Attentional control settings and visual working memory

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Abstract

In the present study, we examined whether visual working memory (VWM) can support attentional control settings (ACSs) by maintaining representations of the visual properties that should capture attention. Beyond enhancing capture by memory-matching stimuli, can VWM representations suppress capture by non-matching stimuli? In Experiments 1a/b, participants maintained a colour in VWM that changed every trial while completing a Posner cueing task with memory matching and memory non-matching colour cues. We replicated the conventional finding that the colour in VWM modulated distractor costs, indicating that the colour was represented in the active state. Yet, this colour had no effect on the capture of visual spatial attention measured via cueing effects, suggesting that merely *remembering* a colour in VWM did not define participants' ACSs. When participants *searched* for the colour in VWM, it did support an ACS that eliminated cueing effects by non-matching colours (Experiment 2), though not if participants searched for two colours stored in VWM (Experiment 3). These findings demonstrate that one active representation in VWM can support ACSs, though active representation alone is insufficient. These findings also speak to the ongoing debate about the automaticity of attentional capture by contributing additional evidence that distractor costs and cueing effects are dissociable measures of attentional capture.

Keywords: attentional control settings, visual working memory, Posner cueing task, attention, attentional capture.

Public Significance Statement

Our complex visual worlds contain too much information for us to process everything that we see at once. To solve this problem, we adopt attentional goals that define which parts of

the world should be processed first. Where are these goals stored in our minds? Here we show that one memory system—visual working memory—can play this role. However, visual working memory is limited to maintaining **one** goal at a time. This research builds on past demonstrations that attentional goals can also be maintained in episodic and semantic long-term memory, raising questions about how these memory systems co-ordinate to help regulate the way our minds and brains make sense of the visual world.

Attentional control settings and visual working memory

Attentional control settings (ACSs) determine which stimuli in our visual environments capture our attention (Becker, Folk, & Remington, 2010; Folk, Leber, & Egeth, 2002; Folk, Remington, & Johnston, 1992; Folk & Remington, 1998; Giammarco, Paoletti, Guild, & Al-Aidroos, 2016; although see: Gaspelin, Ruthruff, & Lien, 2016; Theeuwes, 2010, 2013; Yaron & Lamy, 2020). Which memory system supports ACSs? That is, which memory system maintains representations of the types of stimuli that should capture attention (hence forth referred to as *ACS representations*)? Some studies have demonstrated that episodic long-term memory (Giammarco et al., 2016; Plater, Giammarco, Fiacconi, & Al-Aidroos, 2019) and semantic memory (Goodhew, Kendall, Ferber, & Pratt, 2014; Wyble, Folk, & Potter, 2013) can maintain ACS representations. However, most of the previous research that has attempted to answer this question focussed on the role of visual working memory (VWM), a memory system that can directly interface with perception (Olivers, Meijer, & Theeuwes, 2006) but has a severely limited storage capacity (Cowan, 2001; Luck & Vogel, 1997; Ma, Husain, & Bays, 2014; Phillips, 1974). This previous research demonstrated that having participants remember a simple object (e.g., a red square) using VWM enhances attentional capture by similar stimuli in the environment (i.e., other red stimuli; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005). But ACSs do not only enhance capture by similar stimuli, they also suppress (Gaspelin & Luck, 2018), and even eliminate (Folk et al., 2002; Folk, Leber, & Egeth, 2008; Folk et al., 1992), attentional capture by dissimilar stimuli. For example, when someone has adopted an ACS for the colour red, stimuli matching that colour will capture attention, and stimuli that do not match that colour will not (Folk & Remington, 1998). Thus, if VWM can maintain ACS

representations, then, beyond enhancing capture by matching stimuli, these VWM representations should be capable of eliminating capture by non-matching stimuli.

VWM Representations Modulate Search Distractor Costs

The majority of the evidence that VWM can maintain an ACS representation comes from dual tasks that combine a working memory task with an additional singleton paradigm (Theeuwes, 1992) to examine whether the contents of visual working memory can modulate attentional capture (e.g., Olivers et al., 2006; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008; Theeuwes, 2010). For example, in Olivers et al. (2006), participants memorized a colour, completed a visual search for a target object (i.e., a diamond shape) among several non-target objects (i.e., multiple circles), and then reported the memorized colour. On some trials, a singleton distractor was present during the visual search; this singleton distractor either matched the memory colour or not. The critical finding was that memory matching distractors slowed search more than non-matching distractors (i.e., matching distractors produced greater *distractor costs*), which provides clear evidence that the VWM representation can modulate attentional capture. Importantly, this modulation of attentional capture was accomplished by simply having participants remember a colour using VWM (Olivers et al., 2006).

One other major finding from this line of research is that *only one* VWM representation can modulate attentional capture. For example, van Moorselaar, Theeuwes, and Olivers (2014) had participants memorize one-to-four colours on each trial, complete a visual search, and then do a memory test for the memorized colours. If participants were asked to remember only one colour, then—similar to Olivers et al. (2006)—memory-matching distractors produced greater

distractor costs than non-matching distractors. However, when participants were asked to remember two-to-four colours, the difference in distractor costs was no longer present, suggesting the contents of VWM were not modulating attentional capture. Findings such as these led to the dual-state model of VWM. According to this model, only a single, “active”, VWM representation can bias attentional capture towards perceptually similar stimuli; all other VWM representations are “accessory”, and not capable of guiding attentional capture (Hollingworth & Beck, 2016; Olivers & Eimer, 2011; Peters, Roelfsema, & Goebel, 2012; van Moorselaar et al., 2014). An item is active in VWM when it is the only remembered representation (Olivers & Eimer, 2011; Olivers et al., 2006; van Moorselaar et al., 2014), or if it is determined to be the most relevant representation (de Vries, van Driel, & Olivers, 2017; Dube, Lumsden, & Al-Aidroos, 2019; Olivers et al., 2006; van Moorselaar et al., 2014). The dual state model clarifies that, although representations in VWM can modulate attentional capture, the modulation only occurs for at most one representation, and only when that representation is in the active state. To fully understand the role of VWM in potentially supporting ACSs, it is important to assess this role for both active and accessory representations.

While these past studies measuring search distractor costs clearly demonstrate that VWM representations can modulate capture, there are limits to the utility of this paradigm for studying ACSs. One of the core attributes of ACSs is that they prevent non-matching stimuli from capturing attention (Folk & Remington, 1998; Folk et al., 1992; Folk, Remington, & Wright, 1994), but VWM-based modulations of distractor costs could be entirely explained by an enhancement of capture by matching distractors, regardless of whether or not non-matching stimuli capture attention. Moreover, the interpretation of distractor costs is complicated by effects unrelated to spatial attention. That is, in addition to measuring the capture of visual spatial

attention, distractor costs also reflect non-spatial filtering costs (Al-Aidroos, Harrison, & Pratt, 2010; Becker, 2007; Folk & Remington, 1998). Thus, VWM-based modulations of distractor costs may be unrelated to the control of attentional capture, and may instead be the result of modulations of filtering costs. These limitations can be circumvented using the Posner cueing task (Posner, 1980), which can directly measure the capture of visual spatial attention of both matching and non-matching stimuli.

