IDENTIFYING THE PROPERTIES OF MEMORIES THAT ENABLE ATTENTIONAL GUIDANCE

by
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IDENTIFYING THE PROPERTIES OF MEMORIES THAT ENABLE ATTENTIONAL GUIDANCE

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ABSTRACT

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Keywords: attentional template; short-term memory; learning; visual search; visual memory

While the ability of memory representations to guide attention has been traditionally argued to be due to the direction of internal attention to these representations, a recent study proposed that memory precision enables attentional guidance. In the first part of the present work, we aimed to compare internal attention and precision by manipulating them independently. In Experiment 1, in each trial, two colors were shown. On 70% of the trials, these memory items were sequentially tested. On the remaining 30%, a search task was given to measure attentional guidance. Before either task, a retro-cue indicated which color would be tested first, thus, should be attended. Critically, participants were incentivized to maintain higher precision representation for the second color with difficulty, reward, and feedback. Experiments 2 and 3 controlled for output interference and the automatic retro-cue effects, respectively. In all experiments, the cued item was reported more accurately, despite the incentives for the uncued item, indicating that isolating internal attention and precision in working memory is unattainable. Due to this obstacle, in the second part, we reconsidered precision and internal attention by involving long-term memory. First, to reliably measure attentional guidance, Experiment 4 replicated it with a revised design. Then, Experiment 5 manipulated memory precision by repeating a memory item throughout 5 trials. As the memory precision improved with repetitions, attentional guidance diminished, suggesting that internal attention governs memory-guided attention, rather than memory precision. Overall, the present work implies that (1) working memory precision relies on internal attention, and (2) attentional guidance is driven by internal attention rather than precision.

ÖZET

DIKKATI YÖNLENDIREBILEN BELLEK İZLERINE AIT ÖZELLIKLERIN TESPIT EDILMESI

FATIH SERIN

PSİKOLOJİ YÜKSEK LİSANS TEZİ, TEMMUZ 2022

Tez Danışmanı: Dr. Öğretim Üyesi Eren Günseli

Anahtar Kelimeler: dikkat şablonu, kısa süreli bellek, öğrenme, görsel arama, görsel bellek

Geçmiş çalışmalar bellek temsillerinin dikkati yönlendirme kabiliyetinin iç dikkatin bu temsillere yöneltilerek belirlendiğini öne sürse de yeni bir araştırma bu kabiliyetin temsil netliğinden kaynaklandığını önermektedir. Mevcut çalışmanın ilk kısmında, iç dikkat ve temsil netliğini karşılaştırmak için bunları birbirlerinden ayrı şekilde değiştirmeyi amaçladık. Deney 1'de her denemede önce iki renk gösterildi. Denemelerin %70'inde bellek temsilleri sırayla zorunlu seçim görevi ile test edildi. Geri kalan %30'unda arama görevi ile dikkati yönlendirme ölçüldü. İki görevden de önce bir retro-ipucu hangi rengin önce test edileceğini belirtilerek iç dikkatin bu temsile yönlendirilmesi amaçlandı. Kritik olarak ikinci rengin daha yüksek netlikte tutulması görev zorluğu, ödül ve geri bildirim ile teşvik edildi. Deney 2 ve 3, sırayla, testin karıştırıcı etkisini ve retro-ipucunun otomatik etkisini kontrol etti. Üç deneyde de ipucu verilen temsil, diğer temsile yapılan teşviklere rağmen, daha yüksek isabet ile raporlandı. Bu sonuç çalışma belleğinde iç dikkat ve temsil netliğinin ayrıştırılamayacağı ihtimaline işaret etmektedir. Karşılaşılan bu engelden dolayı ikinci kısımda temsil netliği ve iç dikkat, uzun süreli bellek dahil edilerek, farklı şekilde kavramsallaştırıldı. Önce, dikkati yönlendirme ölçümünü geliştirmek için Deney 4 yeni bir arama görevi kullanarak etkiyi tekrarladı. Ardından Deney 5 temsil netliğini değiştirmek için temsili beş deneme boyunca tekrarladı. Temsil netliği arttıkça dikkati yönlendirmenin azaldığı gözlemlendi. Bu bulgu bellek güdümlü dikkatin belirleyici etkeninin iç dikkat olduğunun göstergesi olarak alınabilir. Özetle, mevcut çalışma, çalışma belleğinde temsil netliğinin iç dikkate dayandığını ve bellek güdümlü dikkatin, temsil netliğinden ziyade, iç dikkat ile belirlendiğini önermektedir.

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But before everything and throughout everything, my elder brother was the one who introduced me to the coolest films, music, and books way before my peers were introduced. Thanks to you I skipped many cringe parts of being a teenager. I wish we had a better environment to grow up in. But, my biggest wish in life now is that you be happy and healthy. Lastly, most of the credit goes to my mother, Nefize. Growing up, although I knew we did not have much, you never made me feel it. Your belief in me had me keep going even when nothing was going right. Although you left this world so young, this world did not deserve you to begin with. Sorry for always being so stubborn and making you sad often. I wish we could talk about everything I have been doing since you passed away. We have a lot to catch up on. But, for now, I hope you are in peace.

Dedication page
Dedicated to the memory of my late mother Nefize

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1. INTRODUCTION

We have the ability to search and find the objects we are looking for in the environment. This allows us to find our friend in a crowd, a certain book in a bookstore, or a particular phrase in a text. These tasks can be carried out successfully even when the target objects are not special in their environment, such as being physically salient (e.g., a red book among green books). Rather, they can be special to the person looking for them, indicating that there are top-down mechanisms that allow the guidance of attention. Our memories of these objects make these common objects salient.

Extensive research has shown that working memory (WM) has the capacity to bias visual attention such that the stimuli that match WM contents capture attention (Downing 2000; Soto et al. 2005; Wolfe 2007). The influential biased competition model suggests that perceptual competition that exceeds the processing capacity of the visual system is biased towards stimuli that share perceptual features with information stored in WM (Desimone and Duncan 1995). Moreover, such WM-driven attentional guidance has been suggested to operate, at least partially, involuntarily. Because behavioral and neural indices observed that attentional guidance takes place even when participants are instructed that these stimuli can never be targets (Olivers, Meijer, and Theeuwes 2006; Soto et al. 2008). However, although remembered, memory representations do not always guide attention (Peters, Goebel, and Roelfsema 2009). This leads to the question of which property of WM items enables attentional guidance. Despite the effect having been demonstrated widely, the causal processes underlying guidance by WM did not receive the same treatment and remain a matter of debate.

