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Getting More From Visual Working Memory: Retro-Cues Enhance Retrieval and Protect From Visual Interference

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Visual working memory (VWM) has a limited capacity. This limitation can be mitigated by the use of focused attention: if attention is drawn to the relevant working memory content before test, performance improves (the so-called *retro-cue benefit*). This study tests 2 explanations of the retro-cue benefit: (a) Focused attention protects memory representations from interference by visual input at test, and (b) focusing attention enhances retrieval. Across 6 experiments using color recognition and color reproduction tasks, we varied the amount of color interference at test, and the delay between a retrieval cue (i.e., the retro-cue) and the memory test. Retro-cue benefits were larger when the memory test introduced interfering visual stimuli, showing that the retro-cue effect is in part because of protection from visual interference. However, when visual interference was held constant, retro-cue benefits were still obtained whenever the retro-cue enabled retrieval of an object from VWM but delayed response selection. Our results show that accessible information in VWM might be lost in the processes of testing memory because of visual interference and incomplete retrieval. This is not an inevitable state of affairs, though: Focused attention can be used to get the most out of VWM.

Keywords: attention, interference, retrieval, retro-cue, working memory

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The visual input reaching our senses is rich, giving us a detailed perceptual experience. This changes as soon as this information is no longer perceptually available and has to be retained in memory. Visual working memory (VWM) holds representations of visual input accessible for later use. Numerous studies have shown that performance in VWM tasks drops steadily as the number of objects to be retained in memory increases (Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Luck & Vogel, 1997; Ma, Husain, & Bays, 2014; Zhang & Luck, 2008, 2011). These findings have led to the conclusion that VWM has a very limited storage capacity.

In recent years, the idea of a fixed storage capacity limit in VWM has been challenged by the finding that focused attention can be used to pull out more information from VWM than accessed under traditional testing conditions. This is demonstrated by the so-called *retro-cue benefit* (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003). In tasks testing VWM, an array of visual objects (e.g., colored dots) is presented and participants have to retain the features of these objects in memory. In recognition tasks (a.k.a. single-probe change detection), a probe object is presented at test in the location of one of the array objects (called the *target*), and participants are asked to decide whether the probe's feature matches the one of the target. In the retro-cue recognition paradigm, presentation of an arrow pointing to the target (i.e., a retro-cue) after offset of the memory array, but before the presentation of the probe yields faster and more accurate decisions than trials without retro-cues or with noninformative cues (e.g., Makovski & Jiang, 2007; Matsukura, Luck, & Vecera, 2007; Maxcey-Richard & Hollingworth, 2013; Rerko & Oberauer, 2013; Sligte, Scholte, & Lamme, 2008).

Besides recognition, another way of testing VWM is to ask participants to adjust (along a continuous dimension) the feature of the probe to match the target's feature stored in memory. This procedure is known as a delayed-estimation or continuous-reproduction task (Prinzmetal, Amiri, Allen, & Edwards, 1998; Wilken & Ma, 2004; Zhang & Luck, 2008). When a retro-cue is presented in the continuous-reproduction paradigm before the onset of the probe, the error in reporting the target's feature is reduced (Makovski & Pertzov, 2015; Pertzov, Bays, Joseph, & Husain, 2013; van Moorselaar, Gunseli, Theeuwes, & Olivers, 2015).

Several hypotheses have been advanced to explain the retro-cue benefit. For example, the retro-cue could be used to selectively protect the cued object from time-based forgetting (see, e.g., Pertzov et al., 2013). This explanation is at least insufficient because a retro-cue benefit is also observed in comparison to a baseline matched in terms of time for decay (Makovski, Sussman, & Jiang, 2008; Murray, Nobre, Clark, Cravo, & Stokes, 2013; Rerko, Souza, & Oberauer, 2014; Souza, Rerko, Lin, & Oberauer, 2014; Souza, Rerko, & Oberauer, 2014). In these studies, the

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retro-cue was presented at the time at which memory was tested in the baseline (no-cue) condition. Hence, the actual test is delayed in the retro-cue condition relative to the baseline condition. These studies show that there is more than protection from time-based forgetting to the retro-cue benefit. Moreover, these studies demonstrate that the retro-cue improves memory performance by delaying some of the processes involved in testing memory.

The aim of the present study is to investigate two hypotheses about how such a benefit arises: The first hypothesis is that the retro-cue protects the cued memory object from visual interference arising at test. The second hypothesis is that the retro-cue provides more time for retrieval of the cued memory object before a decision is made on it. According to this hypothesis, the key feature to yield a focusing benefit is that time is allocated to more fully retrieve a representation before decision making, even if interference has already occurred. Note that these two hypotheses are not mutually exclusive: A retro-cue could make the target representation more robust thereby protecting it from interference, and enhance its retrieval by delaying the onset of decision making stages (i.e., response selection and execution). We next explain these two hypotheses in turn.