Effects of VWM Representations in Cueing Tasks

In Posner cueing tasks that are designed to measure capture, participants monitor a number of locations for the appearance of a target. Shortly before the target appears, a task-irrelevant *cue* stimulus is presented at one location, and participants are instructed to ignore it since it is non-predictive of the target location (Folk et al., 1992; Posner, 1980). Yet, as long as the cue matches the searched-for target (Folk et al., 1992), it will capture attention and produce a *cueing effect* (i.e., faster reaction times for targets appearing at the cued location than at uncued locations). Importantly, cueing effects are not confounded by non-spatial filtering costs (Al-Aidroos et al., 2010; Folk et al., 1992; Giammarco et al., 2016). As well, cueing effects can independently measure capture by non-matching stimuli (i.e., do they produce a cueing effect?), without comparison against matching stimuli. Cueing effects can, therefore, test for the elimination of capture by ACS non-matching stimuli separately from any enhancements of capture by matching stimuli. Consequently, the Posner cueing task provides an important test of ACSs that cannot be accomplished by measuring search distractor costs alone.

Returning to the question of whether VWM can support the representation of ACSs, one study tested whether VWM representations modulate attentional capture when measured using a

Posner cueing task (Kim & Cho, 2016). Participants in this study memorized a coloured circle, completed a modified Posner cueing task, and then reported the memory colour. Consistent with the notion that remembering a single colour in VWM can generate an ACS for that colour, they observed a cueing effect when the cue matched the memory colour, and, critically, no cueing effect when the cue did not match the memory colour. However, while the findings of Kim and Cho (2016) support the conclusion that ACSs can be adopted based on VWM representations, there is other behavioural and electrophysiological research to question this conclusion.

Belopolsky, Schreij, and Theeuwes (2010) used a similar behavioural task as Kim and Cho (2016), but observed the opposite finding. Their task used two colours for the duration of the experiment, and at the start of each trial one was presented to indicate the target colour for that trial's cueing task. While the aim of their study was unrelated to testing the role of VWM in ACSs, their design parallels that of Kim and Cho (i.e., on every trial, participants remember a colour in VWM and then complete a cueing task). Yet, they found that both matching and non-matching cues captured attention, suggesting that ACSs cannot be adopted based on VWM representations. There is also electrophysiological evidence that demonstrates holding a stimulus in VWM is not sufficient to adopt an ACS for that stimulus. Sawaki and Luck (2011, 2013) had participants memorize the orientation of one of two coloured rectangles, and, before testing memory, they presented a distractor display with two coloured circles to be ignored. If participants had formed an ACS for the colour of the target rectangle, then memory-matching distractor circles should have captured attention and elicited the electrophysiological signature of a shift in attention: the N2pc event-related potential. However, their results indicated that the memory-matching distractor circle instead produced a distractor positivity (Pd) event-related potential, indicative of neural suppression of that stimulus. Given the evidence both for and

against VWM ACSs, the goal of the present study was to further investigate the role of VWM in maintaining ACS representations.

The Present Study

In the present study, we investigated the potential role of VWM in supporting ACSs. Building off of the extensive work on this question that measured search distractor costs, in Experiments 1a/b we specifically asked: When an object in VWM modulates search distractor costs, will it also prevent non-matching stimuli from capturing attention (i.e., producing cueing effects)? We followed an approach used previously to measure distractor costs and cueing effects in the same attention task (Al-Aidroos et al., 2010; Folk & Remington, 1998), and expanded upon these studies by having participants complete the task while remembering a colour in VWM.

On each trial of Experiments 1a/b, participants remembered a colour, completed a Posner cueing task, and then reported the memory colour. Cues either matched the colour in memory or not (cue colour: match vs. non-match), and targets either appeared at the cued location or not (target location: cued vs. uncued). Our main question was whether non-matching cues would produce a cueing effect: a response time (RT) difference between cued and uncued trials for non-matching cues. We can also measure distractor costs by thinking of the cue stimulus as a distractor. That is, uncued trials can be thought of as trials with an additional distractor stimulus, since the cue would always draw attention to the wrong location. Note that, for consistency with later experiments that focus on cueing effects, for Experiments 1a/b we will always refer to the task irrelevant stimulus as a cue rather than a distractor, despite using this stimulus to measure both cueing effects and distractor costs. Thus, if we can replicate past demonstrations that VWM

representations modulate search distractor costs, we should observe slower RTs on uncued trials with matching cues than non-matching cues (Olivers et al., 2006).

Beyond the difference in how attentional capture is measured in cueing tasks and the additional-singleton paradigm, these two tasks also differ in timing. In cueing tasks, the task irrelevant stimulus appears before the target, and in distractor tasks, it appears at the same time. Accordingly, we conducted two versions of the experiment: In Experiment 1a, the cue stimulus appeared at the same time as the target, and in Experiment 1b, it preceded the target. To preview the results, participants in both versions exhibited a greater distractor cost for matching cues compared to non-matching cues, replicating the conventional memory-based attentional capture effect. However, both matching and non-matching cues produced cueing effects, indicating that simply remembering a stimulus in VWM is not sufficient for that stimulus to form an ACS, and that the previously reported modulations of capture by VWM are distinct from the control of capture by ACSs.

Experiment 1a

Method

Participants. For all studies, informed consent was obtained from each participant, experimental protocols were approved by the University of Guelph ethics board, and all participants reported having normal colour vision and normal, or corrected-to-normal, visual acuity. A sample of 47 undergraduate students from the University of Guelph (mean age 18.6 years, 41 women and 6 men) participated in Experiment 1a for partial course credit. Two participants were excluded for having 50% (i.e., guessing) or greater errors on the Posner cueing task. Thus, Experiment 1a had a final sample size of 45 participants.

Apparatus, stimuli, and procedure. All experiments were conducted on a desktop computer with a 1280×1024 resolution 75 Hz CRT display. Responses were made on an Xbox controller which was connected to the computer through USB. Participants used a head and chin rest to keep their gaze distance constant at 52 cm from the computer screen for the duration of the experiment.

Participants completed 400 trials presented on a black background; see Figure 1 for an example trial sequence. All trials started with a white central fixation circle (0.14° in diameter) presented for 800 ms. Next, the memory item—a coloured circle 3.0° in diameter—was presented centrally for 1,000 ms, followed by a 600 ms memory delay. The colour was randomly selected from a 360° continuous colour wheel (as described in: Dube, Emrich, & Al-Aidroos, 2017).

After viewing the colour, participants then immediately completed a Posner cueing task, for which they were encouraged to be as fast and as accurate as possible. Four placeholder squares (1.5° sides, with lines 0.01° wide) were arranged 4° above, below, to the left, and to the right of a central fixation circle, and were presented for 600 to 1,600 ms; each of the placeholder squares contained a central “X” mask. Next, the “X” masks were removed, and both the coloured cue and the target were presented simultaneously. On 20% of trials no cue was presented (the “no cue” condition), on 40% of trials the cue was presented in the colour that was displayed at the beginning of the trial (the “colour match” condition), and on 40% of trials the cue was presented in a colour that was 160-180 degrees different on the colour wheel from the memory colour (the “colour non-match” condition). The colour of the non-matching cue was purposefully selected from the opposite side of the colour wheel so that it was very dissimilar from the colour being held in memory. The target was a vertical or a horizontal line (0.5° long) presented inside of one

of the placeholder squares, and participants had to indicate via a button press whether the target was vertical or horizontal. If participants responded incorrectly or did not make a response within 1,200 ms, a 500 Hz tone was played for 50 ms. Cue location, target location, and whether or not the colour of the cue matched the colour presented at the beginning of the trial were fully crossed for each participant to ensure that participants could not use the location and/or the colour of the cue to strategically complete the task.