Traditionally, it has been suggested that internal attention is the primary factor determining whether a representation, or an item, will bias attention (Carlisle et al. 2011; Hollingworth and Hwang 2013; Olivers et al. 2011). Internal attention can be understood as focusing a subset of items among memory items currently being actively maintained. It is argued that when internal attention is directed towards a WM item, that item becomes the attentional template. This template, in turn, produces an attentional bias towards the stimuli that are similar to or matching it. Visual search tasks are typically employed to measure attentional guidance (Olivers 2009). Generally, in these paradigms, participants are first briefly shown and asked to memorize a color. After a short while, they are given a search task such as finding and reporting the direction or location of a tilted line among horizontal and vertical distractor lines. Lastly, after responding to the search task, participants report the color initially shown, either by choosing the color among several options or selecting it on a color wheel as closely as they can. Critically, the search display, in some trials, includes stimuli that have the same color as the color maintained in memory, and in other trials, the stimuli are a completely different, and novel color. The attentional guidance effect is assessed by the slower or less accurate visual search responses in search task trials where a distractor matches the memorized color versus where another irrelevant color.

More recently, it has been put forward that the quality of the WM item is the determining factor of attentional capture. Williams, Brady, and Störmer (2022) claimed that the precision of the WM item accounts for guidance without requiring the notion of template status. They report that guidance is observed only when an item is high precision, regardless of whether internal attention is directed to that item. Participants were given two items to memorize. After the visual search task, participants either reported the color that is probed (forced report), or the color they chose to report (free report). Attentional guidance in the visual search task was not observed only when the participants chose to report the color that had not appeared in the search task as a distractor. In other words, only in trials where the color that appeared as a distractor was not chosen to be reported, it did not guide attention. Assuming that participants choose to report the more precise item, Williams, Brady, and Störmer (2022) concluded that this failure is due to that color not having a high enough precision. Overall, this new account proposed that precision of items enable them to guide external attention, rather than internal attention, and explained the previous findings as precision having been confounded by internal attention as it is a factor that influences precision.

Together, these studies highlight a debate in the literature regarding the main factor that generates involuntary attentional guidance, internal attention versus precision. However, resolving this debate involves a challenge inherent to the relationship between attention and memory: Directing attention towards an item results in better precision (Gunseli et al. 2015; Klyszejko, Rahmati, and Curtis 2014; van Moorselaar et al. 2015; Yoo et al. 2022). This underlying mechanism obscures determining whether the causal element behind attentional guidance is internal attention or precision. To overcome this challenge, the present study attempts to isolate the effects of precision and internal attention in WM.

Experiment 1 aimed to manipulate precision and internal attention independently of each other with task difficulty and retro-cue. In every trial, participants had to memorize two colors, and a retro-cue indicated which color would be asked first, hence, manipulating internal attention. Precision was manipulated by changing the lure alternatives' similarity to the target color in the memory test. To further assist the manipulation of precision, feedback and reward systems were implemented. Attentional guidance was assessed by probing a search task instead of the memory test on 30% of trials. To control for the perceptual and output interference due to the first memory test that presumably confounded the second memory test in Experiment 1, Experiment 2 reversed the order of the memory test on a minority of trials, allowing assessment of precision without perceptual and output interference. Experiment 3 attempted to eliminate the automatic retro-cue effects precisions to assess attentional guidance by reversing the retro-cue role. Experiments 4 and 5 adopted a different approach to manipulate precision and internal attention independently of each other and fix the shortcomings of the first series of experiments. Experiment 4 replicated the classical attentional guidance effect by using a continuous report task to establish parameters for a more sensitive precision estimate. Experiment 5 tackled the research question from the perspective of WM activation and long-term memory (LTM) involvement by reducing WM activation with the repetition of items, based on the findings that repeated memory items are handed over from WM to LTM (Gunseli, Olivers, and Meeter 2016; van Moorselaar, Theeuwes, and Olivers 2016).

Although memory-guided attention is studied extensively (Chen and Hutchinson 2018; Fischer, Moscovitch, and Alain 2021; Hutchinson and Turk-Browne 2012; Soto, Humphreys, and Rotshtein 2007), there is relatively less research on why memory items guide visual attention and therefore, remains a matter of debate. In summary, the present work attempted to contribute to this gap via manipulating internal attention and precision separately. This was aimed to be accomplished first, by integrating retro-cue, task-difficulty, reward, and feedback procedures, and then, by controlling WM activation through repetition. The study holds significant implications for the debate on why WM items guide attention and control over precision WM.

2. ONLINE EXPERIMENTS

2.1 Method

2.1.1 Participants

All participants were Sabanci University students who received course credit in return for their participation. In Experiment 1, 13 (Age range: 19-23, mean: 21.62; 11 female) participants were recruited. In Experiment 2, 10 (Age range: 19-24, mean: 20.8; 6 female) participants were recruited. In Experiment 3, 16 (Age range: 20-24, mean: 21.44; 14 female) participants were recruited. None of the participants reported neuropsychological disorders or color blindness. Although exclusion criteria of 40% accuracy for the memory test (chance level = %33) and 55% accuracy for the search task (chance level = %50) were set, none of the participants were below these criteria. The experiments were approved by the Sabanci University Research Ethics Committee (SUREC) and were carried out according to the principles of the Declaration of Helsinki. Participants signed a consent form before the experiment.

