Multiple states in visual working memory: Evidence from oculomotor capture by memory-
matching distractors

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Abstract

Visual working memory (VWM) representations interact with attentional guidance, but there is controversy over whether multiple VWM items simultaneously influence attentional guidance. Extant studies relied on continuous variables like response times, which can obscure capture – especially if VWM representations cycle through interactive and non-interactive states. We employed an oculomotor paradigm to characterize discrete attentional capture events under both high and low VWM load. Participants held one or two colors in memory, then executed a saccade to a target disk. On some trials, a distractor (sometimes VWM-matching) appeared simultaneously with the target. Eye movements were more frequently directed to a VWM-matching than a non-matching distractor for both load conditions. However, oculomotor capture by a VWM-matching distractor occurred less frequently (by approximately half) under high compared with low load. These results suggest that, without task demands to maintain both, one VWM item is held in an active state at a time.

Keywords: visual attention, visual working memory, eye movements, attentional guidance,

Public Significance Statement: Attention and visual working memory (VWM) are highly interrelated, but many controversies remain about how the contents of VWM influence the guidance of attention. When one item is held in VWM, attention is guided to items with similar features regardless of task demands. More than one item can be held in VWM – can more than one item guide attention? The work presented here suggests that attention is automatically guided toward items matching only one of two colors held in memory at a time, suggesting that items in VWM may cycle through attention-guiding and not-guiding states when more than one item is held in VWM. The method used here demonstrates that a discrepancy between eye movement and typical end-of-trial measures may explain previous conflicting findings.

Although attention and visual working memory (VWM) have long been regarded as deeply connected, controversies regarding the nature of this relationship still abound. Some propose that representations in VWM can be held in different states (Olivers, Peters, Houtkamp, & Roelfsema, 2011), “active” or “accessory,” such that an item held in an active state can influence the guidance of attention, but an item held in an accessory state cannot. When a single item is held in VWM, attention is automatically captured by memory-matching items (e.g., Olivers, Meijer, & Theeuwes, 2006), suggesting that a single item is by default in an active state and influences attentional guidance. When multiple items are held in VWM, however, it is unclear whether the default state of all items will be active, accessory, or a mixture of the two.

In some studies, multiple VWM items interacted with attentional guidance (Bahle, Beck, & Hollingworth, 2018; Beck & Hollingworth, 2017; Beck, Hollingworth, & Luck, 2012; Grubert & Eimer, 2015, 2016; Hollingworth & Beck, 2016), suggesting that multiple VWM items were maintained in an active state, whereas other studies found reduced influence at higher VWM loads (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Soto, Greene, Chaudhary, & Rotshtein, 2012; van Moorselaar, Theeuwes, & Olivers, 2014), suggesting that multiple VWM items were maintained in an accessory state. However, much of the previous work used paradigms that rely on continuous measures like response times (RTs), potentially obscuring the effects of attentional capture by collapsing across capture and non-capture trials, or paradigms for which maintaining multiple VWM items in an active state was task-relevant, potentially over-representing the interaction between VWM and attentional guidance.

To overcome these hurdles, we used a combined memory and eye movement task that has previously shown VWM-based modulation of saccade trajectory (Hollingworth, Matsukura, & Luck, 2013) allowing us to discretely categorize attentional capture and non-capture trials.

Participants were shown one or two colors to remember, then instructed to saccade to a left or right disk. After fixating the target disk, participants completed a forced-choice memory test for one remembered color. On some trials, a distractor disk appeared above or below central fixation simultaneously with the target disk. This distractor sometimes appeared in a VWM-matching color, letting us examine oculomotor capture. Unlike RTs, oculomotor capture provides a discrete measure – did the first saccade go toward the target or the distractor? This allows a clearer view of how the *probability* of attentional capture is affected by memory load.