Protection From Visual Interference

Interference has been shown to contribute to forgetting from VWM (Clapp, Rubens, & Gazzaley, 2009; Logie, Zucco, & Baddeley, 1990; Makovski, Watson, Koutstaal, & Jiang, 2010; McConnell & Quinn, 2000; Souza & Oberauer, 2015). Accordingly, it has been suggested that retro-cues could serve a protective role against interference from additional visual stimuli (Makovski & Jiang, 2007; Matsukura et al., 2007; Sligte et al., 2008). This *protection from interference hypothesis* states that focusing attention on the cued object renders it more robust and less susceptible to visual interference; whereas nonfocused representations in VWM are fragile and can easily be replaced or distorted by subsequent input. The evidence in support of this claim is mixed. Some studies have observed that performance is unimpaired by an interference mask following a retro-cue, whereas performance in no-cue trials was significantly impaired by interference (Makovski & Jiang, 2007; van Moorselaar et al., 2015) or that performance was less impaired by interference in retro-cue trials than in neutral-cue trials (Makovski & Pertzov, 2015). This pattern of findings is the expected one if retro-cuing an object reduces its susceptibility to visual interference. Other studies, however, have observed that interference impairs performance to a similar extent in retro-cue and no-cue trials (Hollingworth & Maxcey-Richard, 2013; Rerko et al., 2014).

In the above mentioned studies the interfering stimuli were irrelevant to the VWM task: Interference was manipulated with the presentation of a perceptual mask (Makovski & Jiang, 2007; van Moorselaar et al., 2015) or of a secondary task during the retention interval (RI) such as visual search (Hollingworth & Maxcey-Richard, 2013), color classification (Rerko et al., 2014), or digit classification (Makovski & Pertzov, 2015). The mixed findings from these experiments do not rule out a special protective role of the retro-cue against interference from stimuli that are task relevant, such as the test display.

The idea that retro-cues protect against interference arising from the test display has been suggested before. Makovski and colleagues (Makovski et al., 2008) have proposed that the probe item in recognition tasks interferes with memory, and that the retro-cue protects the cued object from this interference (the *protection from probe interference* hypothesis). We have tested this hypothesis in earlier work using a version of the continuous-reproduction paradigm in which no probe (i.e., no comparison stimulus in the location of the target) is presented. Participants encoded an array of six colored disks. After the RI, a location cue indicated which object's color participants should reproduce from memory by selecting it from a color wheel. Simply delaying the onset of the color wheel after the location cue, giving participants time to focus the target before responding, improved performance (Souza, Rerko, Lin et al., 2014). This effect cannot be explained by protection of the focused object from probe interference in the narrow sense, because no probe was presented. However, because other relevant and potentially interfering visual information (e.g., the color wheel) is presented at test, a more general *protection from visual interference* hypothesis is still viable. We are not aware of any study that has tried to manipulate the degree of interference introduced by stimuli presented at test, nor investigated how retro-cues can protect representations against its deleterious effects. Accordingly, one of the aims of the present study was to assess the putative role of retro-cues in protecting against visual interference arising at test. We used color as the memoranda, and therefore, we assumed that color information presented at test could interfere with memory because, as shown by Pinto et al., 2013, this information overlaps with the feature stored in WM. Therefore, we sought to demonstrate how retro-cues protect the target representation from interference by color stimuli in the test display.

Retrieval Head Start

The second hypothesis we consider is that, by delaying the memory test, a retro-cue provides a Head Start for retrieval of the target. The retro-cue indicates the object to be tested long before the test situation presents itself. As such it offers the opportunity to retrieve the representation of the cued object before using this information to make a decision. By retrieval we mean the selective access to the target representation. We conceptualize retrieval as the gradual accumulation of information about the target's features in the focus of attention—a process akin to the gradual evidence accumulation process in sequential-sampling models of decision making (e.g., Purcell et al., 2010; Ratcliff & McKoon, 2008; Ratcliff & Rouder, 1998; Teodorescu & Usher, 2013; Usher & McClelland, 2001). Because retrieval accumulates more information over time, prolonging retrieval before making a decision could be expected to improve performance. We will call this explanation the *retrieval Head Start* hypothesis. This hypothesis implies that the retro-cue benefit arises in part from the fact that the retro-cue introduces a temporal separation between retrieval and decision processes. In the absence of a retro-cue, the decision process commences too early, using less accumulated—and hence noisier—information from the retrieval process. In particular, the decision could be influenced too much by other sources of information than the target, including nontarget representations in VWM as well as other visual stimuli. Delaying the decision about a response until more target information has accumulated in the focus of attention reduces the influence of irrelevant or even misleading information on the decision process (Purcell et al.,

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2010). To the best of our knowledge, the retrieval Head Start hypothesis has not been given consideration in the retro-cue literature. To test the predictions of this hypothesis was the second aim of the current study.