2.1.2 Stimuli

The experiments were created using the PsychoPy toolbox (Peirce et al. 2019) in order to carry out the experiment online through internet browsers. Therefore, there was a variance in the screen properties as people used their personal computers to perform the experiments. Nevertheless, they were instructed to remain seated 60 cm away from the screen. The background color was gray (hue saturation value - HSV: [0, 0, .5]). Filled colored circles (diameter 0.8°) were used as memory items. A fixation cross remained at the center of the screen throughout the trial. The fixation cross and all the texts (instructions and feedback) were black (HSV: [0, 0, 0]). On the memory display, two memory items were placed on the left and right sides of the fixation. A triangle (width 0.3°) was used as the retro-cue and shown slightly above the fixation. During the search task, eight lines were distributed evenly around the center. While the distractors were either horizontal or vertical, the target line was tilted 10°. During the memory test screen, three alternatives were located (0.8°) above the fixation and were (0.5°) apart. Memory item colors were picked randomly from among 360 different hues, all of which had the same saturation (.7) and value (.7) in the HSV model. The lure colors on the memory test screen had a hue difference of 28° on the easy, 38° on the medium, and 48° on the difficult condition.

2.2 Experiment 1

2.2.1 Procedure

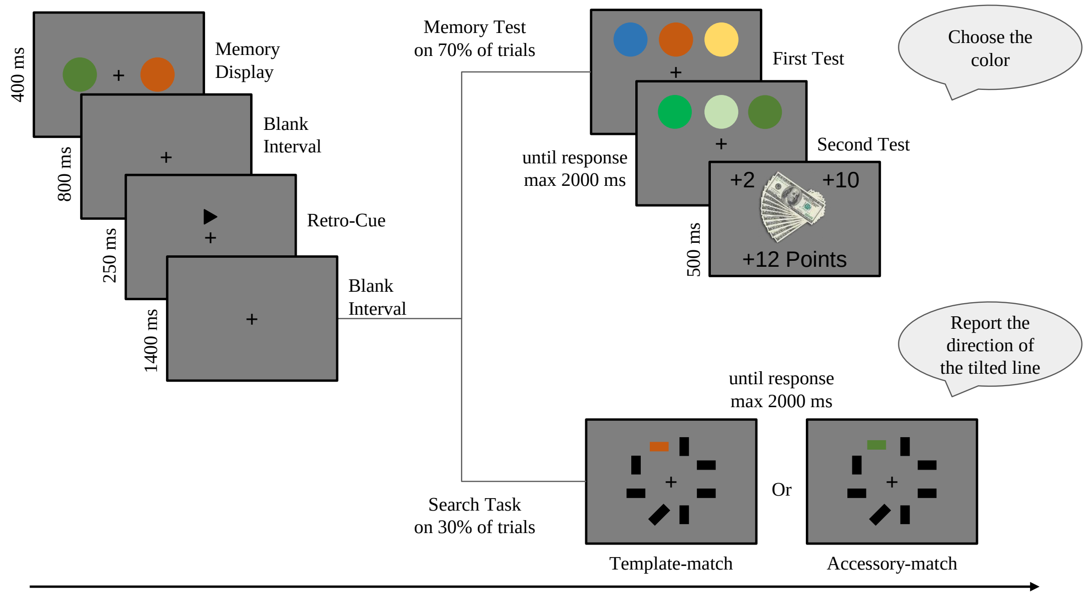
Figure 1 depicts an example trial flow. Each trial started with the presentation of 2 random (controlled for a within-trial difference of at least 150° and between-trial difference of at least 45°) memory items for 400 ms. Then, a blank screen for a retention interval of 800 ms was shown. Following this, a retro-cue randomly pointed to one of the memory item positions, indicating the first item to be tested. After another retention interval of 1400 ms, the memory test was probed on 70% of the total trials, and the search task was probed on the remaining 30

During the memory test, participants were first asked to choose the cued color among 3 alternatives. After the response, participants were asked to pick the uncued color among 3 alternatives. They used “J”, “K”, and “L” keys to pick the left, middle, or the right option, respectively. Critically, participants also knew that the first test would be easy, and the second test would be difficult due to the similarity of the lure colors to the correct color on the test display. However, on 25% of these memory trials, both tests were set to medium difficulty to have comparison trials where both the first and the second tests can be evaluated without the test difficulty confound. For both memory tests and the search task, participants had 2000 ms to respond. After their response to the second memory test or the search task, they received feedback for their accuracy. Additionally, participants were also instructed that memory tests will be rewarded with points. The first test would be rewarded 2 points while the second test would be rewarded 10 points to assist the difficulty manipulation to increase precision for the uncued item. The points received during a trial were shown on the feedback screen. The search task was not rewarded. To further support the difficulty and reward manipulation, after every 5 medium difficulty trials, participants received a warning on the feedback screen if they performed worse for the uncued item than the cued item based on these last 5 medium difficulty trials. The feedback screen lasted for 300 ms unless participants received this warning or failed to respond within the time limit, in which case, the time window was extended to 1000 ms. Including the feedback, the inter-trial interval lasted 1500 ms.

During the search task, participants were asked to find the tilted line among horizontal and vertical distractors and report whether the tilt is toward left or right by pressing “J” or “L” for left tilt or right tilt, respectively. Critically, on every search trial, one of the distractors was colored. On half of these search trials, the colored line matched the cued item, template-match condition, and on the other half, the colored line matched the uncued item, accessory-match condition. These trials would allow us to observe attentional guidance by different representations in WM via slower reaction times (RT) due to the distractor matching memory contents.

Participants performed 12 practice trials prior to the main experiment. If a participant had to repeat the practice phase if they could not perform above chance level for both memory and search tasks. The main experiment had 560 trials in total, 392 of which were memory trials and 168 of which were search task trials. Out of 392 memory trials, there were 98 medium-difficulty trials.