Method

Participants

Thirty University of Delaware (UD) students (18-40 years old) who reported having normal color vision participated for course credit or were compensated \$10/hour for one 1.5-hour session. Based on independent pilot data, we determined we needed a minimum of 19 participants to obtain 95% power to detect the weakest effect present in our pilot data ($\eta_p^2=.48$) at the standard .05 alpha error probability. We recruited until the usable sample included data from 20 participants based on the exclusion criteria outlined in the study preregistration (see Results for criteria). All procedures were approved by the UD Institutional Review Board.

Stimuli, Apparatus, and Procedure

Stimuli were presented on an LCD monitor (120Hz) at a distance of 94 cm. Eye position was recorded at 1000Hz using an Eyelink1000 eye-tracking system. Saccades were defined using a combined velocity ($>35^\circ/\text{s}$) and acceleration ($>9500^\circ/\text{s}^2$) threshold. Participants completed a 9-point calibration at the beginning of each block (every 80 trials) and mid-block as needed.

Figure 1: Illustration of trial events, trial types (T = target, D = distractor, M = match, N = non-match, X = absent), and discrete oculomotor outcomes (“capture”, “no capture”). Participants were instructed to remember the memory array color(s), make an eye movement to a left or right target disk, then indicate which of the two colors presented during the memory test matched a color in memory. The memory array squares could be the same color (load-1) or different colors (load-2). The saccade task yielded five different trial types, depending on whether the target or distractor disks matched a color in memory, for each memory load. All trial types were equally likely and randomly intermixed within each block.

Each trial began with a 500-ms presentation of two colored squares, each subtending 1.2 degrees visual angle (hereafter dva), offset diagonally by 1.13 dva from central fixation (see Figure 1). The memory array squares could be the same color (load-1) or different colors (load-2). After a blank retention interval (700, 800, 900, or 1000-ms), a target disk (0.86 dva) appeared left or right of fixation (disk was centered at 4.61-7.06 dva from fixation) and was equally likely to match or not match one memory color. On some trials, the left/right target disk appeared simultaneously with a distractor disk (0.94 dva) located above or below fixation (2.14 dva from fixation) and could also match a memory color. These factors yielded five trial types for each

memory load: target match, no distractor ($T_M D_X$); target non-match, no distractor ($T_N D_X$); target match, distractor non-match ($T_M D_N$); target non-match, distractor non-match ($T_N D_N$); and target non-match, distractor match ($T_N D_M$). Participants were instructed to saccade to the left/right target disk and ignore up/down distractors. Disks remained on-screen until the participant made an eye movement toward the target¹ or the saccade task timed out (2000 ms). Once the saccade task was completed, two squares (1.2 dva each) appeared on either side of fixation (offset by 2.0 dva) and participants were instructed to indicate via key press which square matched a color in memory (left button for left square match, right button for right square match). One color was from the memory array, and the other was a foil drawn from the same color family.

Object colors were drawn from four color families (reds, greens, blues, or pinks) containing four exemplars each, and objects were presented on a light gray background. On load-2 trials, memory colors were selected from different color families (e.g., one blue, one pink) and colors of any non-matching target or distractor disks were selected from remaining color families (e.g., red, green). When a disk matched a memory color, the matching color could be exact (same exemplar as the memory array) or inexact (different exemplar from the same color family). When the target or distractor was an inexact match, the color exemplar used for the disk reappeared as the foil in the memory test. Thus, there was no incentive to preferentially attend to or fixate disks that matched a color in memory.

Participants first performed 20 practice trials and then 6-8 blocks of experimental trials, depending on how many were completed during the 1.5-hour session. Each block contained 80 total trials, 8 each of the 10 trial types, randomly intermixed.

¹ A threshold was set such that trials terminated successfully when the x-coordinate of the eye position was within 0.86 dva of the target's x-coordinate.

Results and Discussion

One participant was excluded for memory test accuracy no better than chance. Two participants were excluded for executing saccades to a distractor location on 10% or more of distractor-absent trials, indicative of poor eye-tracking or misunderstanding the task. Lastly, seven participants who had 20% or greater trials excluded from one or more conditions due to the following criteria were excluded from analysis: initial saccade faster than 90 ms or slower than 600 ms, initial saccade toward an irrelevant location, or missing eye movement data. Exclusionary criteria were set based on a separate set of pilot data (N=13 collected, N=8 retained for pilot analysis) and were specified in the preregistration. Analyses are based on data from the remaining participants (N=20).