After completing the Posner cueing task, the fixation point was displayed for 400 ms, and then the fixation point was replaced with three similarly coloured circles (3° in diameter); the three colours were each separated by 18 degrees on the colour wheel, and participants had to indicate which one they had seen at the beginning of the trial via a button press. This memory test used three similar colours to help ensure that participants were performing the memory component of the task using VWM, rather than by using verbal working memory to remember the colour category (Olivers et al., 2006). The memory test was not timed; once the participant selected one of the three coloured circles, the next trial started immediately.

Figure 1. Example trial sequence for Experiment 1a. Participants were told to memorize the colour at the beginning of the trial for later report, and then completed a Posner cueing task. For this experiment, the cue and target appeared at the same time, as is typical in the additional-singleton paradigm. Participants were to indicate the direction (horizontal or vertical) of the target line. This trial depicts the cued, colour-match condition. Note that black and white are inverted. The memory probe colours were different hues of the same colour; see the online article for the colour version. For print versions of this article, colour is indicated using grating textures in different orientations.

Statistical analyses. Most of the inferential statistics reported in this paper are null-hypothesis significance tests, however, we have also reported Bayes factors (*BFs*) when interpreting null effects (for a review of *BFs*, see Morey & Rouder, 2011). Briefly, a BF_{01} compares the null model against the alternative model; a ratio with the BF_{01} value greater than 1 indicates evidence in favour of the null model (i.e., no difference between conditions), and a ratio less than 1 indicates evidence in favour of the alternative model. As this is a ratio, the numerator

and denominator can be swapped, thus a BF_{10} compares the alternative model against the null model (i.e., $BF_{10} = 1/BF_{01}$). For ease of interpretation, BF s were reported as values greater than 1, as either BF_{01} (indicating evidence for the null model) or BF_{10} (indicating evidence for the alternative model). Bayes factor values that range from 1–3 indicate anecdotal (insufficient) evidence, 3–10 moderate evidence, and greater than 10 strong evidence. We calculated BF s using JASP version 0.11.1.0 (JASP-Team, 2017) using the default priors (Wagenmakers et al., 2018). JASP was also used to conduct the conventional null-hypothesis significance tests.

Results and Discussion

Working memory task. Participants identified the correct colour during the memory test on 38.8% ($SEM = 1.50\%$) of trials. While this value may seem low, it is above the accuracy rate expected for random guessing (33.3%), and the colour discrimination was intentionally designed to be difficult in order to minimize the contribution of verbal working memory to the task (Olivers et al., 2006). To investigate whether participants were strategically attending to the cues in the colour match condition in order to boost memory performance, a 2 (cue colour: colour match vs. colour non-match) $\times$ 2 (target location: cued vs. uncued) within-subjects ANOVA was conducted on the proportion of correct responses for the memory task; see Figure 2. This ANOVA revealed moderate evidence of no interaction, $F < 1$, $BF_{01} = 4.13$, a statistically significant main effect of cue colour, $F(1, 44) = 7.42$, $p = .009$, $\eta_p^2 = .144$, and moderate evidence of no main effect of target location, $F < 1$, $BF_{01} = 6.29$. These results, and visual inspection of the data, suggest that participants were more accurate at reporting the colour when the cue did not match the colour held in memory than when the cue did match the colour held in

memory, which is the opposite of what we would expect if participants were strategically attempting to use the cue to improve memory performance.

Figure 2. Accuracy data for the memory task for Experiment 1a (left) and Experiment 1b (right). Error bars in this figure, and all subsequent figures, are corrected (Morey, 2008) within-subject standard errors (Cousineau, 2005).

Attention task. Data were trimmed of outliers; for each participant, trials with a RT greater than 2.5 standard deviations from the condition mean were removed (1.25% of trials). Incorrect response trials (i.e., if a participant made an incorrect response for the colour memory task or the Posner cueing task) and trials where a participant did not make a response in time (43.5%) were also excluded from RT analyses. Including error trials in the analyses did not change the pattern of statistically significant results for the distractor cost data or the cueing effect data, though the Bayes factor for the cueing effect's two-way interaction decreased ($BF_{01} = 2.20$).

Distractor costs. To examine distractor costs, a one-way within-subjects ANOVA (uncued match vs. uncued non-match vs. no cue) was conducted on RTs; see Figure 3. The ANOVA

revealed a significant main effect, $F(2, 88) = 24.0, p < .001, \eta_p^2 = .353$, indicating that the type of cue influenced RTs on this task. In order to further assess these RT differences, three paired-samples t -tests were conducted. The planned t -tests revealed statistically significantly longer RTs on uncued trials for cues that matched the colour held in VWM than cues that did not match, $t(44) = 1.97, p = .028$, one-tailed, indicating that the contents of VWM biased attentional capture. RTs were also statistically significantly longer for cues that matched the colour held in VWM than no cue, $t(44) = 5.93, p < .001$, and for cues that did not match the colour held in VWM than no cue, $t(44) = 5.18, p < .001$. Thus, these results replicate the typical VWM-based modulation of search distractor costs (Olivers et al., 2006).

Figure 3. Reaction time data for uncued trials of the Posner cueing task for Experiment 1a (left) and Experiment 1b (right). Numbers inside the bars indicate the error rates (SDs) in the cueing task for each condition. Participants exhibited a distractor cost (i.e., longer RTs) when the cue presented at a different location than the target matched the contents of VWM than when it did not.

Cueing effects. In order to determine whether participants adopted an ACS for the colour held in VWM, a 2 (cue colour: colour match vs. colour non-match) $\times 2$ (target location: cued vs.

uncued) within-subjects ANOVA was conducted on RTs; see Figure 4. The ANOVA revealed moderate evidence of no two-way interaction, $F < 1$, $BF_{01} = 3.84$, indicating there was no difference in the size of the cueing effect between target matching and target non-matching cues. There was moderate evidence of no main effect of cue colour, $F(1, 44) = 1.83$, $p = .183$, $\eta_p^2 = .040$, $BF_{01} = 3.85$, indicating there was no difference in RTs between target matching and target non-matching cues. The main effect of target location was statistically significant, $F(1, 44) = 88.2$, $p < .001$, $\eta_p^2 = .667$, indicating that participants were slower to respond to targets at the uncued location than targets at the cued location. In order to assess whether participants formed an ACS representation for the colour displayed at the beginning of the trial, two planned paired-samples t -tests were also conducted. If participants can form an ACS using VWM, there should be a cueing effect when the cue matched the memory colour, but not when the cue did not match the memory colour (Al-Aidroos et al., 2010; Folk & Remington, 1998; Giammarco et al., 2016). While there was a cueing effect when the colour matched, $t(44) = 6.42$, $p < .001$, there was also a cueing effect when the colour did not match, $t(44) = 7.00$, $p < .001$. Since cues that did not match the colour being held in working memory still elicited cueing effects, these results indicate that participants did not form an ACS exclusively for the colour stimulus represented in VWM.