Figure 2.1 Experiment 1 Example Trial Flow

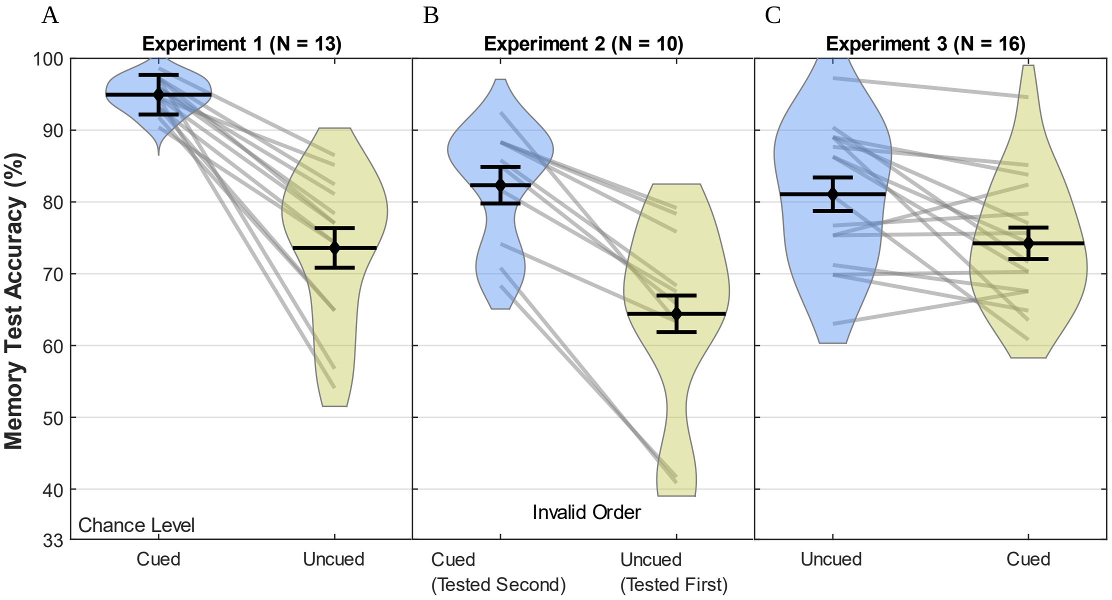


2.2.2 Results

Accuracies[1] for the memory tests were calculated as the percentage of correct answers on medium difficulty trials (Applies for the following experiments as well). Paired samples t-test was conducted to compare first and second memory test performances. Accuracy for the first test (M = 94.94, SD = 2.4) was higher than the second test accuracy (M = 73.6, SD = 10.4). The difference, 21.35 (95% CI [15.33, 27.36]; Cohen's d = 2.14), was significant according to the paired-samples t-test, $t(12) = 7.73$, $p < .001$. The accuracies for medium difficulty first and second tests results are shown in Figure 2A.

The RT results for the correctly answered search task trials showed no significant difference, 5.66 ms (95% CI [-9.71, 21.04]), between the accessory-match (M = 872.82 ms, SD = 130.99 ms) and template-match (M = 867.15 ms, SD = 120.55 ms) conditions, $t(12) = 0.80$, $p = .437$.

Figure 2.2 Memory Test Accuracy Results



Violin plots for memory test accuracies in Experiments 1 (A), 2 (B), and 3 (C). Error bars represent one standard error normalized for within-subjects variance.

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[1] For Experiments 1, 2, 3, and 4, the results were calculated with custom MATLAB scripts. For Experiment 5, JASP was used to carry out the analysis. All the results figures were plotted by custom MATLAB scripts.

2.2.3 Discussion

Experiment 1 demonstrated that participants performed better for the cued item (first memory test) than the uncued item (second memory test) on medium trials despite the task requirements and instructions demanding the opposite. The interpretation of the RTs in the search task depended on the outcome of the manipulations that aimed to establish 2 specific representations, one that is attended to and another that has higher precision. As one of the established representations both had higher precision and was attended to, interpreting the search task results would be misleading. Nevertheless, the obtained memory accuracies can be interpreted to better understand the relationship between internal attention and precision. The results might indicate that precision is the direct consequence of internal attention since attending to one item made it impossible to maintain another item, which was incentivized, with higher precision. However, the perceptual and output interference from the first memory test potentially disrupts the precision of the uncued item, creating an alternative explanation for the lower precision in the second memory test. To assess the item precisions without these interferences, we designed Experiment 2 which reverses the order of memory tests on a minority of the trials.

2.3 Experiment 2

2.3.1 Procedure

To free the precision assessment in the second memory test from the perceptual and output interference from the first test, we made the retro-cue probabilistic in Experiment 2. Experiment 2 had three main differences compared to Experiment 1. First, to create trials where the assessment of the cued item did not interfere with the assessment of the uncued item, retro-cue validity was reduced from 100% to 75%. Second, because retro-cue was not deterministic anymore, during the test screens, a white circle indicated the item that was currently being tested by showing up at the position where that item appeared during the memory display. Lastly, to increase the statistical power and prevent fatigue, the search task was not included. Therefore, on 25% of the trials, participants were given the memory tests in reverse order, uncued item first and cued item second. Again to preserve statistical power, these reverse order trials were also set as the medium difficulty trials as they are the trials analyzed to compare cued and uncued item precisions.

2.3.2 Results

Accuracy for the second tested cued item memory test (M = 82.33, SD = 8.34) was higher than the first tested uncued item memory test (M = 64.42, SD = 13.52). The difference, 17.92 (95% CI [12.16, 23.68]; Cohen's d = 2.23), was significant, t(9) = 7.04, p < .001. Accuracies are plotted in Figure 2B.

2.3.3 Discussion

Experiment 2 showed that the second tested cued item, hence was subject to perceptual and output interference, had better precision compared to the first tested uncued item, hence free from interference. This finding is in parallel with the Experiment 1 interpretation that internal attention is the mechanism that controls precision. Because while subject to interference, the attended item had higher precision compared to the unattended item without interference. Therefore, Experiment 2 suggests that perceptual and output interference does not provide an alternative explanation for the Experiment 1 results that displayed lower precision for the unattended but incentivized item compared to the attended item. Besides interference, retro-cue manipulation might also provide an alternative explanation. It was shown that retro-cue effects on precision are, at least partially, automatic (Berryhill et al. 2012; Schmidt et al. 2002). Based on this, retro-cue effects might be too strong on WM such that it prevents maintenance of the unattended item. Thus, Experiment 3 reversed the function of the retro-cue to control for the automatic effects of the retro-cue.

2.4 Experiment 3

2.4.1 Procedure

Experiment 3 was identical to Experiment 1 except for only one aspect. In this experiment, the function of the retro-cue was reversed such that it indicated the second tested item, which requires high precision, rather than the first tested item, which was to be attended to. Participants were informed about this prior to beginning the experiment. This would allow us to understand the lower precision for the uncued but incentivized item while potentially establishing suitable representations to assess attentional guidance by WM.