We subjected memory test manual response accuracy to a 2 (memory load: load-1, load-2) by 5 (trial type: T_{MDX} , T_{NDX} , T_{MDN} , T_{NDN} , T_{NDM}) repeated-measures ANOVA². There was a significant main effect of memory load [$F(1,19)=163.87$, $p<.001$, $\eta_p^2=.90$ (90% CI: .79, .93)], with accuracy greater under load-1 (M=91.6%, SD=4.6%) compared to load-2 [M=79.3%, SD=7.5%; $t(19)=12.84$, $p<.001$, $\eta_p^2=.90$], but no significant main effect of trial type [$F(4,76)=1.60$, $p=.182$, $\eta_p^2=.08$] or interaction [$F(4,76)=2.43$, $p=.055$, $\eta_p^2=.11$]. Given the dual-task nature of this paradigm and the difficult within-category memory test, reduced performance when two colors were maintained in memory compared to one is not unexpected. Whether the VWM-matching target or distractor disk was an exact or inexact match to a memory array color did not meaningfully interact with memory test performance (see Supplementary Materials for details).

² See Table S1 in the Supplementary Materials for condition means.

The critical analysis for the current study examined the probability that a saccade was directed to a memory-matching distractor. For this, we examined the trajectory of the first eye movement that occurred after the saccade target and distractor (if present) disks appeared. These saccades were categorized as being directed either toward the target (left/right horizontal meridian $\pm 45^\circ$) or toward the distractor (upper/lower vertical meridian $\pm 45^\circ$). As mentioned above, only trials during which the first saccade was directed to a relevant location (up/down/left/right 90° wedge containing a target or distractor disk) were included for analysis [2.6% of all trials rejected]. Trials with eye movements that were excessively fast (< 90 ms) or slow (> 600 ms) [4.9% of all trials rejected] or that were missing eye movement data [1% of all trials rejected] were excluded. For all remaining trials [94.7% of trials retained (some trials met multiple exclusion criteria)], when an initial saccade was directed toward a distractor, the trial was categorized as “capture” whereas if the initial saccade was directed toward the target, the trial was categorized as “no capture.” The proportion of “capture” trials was calculated for each distractor-present condition (see Figure 2).

When multiple representations are being maintained in VWM, there are competing predictions for the likelihood of oculomotor capture by a VWM-matching distractor. If the default state of multiple VWM representations is accessory, we should observe capture on load-1 but not load-2 trials because the VWM representations will no longer interact with attentional guidance. Alternatively, if the default state of multiple VWM representations is active, we should observe similar rates of capture on load-1 and load-2 trials, as VWM representations will interact with attentional guidance regardless of how many are maintained. Lastly, if the default state of multiple VWM representations is a mixture of active and accessory states such that one item is in an active state at any particular time, we should observe reduced oculomotor capture on load-2

compared to load-1 trials, as the VWM-matching distractor will match the one VWM representation held in an active state on load-2 trials less frequently.

Consistent with the third hypothesis, we observed greater oculomotor capture by a VWM-matching distractor compared to a non-matching distractor both on load-1 [26% vs. 6%; $t(19)=7.02$, $p<.001$, $\eta_p^2=.72$] and load-2 trials [12% vs. 6%; $t(19)=5.17$, $p<.001$, $\eta_p^2=.58$]. Importantly, capture was reduced for load-2 compared to load-1 [$t(19)=7.13$, $p<.001$, $\eta_p^2=.73$], suggesting that multiple VWM representations were held in a mixture of active and accessory states. This same pattern of oculomotor capture was present for both exact and inexact VWM-matching distractors (see Supplementary Materials for details). In fact, the reduction in oculomotor capture from load-1 to load-2 was nearly half. If, when multiple items were being maintained in VWM, one item was randomly assigned to an active state and the other item was assigned to an accessory state, a VWM-matching distractor disk would match the active VWM color half as often as when only a single item is maintained in VWM. To quantify this, we compared the capture rate on load-2 trials to half the capture rate on load-1 trials and found no difference [12% vs. 13%; $t(19)=0.76$, $p=.459$, $\eta_p^2=.03$]. A Bayes factor suggested that the null was in excess of three times likelier than the alternative [$BF_{01}=3.34$]. These results suggest that one item at a time is held in an active state under these conditions.