Figure 4. Reaction time data for the Posner cueing task for Experiment 1a (left) and Experiment 1b (right). Numbers inside the bars indicate the error rates (SDs) in the cueing task for each condition. Participants exhibited a cueing effect both when the cue matched the memory colour, and when the cue did not match, indicating they did not adopt an ACS for the colour stimulus represented in VWM.

Error analysis. The same distractor cost ANOVA that was conducted on the Posner cueing task RT data was conducted on error rates in order to determine if a speed/accuracy trade-off was present; see Figure 3. The one-way (cue colour: match vs. non-match vs. no cue) within-subjects ANOVA revealed a statistically significant main effect of cue colour, $F(2, 88) = 4.50$, $p = .014$, $\eta_p^2 = .093$, however, given that participants made more errors for the slowest condition (i.e., the uncued match condition), the distractor cost results cannot be explained by speed/accuracy trade-offs. Additionally, the same cueing effect ANOVA and t -tests were conducted on error rates in order to determine if a speed/accuracy trade-off was present; see Figure 4. The 2 (cue colour: colour match vs. colour non-match) $\times$ 2 (target location: cued vs. uncued) within-subjects ANOVA revealed a statistically significant two-way interaction, $F(1, 44) = 5.98$, $p = .019$, $\eta_p^2 = .120$, moderate evidence to suggest there was no main effect of cue colour, $F < 1$, $BF_{01} = 5.16$, and moderate evidence to suggest there was no main effect of target location, $F < 1$, $BF_{01} = 4.93$. The follow-up t -tests indicated that when the cue colour matched the colour

that was presented at the beginning of the trial, there were significantly more errors when the target was uncued than when it was cued, $t(44) = 2.20, p = .033$. Critically, however, when the cue colour did not match, there was moderate evidence to suggest there was no difference in errors when the target was cued than when it was uncued, $t(44) = 1.14, p = .258, BF_{01} = 3.36$. Thus, the main finding of Experiment 1a—that non-matching cues produced a cueing effect—cannot be explained by a speed/accuracy trade-off.

Experiment 1b

Experiment 1a was designed to use stimulus timings typical of the additional-singleton paradigm, in that the cue and the target appeared at the same time. Experiment 1b was designed to use the stimulus timings typical of cueing tasks. Here, the cue preceded the target by 160 ms. We once again expect that matching cues will produce greater distractors costs than non-matching cues (Olivers et al., 2006). And, if participants can adopt an ACS for a stimulus represented in VWM, then cues matching the colour held in memory should capture visual spatial attention and produce a cueing effect, whereas cues that do not match the colour held in memory should not (Al-Aidroos et al., 2010; Folk & Remington, 1998; Giammarco et al., 2016).

Method

Participants. A new sample of 42 undergraduate students from the University of Guelph (mean age 18.4 years, 29 women and 13 men) participated in Experiment 1b for partial course credit. Two participants were excluded for not following task instructions, and three participants were excluded for having 50% (i.e., guessing) or greater errors on the Posner cueing task. Thus, Experiment 1b had a final sample size of 37 participants.

All equipment and visual stimuli were identical to those in Experiment 1a, but there were a few minor methodological changes for Experiment 1b; see Figure 5. After the placeholder squares and fixation point were presented, the coloured cue was added to the screen for 80 ms. On no-cue trials, the display remained unchanged for 80 ms. Because the appearance of the cue produces a warning signal of the upcoming target that is missing on no-cue trials, we added a 1,000 Hz auditory warning tone to all trials that played for 50 ms. The cue was then removed from the screen for 80 ms, and then the placeholder “X”s were removed from the screen and the target was displayed. As with Experiment 1a, cue location, target location, and whether the colour of the cue matched the memory colour presented at the beginning of the trial were fully crossed for each participant to ensure that participants could not use the location and/or the colour of the cue to strategically complete the task.

Figure 5. Example trial sequence from Experiment 1b. Participants were told to memorize the colour at the beginning of the trial for later report, and then completed a Posner cueing task where the cue appeared 160 ms before the target. Participants were to indicate the direction (horizontal or vertical) of the target line. This trial depicts the cued, colour-match condition.

Results and Discussion

Working memory task. Participants identified the correct colour during the memory test on 38.8% ($SEM = 2.10\%$) of trials. As with Experiment 1a, we examined accuracy on the memory task to assess whether participants were strategically attending to the cues in order to improve memory performance. The 2 (cue colour: colour match vs. colour non-match) $\times$ 2 (target location: cued vs. uncued) within-subjects ANOVA revealed anecdotal evidence of no two-way interaction, $F(1, 44) = 2.13, p = .153, \eta_p^2 = .056, BF_{01} = 1.84$, moderate evidence of no main effect of cue colour, $F < 1, BF_{01} = 5.83$, and moderate evidence of no main effect of target location, $F < 1, BF_{01} = 5.58$. These results favour the conclusion that participants did not strategically use the cues in Experiment 1b to boost memory performance.

Attention task. Data were trimmed of outliers. For each participant, trials with a RT greater than 2.5 standard deviations from the condition mean were removed (1.28% of trials). Incorrect response trials (i.e., if a participant made an incorrect response for the colour memory task or the Posner cueing task) and trials where a participant did not make a response in time

(44.5%) were also excluded from RT analyses. Including error trials in the analyses did not change the pattern of statistically significant results for the cueing effect analysis; however, while the pattern of results looks the same for the distractor cost analysis, the t -test is now $BF_{01} = 5.24$.

Distractor costs. The one-way within-subjects ANOVA (cue colour: match vs. non-match vs. no cue) of RTs on uncued trials revealed moderate evidence of no main effect of cue colour, $F < 1$, $BF_{01} = 5.77$, indicating the type of cue did not influence RTs on this task; see Figure 3. The planned paired-samples t -test revealed statistically significantly longer RTs for cues that matched the colour held in VWM than cues that did not match, $t(36) = 1.79$, $p = .041$, one-tailed, indicating that the stimulus represented in VWM modulated attention. This result is consistent with past literature looking at VWM-based modulations of distractor costs, and with the results of Experiment 1a, but should nevertheless be interpreted with caution given that the ANOVA was not significant, and that the statistics depended on our exclusion criteria.

Cueing effects. The same 2 (cue colour: colour match vs. colour non-match) $\times 2$ (target location: cued vs. uncued) within-subjects ANOVA and planned paired-samples t -tests as in Experiment 1a were conducted on RTs to assess for cueing effects; see Figure 4. The results from Experiment 1b replicated those of Experiment 1a. There was anecdotal evidence of no two-way interaction, $F(1, 36) = 2.88$, $p = .098$, $\eta_p^2 = .074$, $BF_{01} = 1.70$, moderate evidence of no main effect of cue colour, $F < 1$, $BF_{01} = 5.75$, and a statistically significant main effect of target location, $F(1, 36) = 153$, $p < .001$, $\eta_p^2 = .809$. As for the planned paired-samples t -tests, again, both the colour match condition, $t(36) = 14.3$, $p < .001$, and the colour non-match condition, $t(36) = 7.71$, $p < .001$, produced statistically significant cueing effects. These results provide further evidence that, while representing a stimulus in VWM is sufficient to produce VWM-

based modulations of attentional capture (i.e., distractor costs), it is not sufficient to adopt an ACS for that stimulus.