2.4.2 Results

The difference, 6.84 (95% CI [1.77, 11.9]; Cohen's d = 0.72), between the accuracies of first (M = 81.08, SD = 9.65) and second (M = 74.24, SD = 9.051) memory test was significant, t(15) = 2.88, p = .011. The accuracies are shown in Figure 2C. The RT difference, 20.60 ms (95% CI [-7.64, 48.84]), between the correctly answered accessory-match (M = 971.69 ms, SD = 126.84 ms) and template-match (M = 951.08 ms, SD = 90.88) search task trials were not significant, t(15) = 1.56, p = .141.

2.4.3 Discussion

The results replicated the findings in Experiment 1. This rules out another alternative explanation to why it was not possible to maintain the unattended but incentivized item with higher precision. Even after controlling for the automatic retro-cue effects by reversing the function of the retro-cue, maintaining the unattended item with higher precision, despite the difficulty, reward, and feedback manipulations, was not attainable.

However, although the mean accuracies parallel Experiments 1 and 2, we see few participants (four out 16) that diverge from this pattern, unlike the previous experiments where every participant showed the same pattern. The primary explanation could be that, for some participants, retro-cues may indeed lead to automatic prioritization of the cued item, impairing the flexibility of allocating attention (Berryhill et al. 2012; Schmidt et al. 2002). Alternatively, this deviation could also be reflecting misunderstanding of instructions, leading participants to direct their attention in the opposite way. Nevertheless, Experiment 3 can be considered a replication of the previous two experiments as diverging patterns only constitute a minority of the whole data.

2.5 Aggregate Analysis

To overcome the low sample size limitation of the experiments, we collapsed the data across the experiments. Accuracy for the attended item (M = 86.02, SD = 9.81) was significantly higher than the unattended item (M = 71.51, SD = 11.3), according to paired samples t-test, t(38) = 8.07, p < .001.; 95% CI of the difference = [10.87, 18.16]; Cohen's d = 1.29). Additionally, a Bayesian paired-samples t-test yielded overwhelming evidence in favor of the alternative hypothesis that accuracy was higher for the attended item (BF10 $>$ 12300000). 35 out of 39 participants displayed this pattern.

Although it cannot replace a priori power analysis, we ran a post hoc power analysis to estimate the statistical power for the combined analysis. Using the parameters $\alpha = .02$, two-tailed, sample size 39, we carried out the analysis via the G*Power software (Faul et al. 2009) with the smallest effect size among experiments (Experiment 3: Cohen's d = 0.72). Overall, the Bayesian evidence and post hoc statistical power demonstrates that the effect we obtained is reliable.

2.6 Intermittent Discussion

In an attempt to isolate the determinant of attentional guidance by WM items, we have conducted three experiments. The experiments aimed to establish two representations, one that is attended to and another that is unattended but with higher precision. Thus, their guidance performance could be compared to observe whether template status or high precision enable attentional guidance in the external world.

However, all three experiments were unable to establish suitable representations required to interpret the search task RTs. Instead, all the experiments provided one representation that is both attended to and higher precision and another that is lower precision despite the difficulty, reward, and feedback manipulations. This reflects how dominant internal attention is in controlling the maintenance and hence the precision of items in WM. Accordingly, these results are indicative of internal attention being the sole factor in controlling precision in WM. What this interpretation suggests for attentional guidance is that the current debate about internal attention versus precision is stemming from the inseparable nature of these two concepts in WM.

3. REPLICATION & REPETITION

Our first series of experiments could not provide a conclusion to the debate on what determines attentional guidance by WM due to the experiments not attaining suitable representations to interpret guidance performance. Yet, they do inform us about the concepts of attention and precision in WM. However, there were three limitations to these first three experiments: Inseparability of internal attention and precision, online setting, and unreliable search task.

As was discussed under the previous experiments, our attempts could not dissociate internal attention and precision in WM. We tried to manipulate internal attention through retro-cues while trying to manipulate precision with a higher difficulty requirement, higher reward, and feedback. This inability to behaviorally distinguish between internal attention and precision in WM calls for a different approach to understand which property of memories enables them to guide external attention.

The experiments rely heavily on careful control of attention and maintenance of high-precision color representations. Both of these necessities might have been impaired by the fact that these experiments were conducted online on participants' personal computers. Computer screens differ in terms of the quality and the range of colors they display in addition to the different brightness and contrast. They also differ in size, which changes stimulus sizes. Besides the computer properties, the environment also influences the perception, such as the lighting and distance from the screen. The environment is also problematic as it does not resemble laboratory environments that are quiet and away from distractors such as smartphones. Together, the online setting creates a considerable variance that might have negatively affected controlling internal attention and maintaining multiple precise representations.

Besides these, our search task appears to be unreliable. Although it does not inform our attempt to dissociate template and precision theories of guidance, we can still interpret the search task RTs. The experiments established a representation that was both attended to and higher precision. Both the template status and precision theories would predict that this representation would guide attention in comparison to the other item, which was neither attended to, nor higher precision. However, what was observed is that there was no significant difference between the RTs of the template-match and accessory-match conditions. Therefore, we interpreted that our search task was not sensitive enough to assess attentional guidance.

Due to these limitations, we wanted to approach the research question of which factor enables memory-guided attention from a different perspective. As the first series of experiments were not able to dissociate internal attention and precision in WM, we wanted to examine these two concepts in the more general memory-guided attention domain as LTM is also known to guide external attention (Hutchinson and Turk-Browne 2012; Leber, Kawahara, and Gabari 2009; Olivers 2011; Stokes et al. 2012). We tried to accomplish this by improving on the previous work by Gunseli, Olivers, and Meeter (2016) and van Moorselaar, Theeuwes, and Olivers (2016). This approach conceptualizes internal attention as WM activation while precision is conceptualized as WM representations being handed over to LTM. Thus, although dissociation of internal attention and precision in WM might not be behaviorally possible, investigating these two concepts in the wider domain of memory-guided attention could contribute to our research question. In line with the inspired work (Gunseli, Olivers, and Meeter 2016; van Moorselaar, Theeuwes, and Olivers 2016), we expected that (1) memory precision improves as a function of repetition and that (2) memory-guided attention diminishes as WM activation declines. However, before we attempted this approach, we tried to make sure we had acquired a reliable search task to assess memory-guided attention.