Figure 2: Initial saccades were more frequently directed to a memory-matching distractor compared to a non-matching distractor both with a one-item [26% vs. 6%; $t(19) = 7.02$, $p < .001$, $\eta_p^2 = .72$] and two-item [12% vs. 6%; $t(19) = 5.17$, $p < .001$, $\eta_p^2 = .58$] memory load. Critically, oculomotor capture under high load was reduced compared to capture under low load [12% vs. 26%; $t(19) = 7.13$, $p < .001$, $\eta_p^2 = .73$], suggesting that multiple colors were held in a mixture of active and accessory states. Error bars indicate +/- within-subject 95% confidence intervals (Morey, 2008).

One possible explanation for the reduced capture on load-2 trials is that participants were more likely to forget one of the colors on load-2 trials, as indicated by reduced memory test accuracy for load-2 compared to load-1 trials, and were therefore less subject to oculomotor capture by a VWM-matching distractor if it matched a color no longer in VWM. However, when we restrict the capture analysis to trials on which participants responded correctly to the memory test, the same pattern emerges (see Supplementary Materials for details). These results suggest that the reduced capture by a VWM-matching distractor in load-2 compared to load-1 cannot be explained simply by reduced memory of the colors maintained in VWM.

A more parsimonious explanation for the current results is that, when multiple items were maintained in VWM, they were held in a mixture of active and accessory states such that only a single item was in an active state at any particular time. It is unclear, however, whether

individual items in VWM cycle through active and accessory states during a trial or if one item is preferentially maintained in an active state throughout the trial. Either configuration of active and accessory states within VWM, without the task demands to maintain multiple VWM items in an active state, could begin to resolve previously discrepant findings that sometimes suggested guidance of attention by multiple VWM items, while at other times suggested that none of the items in VWM could influence the guidance of attention when multiple items were held in VWM.

Previous work supporting the latter typically relied on RT measures of capture. In fact, if we instead examine the time-to-target-fixation (analogous to RT) in the current dataset, we again find evidence of capture by a VWM-matching distractor on load-1 trials [$M=96\text{ms}$ difference ($T_{ND_M}-T_{ND_N}$); $t(19)=4.49$, $p<.001$, $\eta_p^2=.52$], but not load-2 [$M=17\text{ms}$ difference ($T_{ND_M}-T_{ND_N}$); $t(19)=1.51$, $p=.147$, $\eta_p^2=.11$], a similar pattern to the RT results found by van Moorselaar et al. (2014). This discrepancy between oculomotor and time-to-target-fixation results illustrates the value of discrete measures of capture such as the one used here.

Conclusions

We found clear evidence that maintaining multiple items in VWM reduces, but does not eliminate, attentional capture by memory-matching items. Moreover, the reduction in capture was not significantly different from halving the load-1 capture rate, suggesting that time spent in an “active” state was shared across the multiple items in VWM. Though it is possible to maintain multiple VWM representations in an active state that can simultaneously influence attentional guidance, there is evidence that this configuration of attention and VWM systems is less efficient (Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Stroud, Menneer, Cave, Donnelly, &

Rayner, 2011) and may be more effortful. To mitigate expending unnecessary effort, multiple representations in VWM may not be held in an active state unless required by current task demands. In the absence of these task demands, the present results support the hypothesis that multiple representations in VWM are held in a mixture of active and accessory states.