The Present Study: Protection From Visual Interference and Retrieval Head Start

Across six experiments, we aimed to test the predictions of the visual-interference and the retrieval-head-start hypotheses. To test the predictions of both hypotheses, we looked at performance benefits yielded by focusing attention on one object in VWM in trials with and without visual interference at test, and with or without the requirement to delay different components of the decision process (i.e., response selection or response execution). Table 1 provides an overview of the experiments (E) in the present article. The data and the analysis scripts for all experiments can be accessed in the Open Science Framework (https://osf.io/2576x/).

E1 and E2 used a local recognition task, in which memory is tested by a single probe in the location of one memory object, and participants have to decide whether the probe matches that object of the memory array. In this paradigm, three processing steps must be carried out at test: Retrieval of the target (i.e., the memory object in the probed location), response selection (i.e., comparison of the retrieved representation to the probe and deciding which button to press), and response execution. In the no-cue condition, all these processes are enabled at once with the onset of the probe: Its location identifies the target object, and its feature provides the basis for comparison. The comparison can immediately feed into response selection, and the response can be executed as soon as a decision has been made. At the same time, the probe potentially interferes with the target. The results of Pinto et al. (2013) show that stimuli with information on the same feature dimension as the memoranda, and presented in the same location as the memoranda, have the highest potential for interfering, and hence, local recognition probes can be expected to interfere substantially with memory representations.

In the standard retro-cue condition, after the RI, an arrow is presented pointing at the target's location. Upon this cue, participants can start retrieving the target, but all further decision processes—response selection and response execution—are delayed until test, when the probe is shown. Hence, compared with the no-cue condition, the retro-cue condition delays onset of the visual interference induced by the probe until after focused attention could have made the target representation robust against it. In addition, the retro-cue delays response selection and response execution, thereby enabling a Head Start for retrieval. In our experiments we introduced a third condition that is intermediate between the no-cue and the retro-cue condition. In E1, we presented the probe at the same time as in the baseline condition, but delayed response execution. In E2, we delayed response selection and execution. Figure 1 illustrates the hypothetical processes in the four conditions realized across E1 and E2.

To foreshadow our results, delaying response selection (but not merely delaying response execution) conferred a benefit compared with the no-cue trials, but this benefit was not as large as the benefit yielded by the standard retro-cue condition that delays the onset of the probe. This finding is consistent with a role of both retrieval Head Start and protection from probe interference as combined sources of the retro-cue benefit as outlined in Figure 1.

In E3 to E6, we tested for retro-cue benefits in a continuous reproduction task. We have observed before that recall in this task also benefits from a delay between presentation of a location cue and test

Table 1
Overview of the Experiments (E)

	Sample	Brief description	Findings
E1	n = 16 (15)	Recognition task	Retro-cue benefit
	Age = 25.1 years	Delay *response execution* vs. probe interference	No delay effect
		Delay execution vs. retro-cue	
E2	n = 41[a] (39)	Recognition task	Retro-cue benefit
	Age = 24.3 years	Delay *response selection* vs. probe interference	Delay benefit
		Delay selection vs. retro-cue	
E3	n = 20 (19)	Continuous reproduction task	Delay benefit
	Age = 23 years	Delay *color wheel*	
		Cue-wheel delay (0, .5, 1, 2, or 4 s)	
E4	n = 24	Continuous reproduction task	No delay effect
	Age = 23.8 years	Wheel present throughout the trial	
		Delay *response execution* until tone signal	
		Cue-tone delay (0, .25, .5, or 1 s)	
E5	n = 24	Continuous reproduction task	Delay benefit
	Age = 25.1 years	Wheel removed from screen during delay	
		Delay *response selection*	
		Cue-wheel delay (0, .25, .5, or 1 s)	
E6	n = 24 (20)	Continuous reproduction task	Visual interference effects
	Age = 21.5 years	Vary visual interference (color vs. grey wheel)	Delay benefits
		Delay *response selection* (cue-wheel delay 0 or 1 s)	

Note. The brief description indicates the task used in the experiment, the research question, and the experimental manipulation implemented. The final sample after exclusion of participants because of unusually low performance or experimenter error is shown in parenthesis.
[a] Initially we collected data of 21 participants in E2. Performance in the Delay Selection condition for this sample was in between that of the No-Cue and Retro-Cue conditions. Therefore, we decided to replicate this study and collected an additional sample of 20 students. The same pattern of results was obtained. Therefore, we collapsed the data of the two samples to present it in the current article.

