Experiment 2*.

Results and Discussion

Search RTs

A Bayesian Repeated-Measure ANOVA provided strong evidence for memory-based guidance of Target-Color-Match (BF_{10}= 2.152×10^6) and Distractor-Color-Match (BF_{10} = 1.605×10^6). Moreover, there was very strong evidence for the effect of Orientation-Congruency on RTs (BF_{10} = 72.249), reflecting that participants were faster on congruent trials than on incongruent trials. Crucially, the results showed a substantial evidence for a Target-Color-Match × Orientation-Congruency interaction (BF_{10} = 3.689). To further qualify this effect, we performed a two-tailed Bayesian Repeated-Measure T-test. When the target color did not match (*Figure 5b*), there was a very strong evidence for an effect of Orientation-Congruency (BF_{10} = 799.871); in contrast, when target matched the memory color (*Figure 5a*), there was substantial evidence against an effect of Orientation-Congruency (BF_{10} = 0.245). No evidence for other interaction effects was found.

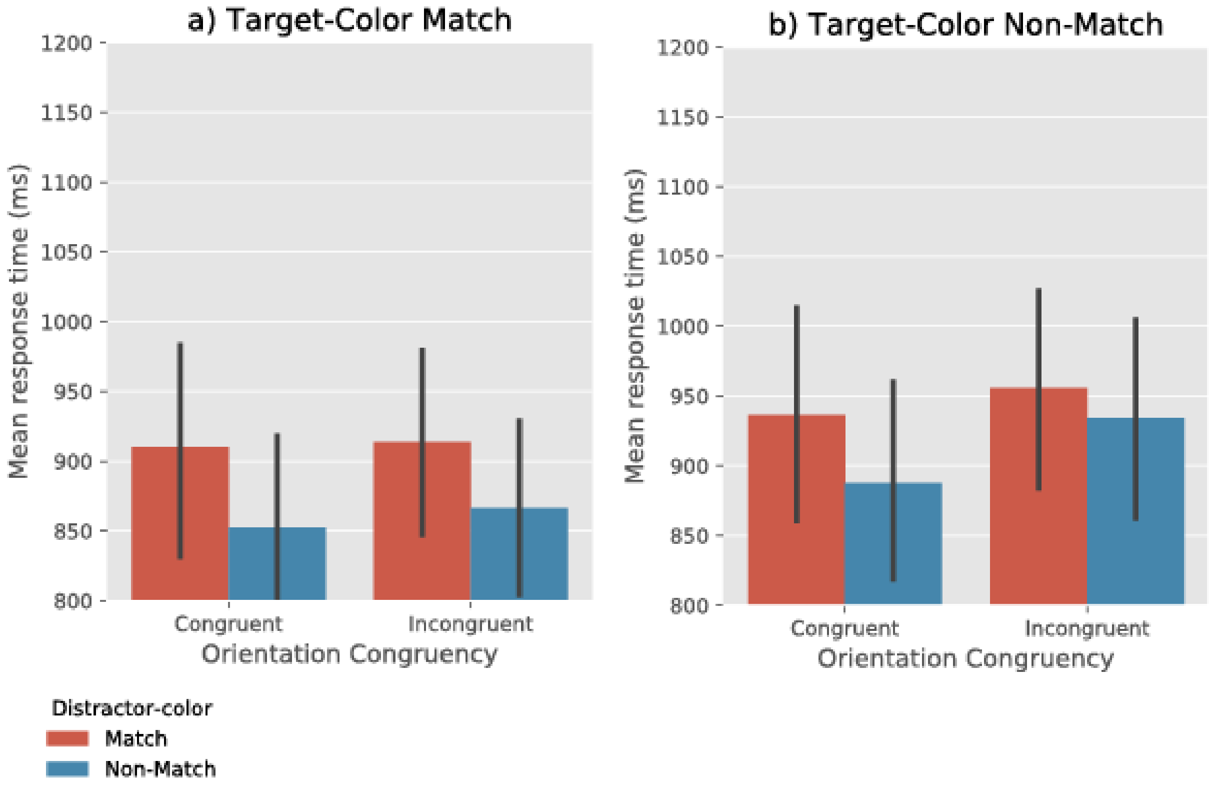

Figure 5. Mean response time as a function of Target-Color-Match, Distractor-Color-Match, and Orientation-Congruency