Error analysis. To assess for speed/accuracy trade-offs, the same distractor cost and cueing effect ANOVAs were conducted on error rates; see Figures 3 and 4, respectively. The one-way (cue colour: match vs. non-match vs. no cue) within-subjects distractor-cost ANOVA revealed anecdotal evidence of a null effect of cue colour, $F(2, 72) = 2.60, p = .081, \eta_p^2 = .067, BF_{01} = 1.48$. Given that participants made more errors for the slow uncued match and no cue conditions, it is unlikely that the distractor cost results were influenced by speed/accuracy trade-offs. The 2 (cue colour: colour match vs. colour non-match) $\times 2$ (target location: cued vs. uncued) within-subjects cueing-effect ANOVA revealed moderate evidence of no two-way interaction, $F < 1, BF_{01} = 3.92$, moderate evidence of no main effect of cue colour, $F < 1, BF_{01} = 5.81$, and anecdotal evidence of no main effect of target location, $F = 3.26, p = .079, \eta_p^2 = .083, BF_{01} = 1.10$. Given that participants made more mistakes for the slower uncued trials than the faster cued trials, the cueing effect results cannot be explained by a speed/accuracy trade-off.

Experiments 1a/b Summary

For these experiments, participants had to hold a colour in VWM, complete a cueing task, and then report the colour at the end of the trial. If the attentional biases associated with remembering items in VWM (i.e., increased distractor costs) are equivalent to adopting an ACS, then only cues that match the colour maintained in VWM should capture visual spatial attention and produce a cueing effect, whereas cues that do not match the colour maintained in VWM should not. We mostly replicated the VWM-based modulation of distractor costs, suggesting that the remembered colour was actively represented in VWM. However, all cues produced a cueing

effect, regardless of whether they matched the colour represented in VWM. Indeed, we found little-to-no differences between the cueing effects produced by matching and non-matching cues in both experiments. Thus, as has been shown many times previously (Olivers et al., 2006, 2011; Soto et al., 2008; Theeuwes, 2010), merely holding a colour in VWM is sufficient to modulate search distractor costs. However, this modulation is not a consequence of participants adopting an ACS for that colour, as both matching and non-matching cues captured attention and produced cueing effects. These results demonstrate that, when simply *remembering* a stimulus, there is a difference between the “active” VWM representation of that stimulus, and adopting an ACS for that stimulus.

Experiment 2

Is it *ever* possible for a stimulus represented in working memory to form an ACS and bias attention? While the results from Experiments 1a/b demonstrate that merely holding a colour in VWM is insufficient for adopting an ACS for that colour, remembering a stimulus is not the same as searching for a it (Olivers & Eimer, 2011; Rajsic, Ouslis, Wilson, & Pratt, 2017). To more directly test whether working memory can support an ACS, participants in Experiment 2 had to memorize *and search for* the target colour presented at the beginning of the trial. Specifically, in the Posner cueing task component of each trial, all four squares on the target screen filled with different colours and a line segment, and participants had to indicate the orientation of the line segment that appeared in the square of the memorized colour. As with Experiments 1a/b, in Experiment 2 the target/memory colour changed on each trial to encourage the use of VWM, and to limit the contribution of LTM. If working memory can indeed support

ACSSs, then participants should only exhibit a cueing effect when the cue matches the target stimulus (Al-Aidroos et al., 2010; Folk & Remington, 1998; Giammarco et al., 2016).

Method

Participants. A new sample of 43 undergraduate students from the University of Guelph (mean age 18.9 years, 37 women and six men) participated in Experiment 2 for partial course credit. Four participants were excluded for having 60% or greater errors on the Posner cueing task. Thus, Experiment 2 had a final sample size of 39 participants.

Apparatus, stimuli, and procedure. All equipment and visual stimuli were identical to those in Experiment 1b. There were several methodological changes for Experiment 2. Participants completed 320 trials total, and were required to report the orientation of the line segment inside the target-coloured square; see Figure 6. The number of trials was reduced, and the tone that played during the cue screen was removed, due to the removal of the “no cue” trials. The cue screen was changed to be more similar to other cueing tasks, with one circle (radius 0.115°) centered 0.038° away from each line of each placeholder square (Becker et al., 2010; Folk & Remington, 1998; Kim & Cho, 2016). To ensure that the cue shape did not match the memory colour shape, the memory colour presented at the beginning of each trial was changed to be a square (3° in height and width). At the end of each trial, one of the placeholder squares filled with the randomly selected target colour (which matched the memory colour at the beginning of the trial), and the other three placeholder squares were filled with three other similar colours, each separated by 18 degrees on the colour wheel. At the same time, four line segments appeared in the placeholders, each with a different orientation: vertical, horizontal, 45 degrees clockwise, and 45 degrees counter-clockwise. The only way for participants to know which line segment

was the target was based on differentiating the colours in the placeholders, thus ensuring that participants were actively searching for the target/memory colour. The locations of the placeholder squares were adjusted to ensure participants did not confuse the line orientation judgement with the location of placeholder squares (which were aligned with the Xbox buttons in Experiments 1a/b). Finally, there was no memory test at the end of trial, since the memory demands were created by the search task. Again, cue location, target location, and whether or not the colour of the cue matched the target colour were fully crossed for each participant to ensure that participants could not use the location and/or the colour of the cue to strategically complete the task.

Figure 6. Example trial sequence from Experiment 2. Participants were told to report the orientation of the line segment that appeared in the placeholder that matched the memory colour. This trial depicts a cued, colour-match condition, and the correct line orientation is vertical.

Results and Discussion

Attention task. Data were trimmed of outliers. For each participant, trials with a RT greater than 2.5 standard deviations from the condition mean were removed (0.62% of trials). Incorrect response trials and trials where a participant did not make a response in time (40.6%) were also excluded from RT analyses. Including error trials in the analyses did not change the pattern of statistically significant results for the distractor cost analyses or the cueing effect analyses, though the main effect of target location in the cueing effect data became marginally non-significant ($p = .061$).

Distractor costs. A planned paired-samples t -test to test for distractor costs indicated statistically significantly longer RTs on uncued trials for cues that matched the colour held in VWM than cues that did not match, $t(38) = 2.14$, $p = .019$, one-tailed; see Figure 7.

Figure 7. Distractors costs on uncued trials of Experiment 2. Numbers inside the bars indicate the error rates (SDs) for each condition. Participants exhibited significantly larger distractor costs for matching cues than non-matching cues.