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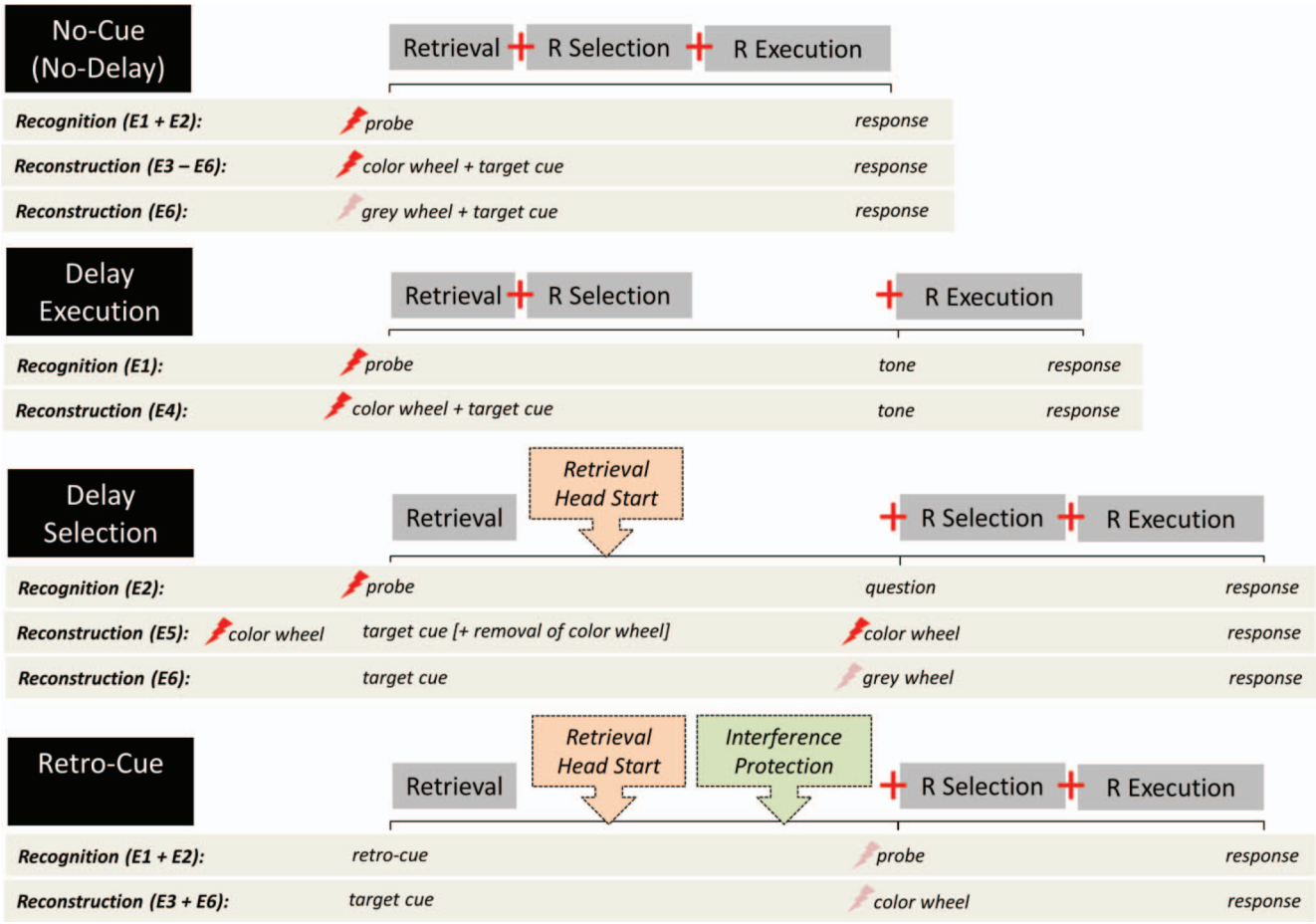

Figure 1. Illustration of the cognitive processes (represented as gray-shaded rectangles) taking place at test in each experimental condition (No-Cue, Delay Execution, Delay Selection, and Retro-Cue) of the recognition and reconstruction tasks used in E1 to E6. The onset of visual interference from the colored probe or the color wheel is illustrated by the red flash symbol (and its attenuation is indicated by a light-shaded flash symbol). We argue that whenever retrieval is separated from response selection, a retrieval Head Start (dotted orange rectangle) allows more information regarding the target to accrue before decision making. Moreover, when retrieval can proceed in the absence of interference, focused attention makes the target representation more robust against visual interference (dotted green rectangle). R = response. See the online article for the color version of this figure.