RT distributions

Similar to Experiment 1, the RT distribution of the Both-Target-Match trials was equally wide as that of the Non-Match trials (BF_{10} = 4.046), as predicted by the MIT hypothesis.

Accuracy

Analysis showed very strong evidence for the effect of Target-Color-Match (BF_{10}= 39.973) and Distractor-Color-Match (BF_{10} = 53.291), revealing that the overall accuracy was higher when the target matched the memory color, and lower when the distractor matched the memory color (*Figure 6*). Moreover, there was a main effect of Orientation-Congruency (BF_{10}

= 1.186×10^{6}), showing that search performance was more accurate when the line-segment orientation in a target was congruent with that in a distractor, compared to when they were incongruent.

In addition, the results revealed very strong evidence for a Target-Color-Match × Orientation-Congruency interaction (BF_{10} = 261.620), and substantial evidence for Distractor-Color-Match × Orientation-Congruency interaction (BF_{10} = 8.154). However, no three-way interaction (Target-Color-Match × Distractor-Color-Match × Orientation-Congruency) was found (BF_{10} = 2.739).

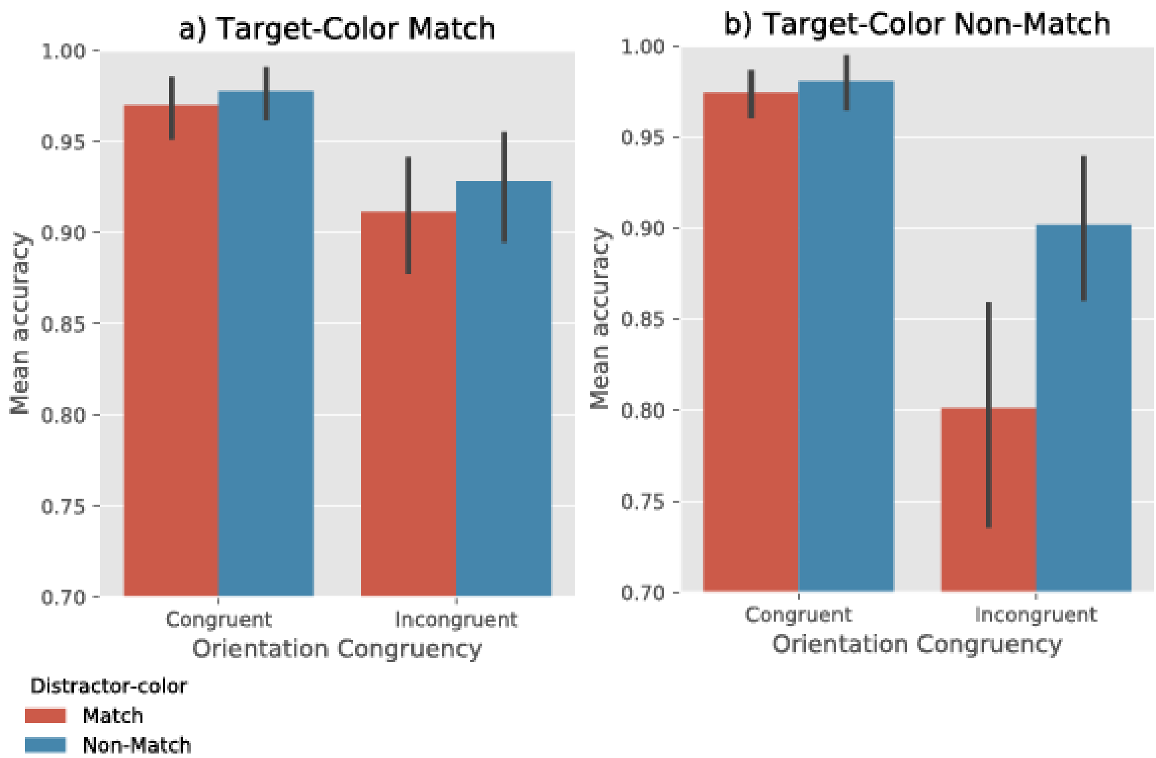

Figure 6. Mean accuracy rate as a function of Target-Color-Match, Distractor-Color-Match, and Orientation-Congruency.

In this experiment, we observed faster overall RTs and stronger congruency effect than in Experiment 1. This suggests that the irrelevant (grey) distractor in Experiment 1 did attract attention, thus reducing overall performance. Nevertheless, we successfully replicated the attentional guidance by the target and the distractor when they match the VWM colors. Importantly, we found that when the target matched the VWM item, the congruency effect largely disappeared. This robust guidance by the memory-matching item is in line with the MIT hypothesis.

Drift-diffusion modeling

As described above, the distribution of correct RTs is very similar for the Non-Color-Match and Both-Color-Match trials; this favors the Multiple-Item-Template (MIT) hypothesis over the Single-Item-Template (SIT) hypothesis. However, we wanted to compare the predictions that both hypotheses make about RT distributions more rigorously.