The current study takes an important step toward resolving an ongoing debate over the nature of interaction between visual attention and VWM systems. The discrepancy between attentional capture effects observed using oculomotor measures – capture under both low and high VWM loads – and those observed using RT-like measures – time-to-target-fixation revealed capture under low but not high VWM load – suggest a possible explanation for the discrepancy in extant studies. Resolution of this debate over the interface between VWM and attention will have implications for the general architecture of attention and memory systems: some models of working memory suggest that only one item can be held in the “focus of attention” and made available for other processes (McElree, 2001; Oberauer, 2002) whereas others suggest that multiple items can influence other processes (Cowan, 2001). Our results suggest that, in the absence of task demands to maintain multiple VWM items in an active state, a single VWM item is held in an active state and can influence attentional guidance.

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Open Practices Statement

This study was formally preregistered and can be accessed via the Open Science Framework at: https://osf.io/bns3y/?view_only=5c8b3683232b4965a755227e1835d7af.

Figure Captions

Figure 1: Illustration of trial events, trial types (T = target, D = distractor, M = match, N = non-match, X = absent), and discrete oculomotor outcomes (“capture”, “no capture”). Participants were instructed to remember the memory array color(s), make an eye movement to a left or right target disk, then indicate which of the two colors presented during the memory test matched a color in memory. The memory array squares could be the same color (load-1) or different colors (load-2). The saccade task yielded five different trial types, depending on whether the target or distractor disks matched a color in memory, for each memory load. All trial types were equally likely and randomly intermixed within each block.

Figure 2: Initial saccades were more frequently directed to a memory-matching distractor compared to a non-matching distractor both with a one-item [26% vs. 6%; $t(19) = 7.02, p < .001, \eta_p^2 = .72$] and two-item [12% vs. 6%; $t(19) = 5.17, p < .001, \eta_p^2 = .58$] memory load. Critically, oculomotor capture under high load was reduced compared to capture under low load [12% vs. 26%; $t(19) = 7.13, p < .001, \eta_p^2 = .73$], suggesting that multiple colors were held in a mixture of active and accessory states. Error bars indicate +/- within-subject 95% confidence intervals (Morey, 2008).

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Supplementary Materials

Table S1: Mean manual response accuracy for memory test for all trial types and memory loads.

	Memory Test Performance for All Trials [% Correct (SD)]	
	Load-1	Load-2
T _M D _X	91.4% (5.4))	81.2% (9.5)
T _N D _X	91.3% (6.5)	80.6% (9.6)
T _M D _N	92.7% (5.7)	79.4% (6.7)
T _N D _N	92.0% (5.0)	76.3% (8.6)
T _N D _M	90.5% (6.3)	78.9% (9.9)

Effect of Exact/Inexact Match on Memory Performance

To examine the effect of exact compared to inexact target/distractor disk color matches on memory test performance, we entered manual response accuracy into a separate 2 (match type: exact, inexact) by 3 (trial type: T_MD_X, T_MD_N, T_ND_M) repeated-measures ANOVA. There was a significant main effect of match type [$F(1,19) = 20.15, p < .001, \eta_p^2 = .51$ (90% CI: .22, .67)], with greater memory accuracy when the target or distractor disk was an exact match ($M = 88.2\%$, $SD = 5.5\%$) than when it was an inexact match [$M = 83.3\%$, $SD = 6.8\%$; $t(19) = 4.61, p < .001, \eta_p^2 = .53$] to a color being maintained in VWM. There was no significant effect of trial type [$F(2,38) = 1.09, p = 0.348, \eta_p^2 = .05$] or interaction [$F(2,38) = 2.72, p = .079, \eta_p^2 = .13$].

Reduced memory test performance when the target or distractor disk was an inexact VWM match suggests that the inexact color may have interfered with the similar color being maintained in VWM (when an inexact match occurred, the color reappeared as the foil in the memory test), or the disk might have been encoded into VWM if the disk was fixated as saccade target

properties are encoded prior to each saccade (Hollingworth, Richard, & Luck, 2008). This potential interference of inexact matches on memory performance did not vary as a function of whether the inexact match appeared on a target or distractor disk.