3.1 Method

3.1.1 Participants

Participant recruitment procedures were the same as in the first series of experiments. There were 17 (Age range: 19-22, mean: 20.88; 11 female) participants in Experiment 4 and 23 participants (Age range: 20-24, mean: 21.43; 16 female) in Experiment 5. None of the participants were excluded from the analysis.

3.1.2 Stimuli

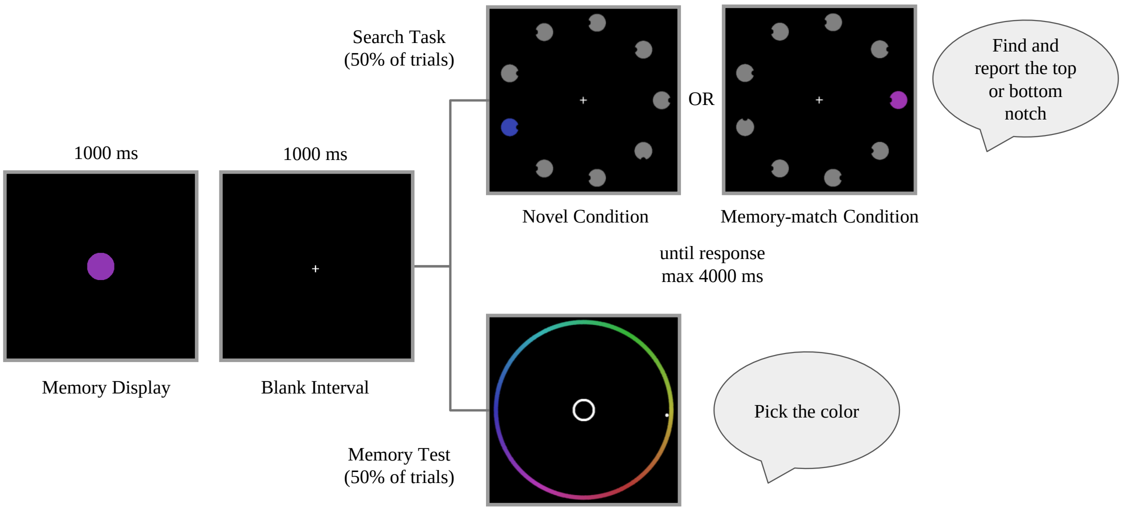
Experiments 4 and 5 were created on MATLAB Psychtoolbox (Brainard 1997; Pelli 1997) and conducted in the psychology labs. A 24-inch monitor with a 60 Hz refresh rate and a 1920x1080 resolution was used. Participants were seated 70 cm away from the screen. The screen background was black (HSV: [0 0 0]). Unlike the previous experiments, there was only one filled circle color (diameter 1.5°) on every trial, which was located at the center of the screen during the memory display. Colors were picked randomly from 360 different hues (HSV saturation: .7; value: .7) but they were at least 60° away from the last trial's color. Whenever there was a blank interval, only a white fixation cross (0.3° width) was drawn on the screen. For the search task, 9 filled gray (HSV: [0 0 .5]) circles (diameter 1.2°) were used as the distractors and the target. Each one of these circles had a circle notch (.35°) on it. These circles were evenly distributed around the center (5.3° away from the center). During the memory test, a color wheel (diameter 12°; HSV saturation: .7; value: .7) was placed at the center.

3.2 Experiment 4

3.2.1 Procedure

To establish a robust task to assess attentional guidance by memory, we reconstructed a simple search task based on previous studies (Gunseli, Olivers, and Meeter 2016; Olivers 2009). Figure 4 depicts a typical trial flow. On every trial, participants first saw a colored disk for 1000 ms to memorize. After a 1000 ms blank interval, on 50% of the trials, they were asked to report the color by clicking on the color wheel. On the remaining 50%, the search task was probed. The task was to find the top or bottom notch on a gray disk, among disks with side notches, and report whether it is a top or a bottom notch by pressing "D" or "C", respectively. critically, on half of these search trials, one of the distractors in the search display was colored as the memory-matching color, the memory-match condition, and on the other half, it matched a novel color, the novel condition. This way we would be able to measure guidance by memory from the slower RTs in the memory-match condition compared to the novel condition. For both the color wheel task and the search task, participants had 4000 ms to respond. Following the response or timeout, a 300 ms feedback screen indicated the response accuracy, in memory test trials, as the error in degrees and in search trials, as "correct/false". including the feedback duration, the inter-trial interval was 1500 ms. There were 360 trials (180 trials per task; 90 trials per search task condition). In addition to these trials, participants completed 15 practice trials before they began the main experiment.