onset, allowing attention to be focused on the target before responding (Souza, Rerko, Lin et al., 2014) even though no probe stimulus was shown that could interfere with memory. Here, we assessed whether a more general protection from visual interference is part of the explanation of retro-cue benefits in this task. Across four experiments we identified one form of visual interference that goes beyond probe interference: Testing VWM using a color wheel interferes with recall because the wheel color close to the target's object location (that is the location participants are attending to) tends to replace the target color in memory. Focusing attention on the target before test shields it against this interference. At the same time we provide evidence that protection from visual interference only partially explains the retro-cue benefit in continuous reproduction. Using the logic outlined in Figure 1, we showed that a retro-cue benefit remains in the presence of visual interference when response selection and execution are delayed (E5), but not when only response execution is delayed (E4). In addition, we show a retro-cue benefit when visual interference is minimized (e.g., by showing a gray wheel, E6). This remaining retro-cue benefit can be explained by a Head Start for retrieval. In a nutshell, our results show that retro-cues both enhance retrieval and protect from visual interference, thereby making information accessible from VWM that would be otherwise lost in the process of testing memory.

Experiments 1 and 2

In E1 and E2 we used a color recognition task to decompose the effects of the retro-cue (see Figure 2a and 2b). In the standard no-cue (control) condition, a probe is presented after a 1-s RI, and participants are asked to decide whether it matches the object in the probed location. In the retro-cue condition, a cue identifying the target is presented after the same RI, and presentation of the

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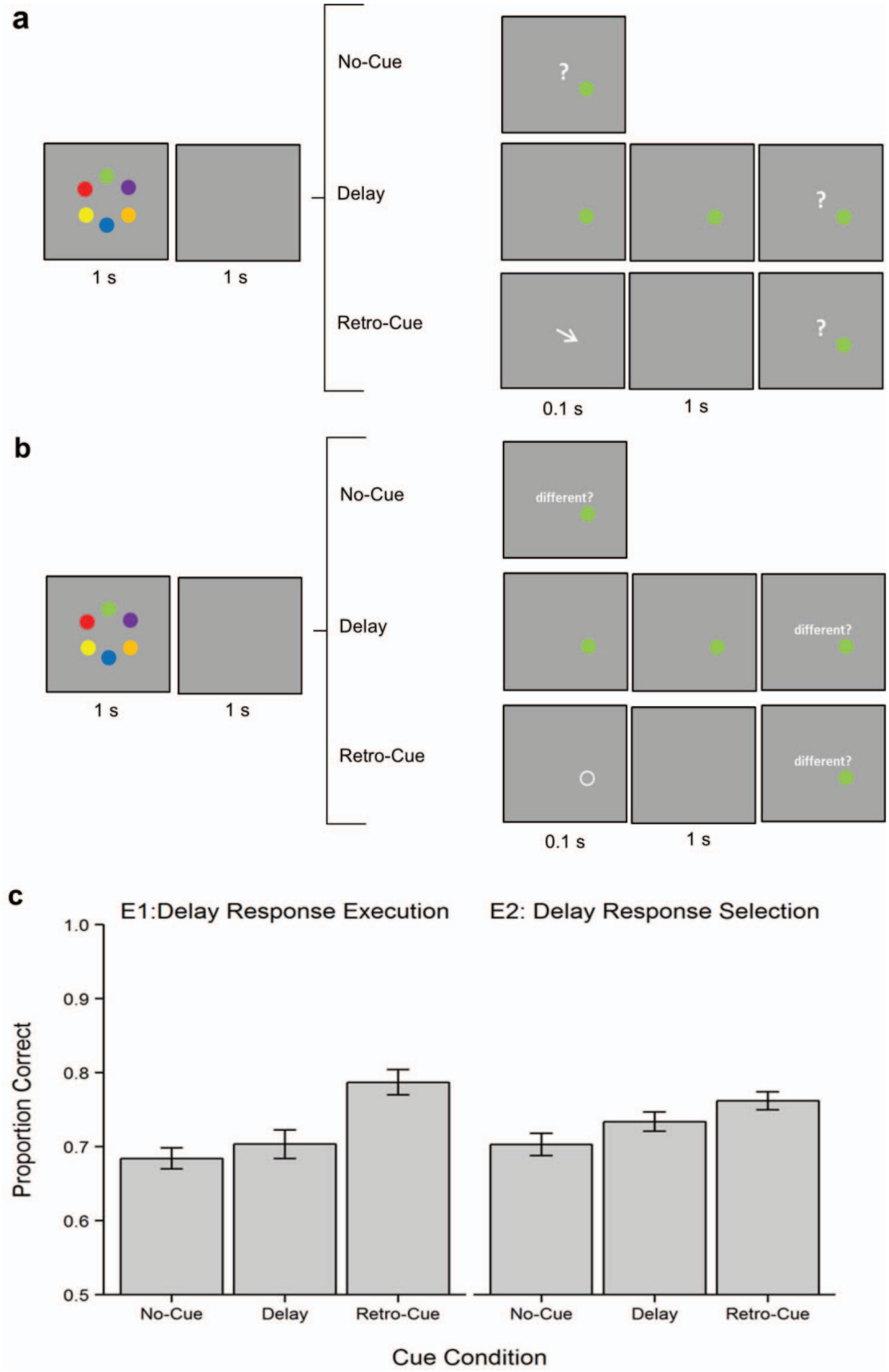