To do so, we used a one-sided drift-diffusion model to simulate RTs and to fit the distribution of correct RTs. The model simulates an Activation Level that changes over time, using four parameters: A Threshold, a Drift Rate, a Noise Level, and a Timeout. At time 0, the Activation Level is 0. At time 1, the Activation Level is incremented by the Drift Rate, as well as by a value that is randomly sampled from a normal distribution with a standard deviation that is equal to the Noise Level. Because we constrain the Drift Rate in our model to be a positive value, the Activation Level increases over time, although with an element of randomness. The point in time at which the Activation Level reaches the threshold is taken as the simulated RT. If the Activation Level has not reached a Threshold after a Timeout number of samples, the simulation is started again, until a valid RT is simulated. A higher Drift Rate results, on average, in lower simulated RTs. A higher Noise Level results in more variable simulated RTs.

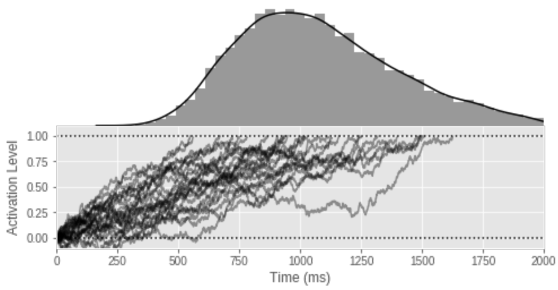

Figure 7. An illustration of the single-sided drift-diffusion model. The lower part shows how the Activation Level evolves over time, until it exceeds a Threshold. The upper part shows the resulting distribution of simulated RTs.

The Threshold was set to a constant value of 1. The Timeout was set to a constant value of 2000, corresponding to the 2000ms timeout in our experiments. The Drift Rate and Noise Level were determined for each participant separately, by taking all the correct RTs for a given participant, and rank-ordering them from fast to slow. Next, we simulated the same number of RTs, using a candidate pair of values for the Drift Rate and Noise Level, and similarly rank-ordered these simulated RTs. We then took the residual sum of squares (RSS) of the real and simulated RTs. The Drift Rate and Noise Level were then chosen such that they minimized the RSS for a given participant.

Next, we constructed two models that embodied the predictions of the MIT and SIT hypotheses. To do so, we added one additional parameter, Drift Rate Change, which was added to the basic Drift Rate to simulate the reduced RTs (facilitation) when attention was guided by the Target, and subtracted from the basic Drift Rate to simulate the increased RTs (interference) when attention was guided by the Colored Distractor.