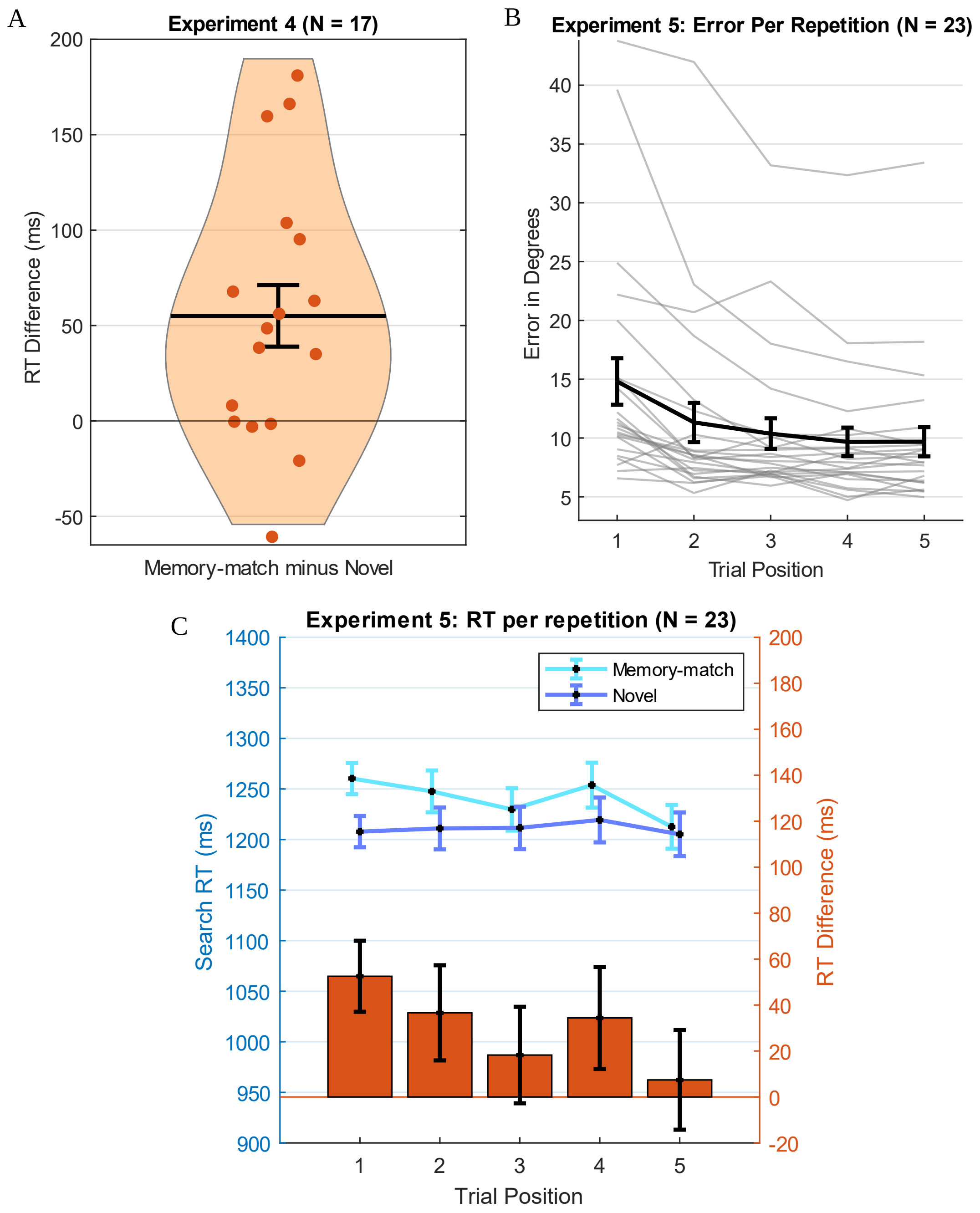
Figure 3.1 Experiment 4 Example Trial Flow



3.2.2 Results

Memory error in the color wheel task was calculated as the deviation of the selected color from the original color in angular degrees on the color wheel for each participant. The mean memory error was 12.61°. For the search task, we analyzed the correctly responded trials only. Participants were on average slower in the memory-match condition (M = 1357.2 ms, SD = 234.72 ms) compared to the novel condition (M = 1302.1 ms, SD = 236.16 ms). The difference, 55.08 ms (95% CI [19.85, 90.31]), was significant, t(16) = 3.32, p = .004, with an effect size of 0.803 (Cohen's d). The results are plotted in Figure A.

Figure 3.2 Experiments 4 and 5 Results Figures



Experiment 4 search task RT results are plotted as the difference between memory-match and novel conditions for each participant (A). Dots represent individual data. Experiment 5 memory test error is plotted as a function of repetitions (B). Thin lines represent individual data. Experiment 5 search task RT is plotted as a function of time repetition (C) both as separately for conditions with line graphs and as their difference with bar graphs. In all three figures, error bars represent one standard error normalized for within-subjects variance.

3.2.3 Discussion

Experiment 4 attempted to build a reliable configuration to measure memory-guided attention. The results showed that the purpose was achieved with considerable effect size, providing a paradigm to utilize while observing the change in guidance as the memory item is repeated throughout the trials.

3.3 Experiment 5

3.3.1 Procedure

Experiment 5 was identical to Experiment 1 except that the memory item was repeated for 5 trials. After 5 trials, a new memory item was repeated. The experiment was also considerably longer to acquire a sufficient number of trials per repetition and task. There were 660 trials in total. This provides 66 trials per repetition per task and 33 trials per search task condition per repetition.

3.3.2 Results

The quadratic contrast analysis showed a significant effect of repetition on memory error in the memory test, $t(88) = 3.74$, $p < .001$, indicating a decrease in memory error as a function of repetition. The memory error scores per repetition are plotted in Figure 4B. To observe the effect of repetition on attentional guidance, we calculated guidance scores by subtracting RT scores of the novel condition from the RT scores of the memory-match condition. The repeated measures analysis of variance (ANOVA) on these guidance scores per repetition was not significant, $F(4, 88) = 0.66$, $p = .611$. However, while there was a significant attentional guidance effect for the 1st repetition according to the comparison of the novel and memory-match conditions, $t(22) = 3.32$, $p < .015$, there was no significant difference for the 2nd, 3rd, 4th, and 5th repetitions, indicating that guidance faded after the 1st repetition. Although ANOVA for the guidance scores per repetition was not significant, Bayesian pairwise comparisons yielded no strong evidence for the null hypothesis in any of the comparisons ($BF01 < 4$), indicating a potentially insufficient statistical power. The results for the RTs per condition and per repetition are shown in Figure 4C.

3.3.3 Discussion

Paralleling the previous research (Gunseli, Olivers, and Meeter 2016; van Moorselaar, Theeuwes, and Olivers 2016), memory precision improved with the repetition of the memory item, suggesting the handing over of memory representations from WM to LTM and decline of WM activation. Another support for declining WM activation can be drawn from a recent preprint (Hirschstein and Aly 2022), suggesting that WM and LTM cooperate to guide attention when they share the domain. Therefore, if WM activation was not declining, we would, at least, observe constant guidance through repetitions. While the comparisons of guidance scores between the repetitions showed no significant difference, the guidance effect was present in the 1st repetition but disappeared after the 1st repetition. As WM activation decreased and LTM involvement increased, attentional guidance diminished, suggesting that memory-guided attention is driven by internal attention directed to the memory representation rather than the quality of the memory representation.