Figure 2. Panel a: Color recognition task used in E1. Panel b: Color recognition task used in E2. Panel c: Proportion of correct responses in each of condition of E1 and E2. The Delay condition involves delay of response execution in E1, and of response selection in E2. Error bars depict 95% within-subjects confidence intervals (Cousineau, 2005). See the online article for the color version of this figure.

probe is delayed. In E1 we introduce a third, intermediate condition in which the probe is presented after the 1 s RI, but response execution is delayed. In E2, the intermediate condition delays response selection and response execution. The intermediate conditions give rise to probe interference in the same way, and at the same point in time, as the no-cue baseline condition, but they provide a Head Start for retrieval before the subsequent processing steps of response selection or response execution. To the extent that the retro-cue benefit arises from probe interference, performance in the standard retro-cue condition (that delays probe interference) should be better than performance in all other conditions. To the extent that Head Start for retrieval contributes to the retro-cue benefit, there should be an advantage for delaying response selection, response execution, or both, in comparison to the baseline condition, even though probe interference is held constant across these conditions.

Method

Participants. In total, 57 students of the University of Zurich took part in E1 and E2. The sample in each experiment is detailed in Table 1. In all experiments reported here, participants received financial reimbursement (15 CHF per 1-hr session) or partial course credit. Participants read and signed an informed consent form before the experiment, and were debriefed at the end.

Materials. The tasks in all experiments were programmed in MATLAB using the Psychopsysics toolbox (Brainard, 1997; Pelli, 1997). Across all experiments, participants were tested in individual booths at unconstrained viewing distance (ca. 50 cm). Moreover, they were required to perform articulatory suppression (AS) by constantly repeating "*der-die-das*" throughout the trial. Participants were reminded of the AS procedure in the beginning of each block of trials. In E1 and E2, the memory objects and probes were selected from a set of 12 distinct colors (i.e., beige, yellow, orange, red, brown, magenta, light green, dark green, turquoise, dark blue, purple, and black).

Experiment procedure. In all experiments reported in the current study, the memory array contained six colored disks (radius 1.16°) centered on an imaginary circle (radius 6.62°) on a gray background. The memory array was presented for 1 s, followed by a RI of 1 s, during which the entire screen turned gray. Conditions (in each experiment) differed regarding the events after the RI. Note that in all experiments, the retro-cue trials had an overall longer RI than the no-cue (or 0-s Delay) condition to rule out protection from decay as an explanation of our effects. Time to respond to the memory test was unconstrained. Between trials, a blank screen was shown for 1 s.

In each experiment, participants completed practice trials before the actual test trials, which did not enter the final analyses. All manipulations were implemented in a within-subjects design, and trials were split evenly between experimental conditions.

E1: Delay of response execution. In this experiment, memory for an array of colors was tested by presenting a recognition probe (radius 1.16°) in one of the locations previously occupied by a memory object (see Figure 2a). The task was to decide whether the probe color matched the color of the object in the same location (50% of the probes were match; mismatch probes were equally likely to have a color that was presented in another memory location or a new color). As shown in Figure 2a, there were three types of trials. In *No-Cue* trials, after the RI, a probe and a question mark were presented at the same time. In *Retro-Cue* trials, an arrow was shown after the RI for 100 ms, indicating the location of the object to be tested. The probe and question mark were shown 1 s later. In *Delay Execution* trials, the probe was shown at the end of the RI, but the question mark was delayed by 1.1 s. The question mark indicated that a response could be entered. Therefore, the Delay Execution condition enables retrieval of the target, response selection (i.e., comparison of the target to the probe and deciding which response button to press), but not response execution. In response to the question mark, participants pressed the left-arrow key in the keyboard for a match response and the right-arrow for a mismatch response. If participants responded before the question mark was shown, a tone sounded indicating an invalid anticipation response. Trials with anticipation responses were discarded from subsequent analyses. Visual feedback (right or wrong) was provided regarding the accuracy of the (validly entered) response for 500 ms. Participants completed 540 test trials across 10 blocks, and 12 practice trials in the beginning of the session. Trials of each condition were randomly intermixed.