The MIT and SIT hypotheses make slightly different predictions about the Drift Rate in the different conditions (Table 1). In a nutshell, the MIT hypothesis predicts that a Target Match should result in facilitation on every trial, and that a Distractor Match should result in interference on every trial, and that the two should cancel each other out on Both Match trials.

In contrast, the SIT hypothesis predicts that a Target Match should result in facilitation on only 50% of trials, because only one of the two VWM items serves as an attentional template, and thus the probability of the Target matching the attentional template is only 50%. For the same reason, a Distractor Match should result in interference on only 50% of trials, and the Both Match condition should be a mixture of 50% facilitation and 50% interference.

Table 1

The Drift Rate in each condition as predicted by the MIT and SIT hypotheses. The percentages indicate the percentage of trials on which the Drift Rate has a particular value.

Trial Type	**MIT hypothesis**	**SIT hypothesis**
Non-Color-Match	100%: Drift Rate	100%: Drift Rate
Target-Color-Match	100%: Drift Rate + Drift Rate Change	50%: Drift Rate + Drift Rate Change 50%: Drift Rate
Distractor-Color-Match	100%: Drift Rate - Drift Rate Change	50%: Drift Rate - Drift Rate Change 50%: Drift Rate
Both-Color-Match	100%: Drift Rate	50%: Drift Rate + Drift Rate Change 50%: Drift Rate – Drift Rate Change

For each participant separately, and for the MIT and SIT hypotheses separately, we then determined the Drift Rate Change parameter, while keeping the other parameters as previously determined. This was done by taking all the correct RTs for a given participant, ordering them first by trial type (Non-Color Match, Target Color-Match, Distractor-Color-Match, Both-Color-Match) and then rank-ordering them from fast to slow within each Condition. We then simulated the same number of RTs, using a candidate value for the Drift Rate Change, and similarly ordered these simulated RTs. The Drift Rate Change was then chosen such that it minimized the RSS between the real and simulated RTs.

To test which hypothesis could best account for the data, we compared the RSS for the MIT hypothesis with the RSS for the SIT hypothesis with a default Bayesian two-sided paired-samples t-test. This revealed 'extreme' evidence (BF10 = 52,874) in favor of the MIT hypothesis. To qualitatively compare the MIT and SIT hypothesis to the human data, we generated RT distributions, which were *z*-scored for each participant for visualization. As shown in *Figure 8*, the MIT hypothesis characterizes the human data much better than the SIT hypothesis does.

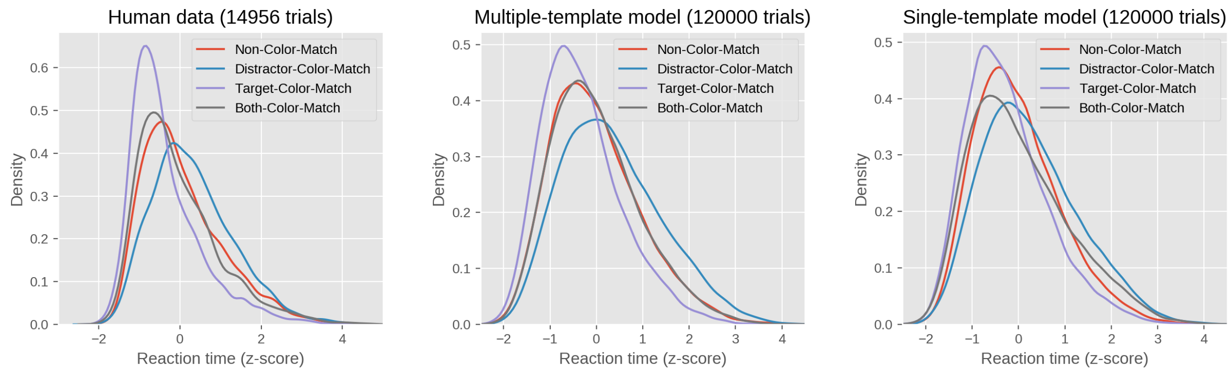

Figure 8. a) Distribution of correct RTs for the human participants (kernel-density estimates; z-scored per participant). b) Distribution of RTs simulated by the Multiple Item Template (MIT) hypothesis. c) Distribution of RTs simulated by the Single-Item-Template (SIT) hypothesis.