Furthermore, if the trend of guidance scores per repetition is interpreted, although a gradual decrease is present, a rebound is observed on the 4th repetition. This resembles the results of van Moorselaar, Theeuwes, and Olivers (2016) where they find a resurgence in the last few repetitions. It is interpreted as the participant's anticipation of and preparation for the next color to facilitate the encoding which results in restored WM activation. This strategic use of WM is in line with Reinhart, Carlisle, and Woodman (2014) where although an EEG measure (contralateral delay activity; CDA) of WM involvement is declining with the repetition, it resurges with the introduction of higher reward, suggesting flexible employment of WM.

Experiment 5 provides a conceptual replication of van Moorselaar, Theeuwes, and Olivers (2016) with a continuous report task and a different search task. Critically, by presenting the search task and memory test on different trials, rather than presenting the memory test after the search task, we unconfounded the memory test from the encounter with, hence resampling, the memory item during the search task. This allowed us to discuss memory quality and attentional guidance free from a potential circularity between them.

4. GENERAL DISCUSSION

Although memory-guided attention is a widely studied area (Chen and Hutchinson 2018; Fischer, Moscovitch, and Alain 2021; Hutchinson and Turk-Browne 2012; Soto, Humphreys, and Rotshtein 2007), the underlying property of memory representations that enable them to guide external attention remains unclear. Thus, through several experiments, the present work attempted to investigate this underlying property. Previous research was divided in terms of whether internal attention, via creating attentional templates (Hollingworth and Hwang 2013; Olivers et al. 2011), or precision of memories (Williams, Brady, and Störmer 2022) determine whether a memory representation guides attention.

Experiments 1 to 3 tried to resolve the debate with a design to independently manipulate internal attention and precision. The attempt was unable to find a dissociation between these two concepts. This result held despite controlling for the perceptual and output interference on the unattended item and automatic retro-cue effects on the attended item. We interpret this lacking dissociation as stemming from the dominating role of internal attention in determining the precision of WM representations, as all three experiments demonstrated that the attended item had higher precision despite the unattended item was incentivized with higher precision requirement, higher reward, and feedback.

However, our interpretation of the results is based on severe testing of the hypothesis that precision and internal attention in WM are separable. That is, it might be the case that there is a mechanism that controls precision in WM beyond internal attention, but it is, at least with our manipulations, unable to surpass the effects of internal attention. In other words, our design and criteria may not have been sensitive enough to observe this other mechanism. In line with such dissociation, recent work demonstrated that neural measures of WM activity and internal attention do not overlap (Gunseli et al. 2015; Günseli et al. 2019; Hakim et al. 2019; van Driel et al. 2017).

As the first series of experiments were unable to decouple precision from internal attention, we took a different approach by conceptualizing precision as LTM involvement, and internal attention as WM activation. By using a reliable assessment of attentional guidance with the replication in Experiment 4, Experiment 5 monitored the guidance effect as representations were handed over from WM to LTM. The results suggested that although memory precision improved with repetitions, attentional guidance rapidly diminished, replicating the findings of previous research (Gunseli, Olivers, and Meeter 2016; van Moorselaar, Theeuwes, and Olivers 2016). We found that even on the second repetition of the memory item, there was no significant guidance effect. This indicates that memory-guided attention is driven more by the direction of internal attention, hence attentional templates (Carlisle et al. 2011; Hollingworth and Hwang 2013; Olivers et al. 2011), rather than the quality of memories (Williams, Brady, and Störmer 2022).

This conclusion is in line with the biased competition model (Desimone and Duncan 1995) which argues that WM activation readies perceptually matching representations causing them to be more easily triggered when they are actually shown. However, internal attention can hardly be the sole determinant of attentional guidance. Rather, it can be considered as the strongest mechanism to bias external attention. This is due to the finding that LTM representations can involuntarily bias attention as well (Olivers 2011; Zhao, Al-Aidroos, and Turk-Browne 2013), ruling out the explanation that LTM representations are first activated in WM, or internally attended, and then guide attention. Since LTM representations are able to bias attention without being attended to, it might be the case that multiple mechanisms can enable memories to guide attention. Future research can also help explore other mechanisms that seem to operate on LTM representations by creating even more sensitive involuntary guidance tasks to test possible candidates, such as precision, context similarity, and the number of memory traces.

Nevertheless, literature offers an alternative explanation for diminishing attentional guidance as a function of repetitions. It has been demonstrated participants can be instructed to suppress certain distractors (Arita, Carlisle, and Woodman 2012; Beck and Hollingworth 2015) and that this suppression ability can emerge with learning as well (Gaspelin and Luck 2018; Vatterott and Vecera 2012). Thus, the RT results of Experiment 5 might reflect learned distractor suppression as, in our design, the memory contents, if they appear, only match the distractors. Nevertheless, research suggests that even with learning throughout several sessions, the control over attentional guidance is limited (Sasin et al. 2022). Together with the few repetitions of the memory item, and the infrequent search task in our design, it is uncertain if suppression is led to reduced attentional guidance. Yet, the explanation remains noteworthy. One way to control for this possible suppression effect would be to include a condition where the memory item matches the target in the search task to prevent learning. This approach requires a considerably higher number of trials but can be potentially overcome by lowering the number of repetitions as the memory precision reached an asymptote before the last repetition.

In addition, our first series of experiments involve various limitations. Together with the online setting, our three-alternative forced-choice precision assessment does not provide the best tool to interpret accuracy results compared to the continuous report tasks. Moreover, to preserve resources, we relied on the outcomes of previous works (Machizawa, Goh, and Driver 2012) instead of providing individual manipulation checks for the instructions to keep the unattended item with high precision, namely the more difficult memory test, higher reward, and warning feedback. In addition, it is hardly possible, with behavioral techniques, to make sure whether participants attended the cued item while numerous manipulations incentivizing the uncued item. Collectively, these limitations exhibit that to resolve whether precision and internal attention can be dissociated, a design tracking of neural underpinnings of attentional and memory processes is required.

In summary, our attempt to find out whether internal attention or precision decides the attentional guidance ability of memory items lead us to two conclusions: (1) internal attention and precision are integral in WM, and (2) attentional template status of memories drives memory-guided attention rather than their precision. Thus, our work suggests that although a representation, indeed, needs to be precise enough to guide attention to the stimuli matching it, the attentional template status, as a consequence of the direction of internal attention towards it, enables that representation to guide external attention.

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