Table S2: Mean manual response accuracy for memory test split by whether the memory-matching target/distractor disk was an exact (same color exemplar) or inexact (different color exemplar from the same color family) match.

	Memory Test Performance Split by Exact/Inexact Match [% Correct (SD)]	
	Exact	Inexact
T _M D _X	90.5% (6.2)	82.2% (9.1)
T _M D _N	87.8% (5.7)	84.6% (7.4)
T _N D _M	86.4% (7.5)	83.2% (8.7)

Effect of Exact/Inexact Match on Oculomotor Capture

To examine whether the probability of oculomotor capture was modulated by whether the VWM-matching distractor was an exact or inexact match, we conducted a parallel set of comparisons for exact and inexact VWM-matching distractors. We again observed greater oculomotor capture by a VWM-matching distractor compared to a non-matching distractor both for exact [load-1: 30% vs. 6%, $t(19) = 6.83$, $p < .001$, $\eta_p^2 = .71$; load-2: 13% vs. 6%, $t(19) = 4.96$, $p < .001$, $\eta_p^2 = .56$] and inexact matches [load-1: 22% vs. 6%, $t(19) = 6.02$, $p < .001$, $\eta_p^2 = .67$; load-2: 12% vs. 6%, $t(19) = 3.85$, $p = .001$, $\eta_p^2 = .44$]. Importantly, capture was reduced for load-2 compared to load-1 both when the distractor disk was an exact [13% vs. 30%, $t(19) = 6.01$, $p < .001$, $\eta_p^2 = .66$] and inexact match [12% vs. 22%, $t(19) = 4.88$, $p < .001$, $\eta_p^2 = .56$]. Oculomotor capture under load-1 was greater for exact compared to inexact matching distractors [30% vs.

22%, $t(19) = 2.93$, $p = .009$, $\eta_p^2 = .31$], suggesting that a VWM-matching distractor that did not exactly match the color in memory was less likely to provoke an eye movement to that object. This is not unexpected since some inexact VWM-matching distractors could be quite different from the original color even though the colors were in the same color family (for example, if the memory color is light blue, a dark blue inexact match may be less likely to result in oculomotor capture than a medium blue inexact match). However, when multiple colors were maintained in VWM, there was no difference in the probability of oculomotor capture by an exact or inexact VWM-matching distractor [13% vs. 12%, $t(19) = 0.80$, $p = .432$, $\eta_p^2 = .03$]. The latter possibility is consistent with reduced precision of memory items under load-2 than load-1, but regardless capture was reduced for both exact and inexact matches under load-2 compared with load-1.

To further examine the role of precision, we next examined oculomotor capture as a function of memory test accuracy. If reduced precision of VWM representations under load-2 is responsible for reduced capture effects, then we should expect that accurate memory test trials (when, presumably, precision was better on average than inaccurate memory test trials) should show reduced capture compared with inaccurate memory test trials.

Oculomotor Capture for Correct Memory Trials

When the oculomotor capture analysis was restricted to trials on which participants responded correctly to the memory test, we observed the same pattern of results as when all trials were included: oculomotor capture was greater for VWM-matching than non-matching distractors both for load-1 [26% vs. 6%; $t(19) = 7.44$, $p < .001$, $\eta_p^2 = .74$] and load-2 trials [12% vs. 6%; $t(19) = 4.53$, $p < .001$, $\eta_p^2 = .52$], and observed capture was reduced for load-2 compared to load-1 trials [12% vs. 26%; $t(19) = 7.66$, $p < .001$, $\eta_p^2 = .76$]. In sum, even though restricting

the oculomotor capture analysis to correct memory trials disproportionately reduced the number of load-2 trials included for analysis (due to reduced memory accuracy), we still find reduced but present oculomotor capture by VWM-matching distractors when multiple colors are maintained in VWM.

References

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