General Discussion

Here we report that multiple working-memory representations guide attention concurrently, thus providing crucial behavioral evidence for a long-standing debate in the field of visual working memory (VWM). In our experiments, participants remembered two colors. Next, they performed a visual-search task in which the color of the target and that of a distractor could match, or not match, a color in VWM. We found that search was faster when there was a target-color match, showing that attention was guided towards memory-matching targets; similarly, we found that search was slower when there was a distractor-color match, showing that attention was (mis)guided towards memory-matching distractors.

To further test the predictions of the MIT and SIT hypotheses, the orientation of the line-segment inside the search target was manipulated to be either the same (i.e., congruent) or opposite (i.e., incongruent) to the line segment inside the distractor. Overall, this should result in an Orientation-Congruency effect, such that RTs are slowed on incongruent compared to congruent trials. However, the MIT and SIT hypotheses make different predictions about when this congruency effect should be strongest. Specifically, the MIT hypothesis predicts that the congruency effect should be strongest on both-match trials (i.e. when both the target and the distractor matched the memorized colors). This prediction follows because only in that case attention would be drawn simultaneously towards the distractor and the target, thus creating the strongest interference (and thus the strongest congruency effect) in that condition. The SIT hypothesis makes no such prediction, because on both-match trials, attention would be guided either by the target or by the distractor dependent on which of the colors was used as a template color, but not by both, and thus there is no reason to predict increased interference. Although, we did *not* find an increased congruency effect on both-match trials, we *did* find that the congruency effect was largely absent whenever there was a target match. This suggests that attention was guided towards the target on 100% of trials, so strongly even that interference by the orientation of the line-segment inside the distractor was largely absent. Although we did not predict this, it is consistent with the MIT hypothesis. However, this effect was present only in the RTs of Exp. 2, where the grey (irrelevant) distractor was removed. Therefore, this result should be interpreted with caution.

Additionally, we analyzed the RT distribution for both-match and no-match trials (i.e. when neither the target nor the distractor matched the memorized colors). The MIT hypothesis predicts that the distribution for both-match and no-match trials should be the same (or at least similar). This follows from the MIT hypothesis, because on both-match trials, the facilitation due to attention being guided towards the target and the interference due to attention being guided towards the distractor should cancel each other out. In contrast, the SIT hypothesis predicts a wider distribution for both-match trials than for no-match trials. This follows from the SIT hypothesis, because attention is guided either by the target or by the distractor in both-match trials (but never by both), thus resulting in a bimodal distribution that is wider than the distribution for no-match trials. Consistent with the MIT hypothesis, we found that the RT distribution for both-match trials resembled that for no-match trials. To confirm this conclusion, we simulated the individual trials of RTs based on the predictions of the MIT and the SIT hypothesis by means of a drift-diffusion model. Crucially, the observed data showed a better match to the simulated RTs based on the MIT hypothesis.

Taken together, our results provide evidence against the SIT hypothesis, which posits that there can only be one template active in working memory at one time to bias visual selection (van Moorselaar, Theeuwes, & Olivers, 2014; Olivers et al., 2011). And we show behavioral and computational evidence for simultaneous guidance of multiple VWM items, providing strong support for the MIT hypothesis.

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Availability of Data and Materials

All experimental data and materials can be found on the OSF (Open Science Framework): https://osf.io/knmu2/