Cueing effects. The same 2 (cue colour: colour match vs. colour non-match) $\times$ 2 (target location: cued vs. uncued) within-subjects ANOVA and planned paired-samples t -tests as in Experiments 1a/b were conducted on RTs; see Figure 8. The two-way interaction was statistically significant, $F(1, 38) = 7.15, p = .011, \eta_p^2 = .158$, there was moderate evidence of no main effect of cue colour, $F < 1, BF_{01} = 3.99$, and the main effect of target location was statistically significant, $F(1, 38) = 8.85, p = .005, \eta_p^2 = .189$. As for the paired-samples t -tests, the cueing effect for the colour match condition was statistically significant, $t(38) = 3.70, p < .001$, and there was moderate evidence of no cueing effect for the colour non-match condition, $t(38) = .089, p = .930, BF_{01} = 5.77$. These results provide evidence that observers can adopt an ACS for a stimulus represented in VWM. By having participants memorize *and* search for the target colour on each trial, participants formed an ACS representation for the target colour such that only cues that matched the target colour captured visual spatial attention.

Figure 8. Cueing effects for Experiment 2. Numbers inside the bars indicate the error rates (SDs) for each condition. Participants exhibited a cueing effect only when the cue matched the target colour, indicating they successfully adopted an ACS for the colour held in VWM.

Error analysis. The same ANOVA and *t*-tests that were conducted on the RT data were conducted on error rates; see Figures 7 and 8. It should be noted that the error rates for Experiment 2 were designed to be high for the same reason that error rates on the memory task in Experiments 1a/b were high: Fine colour discriminations helped to ensure that participants used VWM to remember the target colour rather than simply remembering the colour category using verbal working memory (Olivers et al., 2006). The distractor effect *t*-test revealed moderate evidence of no difference in error rates between the uncued match condition and the uncued non-match condition, $t(38) = 1.18, p = .246, BF_{01} = 3.05$, thus, there was no speed/accuracy trade-off for the distractor effect data. The cueing effect ANOVA conducted on error rates revealed a statistically significant two-way interaction, $F(1, 38) = 8.31, p = .006, \eta_p^2 = .179$, anecdotal evidence of no main effect of cue colour, $F(1, 38) = 3.75, p = .060, \eta_p^2 = .090, BF_{01} = 1.05$, and moderate evidence of no main effect of target location, $F(1, 38) = 1.51, p = .226, \eta_p^2 = .038, BF_{01} = 3.55$. On colour-match trials, cued targets were reported more accurately than uncued targets, $t(38) = 2.88, p = .006$, which is the opposite pattern expected by a speed/accuracy trade-off. And on colour non-match trials, there was anecdotal evidence of no difference in cued and uncued error rates, $t(38) = 1.45, p = .155, BF_{01} = 2.21$. Again, the effects on RT cannot be explained by speed/accuracy trade-offs.

Experiment 2 Summary

For this experiment, participants had to memorize and search for the target colour represented in VWM, as that colour defined the target on the current trial; participants were

successfully able to adopt an ACS representation for one target colour, as only cues that matched this target colour captured attention and produced a cueing effect. Experiment 2 provides evidence that VWM may be used to maintain an ACS representation, as only cues that matched the target colour captured visual spatial attention and produced a cueing effect.

Experiment 3

The results of Experiment 2 provide evidence that observers can use VWM to support an ACS representation. Yet, there is still an open question: Can VWM support *more than one* ACS representation? Using a similar methodology as Experiment 2, in Experiment 3, participants memorized and searched for either one or two target colours per trial. If participants are able to maintain multiple ACS representations in VWM, then, on two-target trials, they should exhibit a cueing effect when the cue matches either of the two target colours, and they should not exhibit a cueing effect for non-matching colours (Al-Aidroos et al., 2010; Folk & Remington, 1998; Giammarco et al., 2016). However, the dual-state model of VWM suggests that only one “active” VWM representation may bias attention; if the dual-state model extends to ACSs, then no cues should capture attention when participants are searching for multiple VWM targets. For distractor costs, on the uncued two-target trials, as both memory colours should be in an accessory state (Olivers et al., 2011), there should be no difference between matching and non-matching cues. To preview the results, on two-target trials, participants did not exhibit a distractor cost, and, critically, participants did not exhibit a cueing effect for any cue colour.

Method

Participants. A new sample of 34 undergraduate students from the University of Guelph (mean age 18.6 years, 31 women and 3 men) participated in Experiment 3 for partial course credit. Five participants were excluded for having 40% or greater errors on the Posner cueing task. Thus, Experiment 3 had a final sample size of 29 participants.

Apparatus, stimuli, and procedure. All equipment and visual stimuli were identical to those used in Experiment 2. Participants completed 192 one-target trials, and 384 two-target trials; see Figure 9 for a two-target trial example. On two-target trials, one memory colour was presented 10° above the centre of the screen, and one was presented 10° below the centre of the screen. To ensure enough trials per condition due to the difficult task demands, several methodological changes were made. There were only two placeholder squares; one was 4.1° to the left of the centre of the screen, and one 4.1° to the right of the center of the screen. The two colours that filled the placeholder squares at the end of the trial were separated by 25 degrees on the colour wheel. Participants had to indicate the orientation of the line segment (vertical or horizontal) inside the target-coloured placeholder square. Again, cue location, target location, and whether the colour of the cue matched one of the memory colours presented at the beginning of the trial were fully crossed for each participant to ensure that participants could not use the location and/or the colour of the cue to strategically complete the task.

Figure 9. Experiment 3 methodology. Participants completed a Posner cueing task with a pre-cue before target presentation, and were told to report the orientation of the line segment that appeared in the target-coloured square. This trial depicts a “cued match relevant” trial with two memory colours; the target location is cued, and the colour of the cue matched the target memory colour. The correct line orientation is vertical.

Results and Discussion

Attention task. Data were trimmed of outliers. For each participant, trials with a RT greater than 2.5 standard deviations from the condition mean were removed (1.80% of one-target trials and 1.22% of two-target trials). Incorrect response trials (i.e., if a participant made an incorrect response for the Posner cueing task) and trials where a participant did not make a response in time (18.1% of one-target trials and 28.9% of two-target trials) were also excluded from RT analyses. Including error trials in the analyses did not change the pattern of statistically

significant results for the cueing effect data, except that the two-target trials t -test for the match irrelevant condition became statistically significant ($p = .042$, one-tailed) and some of the Bayes factors became anecdotal (i.e., $BF < 3$), but continued to provide evidence favouring the original conclusions. Similarly, in the distractor cost data, the t -test for the two-target condition became statistically significant ($p = .007$, one-tailed).

Distractor costs. A 2 (cue colour: match vs. non-match) $\times 2$ (number of targets: one target vs. two targets) within-subjects ANOVA was conducted on the RTs for the uncued trials; see Figure 10. The ANOVA revealed moderate evidence of no interaction, $F < 1$, $BF_{01} = 4.22$, a statistically significant main effect of number of targets, $F(1, 28) = 74.0$, $p < .001$, $\eta_p^2 = .726$, and anecdotal evidence of no main effect of cue colour, $F(1, 28) = 2.00$, $p = .169$, $\eta_p^2 = .067$, $BF_{01} = 2.09$. To follow up on the non-significant interaction, two planned paired-samples t -tests were conducted. Although the RTs on uncued trials were generally slower for matching than non-matching trials, the differences were not statistically significant for either one-target trials, $t(28) = 0.97$, $p = .171$, $BF_{01} = 2.02$, one-tailed, or two-target trials. $t(28) = 1.25$, $p = .221$, $BF_{01} = 2.50$. While a significant difference would be expected by the dual-state model of VWM-based attentional capture for one-target trials (Olivers et al., 2006), the lack of an effect for two-target trials is consistent with the dual-state model: VWM-based modulations only occur when one item in memory is prioritized for the active state.