E2: Delay of response selection. The task in E2 was similar to the one described in E1 with the following exceptions (see Figure 2b). Participants were instructed that the left and the right arrow keys indicated "yes" and "no" responses, respectively, to one of two possible questions. At test, one of two question ("identical?" or "different?") was shown in the center of the screen instead of the "?" shown in E1. Each of the questions occurred in an equal proportion of the trials. Participants had to consider the probe and the question to select the correct response (e.g., for a match probe, the question "identical?" required a "yes" response, but the question "different?" required a "no" response). Hence, in this experiment, instead of a Delay Execution condition, there was a *Delay Selection* condition because after the onset of the probe, participants could start retrieving the target object but they could not carry out response selection and execution. A further minor difference from E1 was that the retro-cue was a white circle frame (radius 1.16°) presented at the location of the memory object to be probed instead of an arrow. Participants completed 528 test trials and 12 practice trials. Trials of each condition were randomly intermixed.

Data analyses. We submitted our data to Bayesian *t* tests and Bayesian analyses of variance, BANOVA (Rouder, Morey, Speckman, & Province, 2012). All analyses were performed in R (R Core Team, 2014) using the BayesFactor 0.9.11 package (Morey & Rouder, 2014). This package estimates the likelihood of the data in light of two models: a Null model (M_0) and an Alternative model (M_1) that includes the predictors of interest (and interactions thereof). The ratio of the likelihood of these two models is the Bayes factor (BF). The BF provides a factor by which our ratio of prior beliefs in the tested models should be updated in light of the data. For example, if the comparison of the No-Cue condition to the Delay condition returns a BF of 10, then the data are 10 times more likely under the assumption that these conditions do differ from each other than under the assumption that they are the same, and we should update our beliefs concerning the relative merits of the two models accordingly. If the returned BF is 0.1, then the data are 10 times more likely under the assumption that the two conditions do not differ from each other (to get to this number, one only needs to compute 1/BF). BFs below 3 are usually regarded as

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"weak" evidence, between 3 and 10 as "substantial" evidence, between 10 and 100 as "strong" evidence, and above 100 as "decisive" evidence in favor of the model under consideration (Kass & Raftery, 1995).

Results and Discussion

The main dependent variable in E1 and E2 was proportion of correct responses. We removed from the analysis anticipation responses, which only occurred in the delay conditions (Delay *Execution* in E1: $M = 0.107$, $SD = 0.08$; Delay *Selection* in E2: $M = 0.012$, $SD = 0.024$). One participant in E1 was excluded because of a high proportion of anticipation responses (52.8%). Moreover, two participants in E2 were excluded because of overall performance close to chance level (i.e., 55.7 and 53.8%). Inclusion of these participants in the analysis does not change the pattern of results.

Figure 2c presents the results of E1 and E2. For each experiment, paired-samples Bayesian *t* tests were used to compare performance between experimental conditions. In E1, there was no evidence that delaying response execution improved performance: the comparison of the No-Cue condition to the Delay *Execution* condition yielded a BF = 0.86, indicating that the evidence slightly favored the Null hypothesis. The Retro-Cue condition yielded better performance than the No-Cue condition (BF = 503′407) and the Delay *Execution* condition (BF = 1′767). In E2, the Delay *Selection* condition yielded better performance than the No-Cue condition (BF = 8.4). The Retro-Cue condition, however, still yielded better performance than both the No-Cue condition (BF = 45′131) and the Delay Selection condition (BF = 20.8).

The BFs reported above were computed for the Alternative hypothesis that the two conditions under comparison show a difference (in whatever direction). However, our experimental hypotheses predict improvements in the comparison of No-Cue to the Delay condition (Retrieval Head Start hypothesis), and in the comparison of the Delay condition to the Retro-Cue condition (Protection from interference hypothesis). Hence this analysis underestimates the BFs supporting these hypotheses. Adjusting for the expected direction of the effects doubles the evidence supporting these hypotheses. For E1, the comparison of No-Cue to Delay *Execution* yields a BF = 1.6 (still ambiguous to support a benefit), whereas comparison of Delay *Execution* to Retro-Cue yields overwhelming evidence for a benefit (BF = 3′534). In E2, the comparison of No-Cue to Delay *Selection* condition yields strong evidence for a retrieval Head Start benefit (BF = 16.7) and comparison of Delay *Selection* to Retro-Cue yields very strong evidence for protection from interference (BF = 41.5).[1]

In summary, the results of E1 and E2 show that retro-cue benefits in local-recognition tasks are due, in part, to the delay of response selection. This finding is consistent with the prediction of the retrieval Head Start hypothesis: The separation of retrieval and decision components is beneficial to performance because participants can use a more fully retrieved representation to compare with the probe and select a response. It is not sufficient to force participants to delay entering of the response. In this case, participants might simply withhold from pressing the key during the delay, but have the motor response prepared. As such, they do not benefit from a more fully retrieved representation for selecting the response.