Figure 10. Distractor costs for uncued trials of Experiment 3. Numbers inside the bars indicate the error rates (SDs) for each condition. The differences between match and non-match trials were not statistically significant.

Cueing effects. We started our examination of cueing effects with the one-target condition, which provides a replication of the conditions in Experiments 1a/b, and 2. The same 2 (cue colour: colour match vs. colour non-match) $\times$ 2 (target location: cued vs. uncued) within-subjects ANOVA and planned paired-samples *t*-tests used in these earlier experiments were conducted on the RTs for the one-target condition; see Figure 11. The two-way interaction was statistically significant, $F(1, 28) = 6.78, p = .015, \eta_p^2 = .195$, there was anecdotal evidence of no main effect of cue colour, $F(1, 28) = 1.40, p = .246, \eta_p^2 = .048, BF_{01} = 1.93$, and anecdotal evidence of no main effect of target location, $F(1, 28) = 2.24, p = .145, \eta_p^2 = .074, BF_{01} = 2.98$. The cueing effect for the colour match condition was statistically significant, $t(28) = 2.66, p = .013$, and there was moderate evidence of no cueing effect for the colour non-match condition, $t(28) = 0.82, p = .419, BF_{01} = 3.72$. These results replicate those of Experiment 2, providing further evidence that observers can adopt an ACS for a single stimulus represented in VWM.

New for Experiment 3, we conducted a 3 (cue colour: match relevant vs. match irrelevant vs. non-match) $\times$ 2 (target location: cued vs. uncued) within-subjects ANOVA on RTs from the two-target condition. For these analyses, “match relevant” refers to when the cue and the target were the same colour from the memory array, and “match irrelevant” refers to when the cue was one memory-array colour, and the target was the other memory-array colour. The analysis revealed moderate evidence of no interaction, $F < 1$, $BF_{01} = 4.41$, a statistically significant main effect of cue colour, $F(2, 56) = 9.20$, $p < .001$, $\eta_p^2 = .247$, and moderate evidence of no main effect of target location, $F < 1$, $BF_{01} = 4.80$. Planned paired-samples t -tests of each cueing effect revealed moderate evidence of no cueing effect for the relevant colour match condition, $t(28) = 0.50$, $p = .622$, $BF_{01} = 4.52$, and non-match condition, $t(28) = .951$, $p = .350$, $BF_{01} = 3.35$, and anecdotal evidence of no cueing effect for the irrelevant colour match condition, $t(28) = 1.18$, $p = .249$, $BF_{01} = 2.71$. When participants searched for two colours simultaneously, we found little-to-no evidence that any cues captured visual spatial attention.

Figure 11. Reaction time data for Experiment 3's Posner cueing task. Numbers inside the bars indicate the error rates (SDs) for each condition. Participants exhibited a cueing effect only for the one target condition when the cue matched the target colour, indicating they successfully adopted an ACS when

searching for one colour maintained in VWM. Participants did not exhibit cueing effects for the two target condition, indicating they did not adopt an ACS when searching for two colours maintained in VWM.

Error analysis. For distractor costs, the same ANOVAs and *t*-tests that were conducted on the RT data were conducted on error rates; see Figures 10 and 11. The ANOVA revealed a statistically significant interaction, $F(1, 28) = 5.97, p = .021, \eta_p^2 = .176$, a statistically significant main effect of number of targets, $F(1, 28) = 117, p < .001, \eta_p^2 = .807$, and anecdotal evidence of no main effect of cue colour, $F(1, 28) = 2.91, p = .099, \eta_p^2 = .094, BF_{01} = 2.93$. In the one target condition, there was no difference in error rates between match and non-match uncued trials, $t(28) = 0.60, p = .722, BF_{01} = 7.53$. The same comparison was significantly different on two-target trials, $t(28) = 3.05, p = .002$; however, as participants made more errors in the slower condition, the results cannot be explained by speed/accuracy trade-offs.

For cueing effects, the one target ANOVA conducted on error rates revealed no differences (all F s < 1 , all BF_{01} s > 3.32). Similarly, the follow-up *t*-tests indicated no differences in error rates (both t s < 1 , both BF_{01} s > 3.93). The cueing effect for the two targets ANOVA conducted on error rates revealed a statistically significant two-way interaction, $F(2, 56) = 4.16, p = .021, \eta_p^2 = .129$, a significant main effect of cue colour, $F(2, 56) = 6.42, p = .003, \eta_p^2 = .186$, and moderate evidence for no main effect of target location, $F < 1, BF_{01} = 6.11$. The follow-up *t*-tests indicated no difference in error rates when the target was uncued than when it was cued for the relevant match condition, $t(28) = 0.86, p = .394, BF_{01} = 3.60$, significantly higher error rates when the target was uncued than when it was cued for the irrelevant match condition, $t(28) = 2.70, p = .012$, and non-significantly higher error rates when the target was cued than when it was uncued for the non-match condition, $t(28) = 1.89, p = .069, BF_{01} = 1.07$. It is potentially problematic that responses in the irrelevant match condition are more accurate for cued trials than uncued trials, as this may reflect a cueing effect on accuracy. There are some reasons to

believe that this difference may simply be a Type-I error. First, cueing effects do not usually affect accuracy, and instead only influence response speed (Prinzmetal, McCool, & Park, 2005). Second, given the number of tests for speed/accuracy trade-offs conducted across experiments, we should expect at least one Type-I error. Third, and most importantly, if we were going to see a cueing effect in only one condition, we would expect to see this difference for the relevant match condition, which most closely resembles the one target match condition. Thus, while we are not particularly concerned about this one statistic in this experiment, it should be monitored for future studies.

Experiment 3 Summary

For this experiment, participants had to memorize and search for either one or two target colours. The results from Experiment 3's one-target trials replicate the findings from Experiment 2: observers are able to form a VWM ACS when they are searching for one target stimulus. However, the results from Experiment 3's two-target trials indicate that observers are not able to adopt a VWM ACS for two targets at the same time, such that both targets are able to guide attentional capture.

General Discussion

An ACS determines which stimuli will capture visual attention, and which stimuli will not (Al-Aidroos et al., 2010; Becker et al., 2010; Folk et al., 2002, 1992; Folk & Remington, 1998; Giammarco et al., 2016). In Experiments 1a/b, when participants simply remembered a colour for later report that changed every trial (i.e., requiring VWM), cues that did not match the colour still produced a cueing effect. We can therefore conclude that simply remembering a

stimulus in VWM is not sufficient to adopt an ACS for that stimulus, even when that stimulus is represented in the active state. Conversely, in Experiments 2 and 3, when participants *searched* for one target colour that changed every trial, participants were able to adopt an ACS using VWM, such that only cues that matched the target colour produced a cueing effect. We can therefore conclude that observers can adopt a VWM ACS when they are searching for one target stimulus. But what about when they are looking for more than one target? Interestingly, the results of Experiment 3 suggest that it is not possible to adopt a VWM ACS for more than one target, as no cues captured attention when participants searched for two target colours. The results presented here advance our understanding of ACSs by providing evidence that VWM can maintain one ACS representation capable of guiding attentional capture.

What ACS did Participants in Experiments 1a/b Adopt When *Remembering* a Colour?

It is clear that participants in Experiments 2 and 3 were able to adopt a VWM ACS representation for one stimulus, as only cues that matched the searched-for target colour captured visual spatial attention and produced a cueing effect. So why, then, did all cues capture attention in Experiments 1a/b? In contrast to Experiments 2 and 3, participants in Experiments 1a/b did not have to search for the memory colour. As their task was to search for a single line segment, it is possible that participants in Experiments 1a/b adopted an ACS for *singletons*. If participants adopted a singleton ACS, then any singleton—including the singleton cue that appeared just before the line segment—would capture attention, as was observed in Experiments 1a/b (Folk & Remington, 1998). The important finding from these initial experiments is that, although we replicated the conventional VWM-based modulation of attentional capture (i.e., distractor costs), we found no evidence for a modulation of the control offered by ACSs (i.e., cueing effects).

Accordingly, whatever ACS participants adopted in Experiments 1a/b—singleton or otherwise—it is unlikely that this ACS was based on a representation in VWM, since we know that the *memory colour* occupied the “active” representation in VWM. Moreover, Experiments 1a/b clarify that VWM-based modulations of distractor costs do not always reflect the control of spatial attentional capture, and, instead, may reflect the regulation of non-spatial aspects of visual processing, as discussed next.

Controlling Cueing Effects through ACSs vs. Modulating Distractor Costs through VWM

There has been a long debate in the field about the automaticity of attentional capture: Is the capture of visual attention contingent on our top-down goals (i.e., ACSs), or is it based on bottom-up saliency? One potential point of contention within this debate is that the evidence favouring each conclusion has typically come from different experimental paradigms. Studies in support of contingent capture often make use of the Posner cueing task (Folk & Remington, 1998; Giammarco et al., 2016; Posner & Cohen, 1984), whereas those in support of automatic capture often use the additional singleton paradigm (Olivers et al., 2006; Theeuwes, 1992). While both paradigms measure “attentional capture”, what constitutes capture differs between these tasks. Cueing effects measure a strictly spatial component of attention, as they compare target processing at cued versus uncued spatial locations (Kiss, Van Velzen, & Eimer, 2008). In contrast, distractor costs measure how much search is slowed given different types of distraction, and thus are sensitive to non-spatial effects, such as filtering costs (Becker, 2007; Folk, 2013; Folk & Remington, 1998). Accordingly, it has been recognized that the divergent conclusions coming from these tasks could reflect differences in what aspects of visual processing are being measured, and thus differences in how attentional capture is being defined.

The data from Experiments 1a/b provide further evidence that cueing effects can be distinguished from distractor costs. While simply remembering a stimulus using VWM was sufficient to modulate distractor costs in both experiments, there was no evidence for a concurrent modulation of cueing effects. Indeed, the evidence favoured the conclusion of no memory-based modulation of cueing effects. Interestingly, whereas attentional control typically affects cueing effects (Folk & Remington, 1998; Folk et al., 1992, 1994) and not distractor costs (Olivers et al., 2006; Theeuwes, 1992; van Moorselaar et al., 2014), here we complete the double dissociation by showing that VWM-based control from “remembering alone” modulates distractor costs but not cueing effects. The null effect of memory on cueing effects in Experiments 1a/b should, of course, be interpreted with caution, especially given that the evidence only anecdotally favoured the null in Experiment 1b, and given the past demonstration that remembering alone can sometimes modulate cueing effects (Kim & Cho, 2016). That said, attentional capture measured via distractor costs does seem to be more sensitive to remembered representations in VWM than capture measured via cueing effects.

Additional evidence of the dissociation between cueing effects and distractor costs also resulted from the manipulation of cue timing in Experiments 1a/b. While cueing effects are often measured with cues that appear shortly before the target (Posner & Cohen, 1984), distractor costs are often measured with the simultaneous presentation of distractors and targets (Theeuwes, 1992). By using both simultaneous cues (Experiment 1a) and pre-cues (Experiment 1b), Experiment 1 provides another interesting dissociation between cueing effects and distractor costs. The cueing effect was larger for pre-cues than simultaneous cues, as evidenced by a cueing effect $\times$ experiment interaction: $F(1, 80) = 249, p < .001, \eta_p^2 = .174$ (see Figure 4). Whereas the distractor cost was larger for simultaneous cues than pre-cues, as evidenced by a distractor cost

(uncued match vs. no cue) $\times$ experiment interaction: $F(1, 80) = 13.9, p < .001, \eta_p^2 = .148, BF_{10} = 74.6$ (see Figure 3). If cueing effects and distractor costs measured the same aspects of attentional capture, then the changes in the size of these effects should be in the same direction. From our perspective, any attempt to resolve the debate on the automaticity of attentional capture by reconciling the findings from cueing tasks and additional-singleton tasks will need to recognize that these tasks provide somewhat divergent definitions of attentional capture.

VWM ACSs and the Dual-state Model

The novel contribution of Experiments 2 and 3 is the finding that participants can form a VWM ACS when they memorize and search for one target stimulus, but not when they search for more than one target stimulus. This finding aligns well with the dual-state model of VWM, which claims that only one item in VWM can be represented in the active state and interface with perception (Olivers et al., 2006; van Moorselaar et al., 2014; although see: Beck, Hollingworth, & Luck, 2012; Beck & Vickery, 2019; Dube, Basciano, Emrich, & Al-Aidroos, 2016; Hollingworth & Beck, 2016). When participants searched for two target colours, because neither colour had priority, it is possible that both colours were represented in the accessory state, thus unable to regulate attentional capture (Olivers et al., 2006; van Moorselaar et al., 2014). Interestingly, in Experiments 1a/b, we found that the memory colour was maintained in the active state (i.e., modulated distractor costs), but did not instantiate an ACS specific to that colour. Consequently, if our account of why only one VWM representation can support ACSs is correct, we can conclude that representation in the active state is necessary for establishing a VWM-based ACS, but not sufficient.

Conclusions

The results from the experiments presented here advance our understanding of the memory systems that support ACSs. Previous research has shown that we can develop an ACS for multiple complex visual objects using episodic long-term memory (Giammarco et al., 2016; Plater et al., 2019) or for words using semantic memory (Goodhew et al., 2014; Wyble et al., 2013), and Experiments 2 and 3 in the present research provide firm evidence that we can adopt an ACS for colours on a trial-by-trial basis using VWM. More research is needed to determine how these various memory systems work together to support ACSs; the majority of previous ACS research could have been supported by multiple memory systems, perhaps the most likely of which is LTM, as participants were often instructed to search for the same target (or targets) on multiple trials in a row (see Carlisle, Arita, Pardo, & Woodman, 2011; Woodman, Carlisle, & Reinhart, 2013). Here we show that, while people can have an active representation in VWM that biases distractor costs, this representation does not necessarily define an attentional control set (Experiments 1a/b). That said, observers can use VWM to support ACSs, though this is only possible when actively searching for—at most—one target stimulus (Experiments 2 and 3).

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