This retrieval Head Start benefit is only part of the story though: A retro-cue also makes the cued object more robust against the interference produced by the probe stimulus. The latter finding is a natural prediction of the protection from probe interference hypothesis (Makovski et al., 2008). However, the probe may not be the only visual stimulus occurring at test that has similar features as the information currently held in WM. As discussed in the introduction, we have observed retro-cue benefits in a study using a continuous-reproduction task in which no probe stimulus was displayed at test (Souza, Rerko, Lin et al., 2014). In light of the results of E1 and E2, there are two possible explanations to account for the retro-cue effect in continuous reproduction: Either only retrieval Head Start contributes to retro-cue benefits in that task, or color information presented at test interferes with color memory, and retro-cues protect from this interference in a broader sense than implied in the probe interference hypothesis. Hence in our subsequent experiments, we aimed at assessing the degree with which presentation of color information at test impairs retrieval even in conditions without a probe stimulus. If that is the case, it would provide support to the more general hypothesis that retro-cues protect from visual interference arising at test.

Experiment 3

In E3 we used a continuous color reproduction task in which the precise color of a cued dot had to be reproduced from memory using a color wheel. In this task, no probe is shown at the location of the memory object and hence probe interference does not play a role. To assess the benefits of focused attention in this task, we varied the time between onset of the location cue and the color wheel as a means of producing an analog of the retro-cue benefit (namely, a delay benefit). This delay allows people to focus attention on the target before starting response selection, but it also delays the potential interfering effect of the color wheel. Therefore, the cue-test delay confounds additional time for retrieval and protection from color interference. Whereas E3 does not yet disentangle these variables, it allowed us to establish to what extent the color wheel interferes with retrieval, and to identify the source of this interference.

Method

Participants ($n = 20$) completed a continuous color-reproduction task. The colors of the memory objects were selected from 360 hues evenly spaced on the hue dimension of the HLS (*hue*, *lightness*, or *saturation*) color space (saturation = 1 and lightness = 0.5). Colors in the memory array were selected at random from the set of 360 colors (that comprised a continuous color wheel) with the constraint that the minimum distance be-

[1] E2 has about twice as many participants as E1. One may wonder what the impact of doubling the sample size in E2 is. To address this concern, we have performed sequential sampling analyses (i.e., computed the BF after entering each participant in the pool) which are provided in the online Supplemental Materials. This analysis shows that between $n = 20$ to $n = 39$, evidence supporting a Retrieval Head Start benefit (No-Cue vs. Delay) decreased from 100 to 16, whereas evidence supporting an additional effect from Protection from interference (Delay vs. Retro-Cue) increased from 5 to 30. This analysis also shows that BFs remained relatively stable around the final BF values from $n = 30$ to $n = 39$.

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tween every two objects in the memory array was of 20° in color space. At test, participants had to reproduce the precise color of a target object (indicated by a recall cue) using a color wheel (see Figure 3a). The location cue was a white circle frame displayed in the location of the target together with a central white arrow pointing to it. After a delay of 0, 0.5, 1, 2, or 4 s, the color wheel (randomly rotated from trial to trial) and the mouse cursor (in the center of the screen) appeared, indicating that a response could be made. The delay was assumed to allow retrieval of the cued object in the absence of the opportunity to select a response, and also to delay the putative interference introduced by the color wheel. Each of the delay conditions was presented in separate blocks of trials (order counterbalanced across participants). Participants responded by clicking on a point in the color wheel. There were 80 trials per test block and 3 practice trials in the beginning of each new block.

Data Analysis

As a first step in assessing performance in the continuous reproduction task, we computed the angular deviation (in the color wheel) between the response given by the participant and the target's true color. Deviations can range between −180 and 180 degrees. Figure 4a shows the distribution of deviations from the target color obtained in E3 for each delay condition. This distribution of deviations can be modeled as a mixture of three theoretical components: (a) a circular normal distribution (i.e., a von Mises distribution) centered on the target color, reflecting the successful retrieval of the target color, with the *SD* of this distribution indicating the precision with which objects are stored in VWM; (b) a von Mises centered on the color of a nontarget object, reflecting the incorrect retrieval of another object from the memory array than the cued one; and lastly; and (c) a uniform distribution reflecting failures to retrieve information from VWM, which could reflect guessing responses (Bays et al., 2009; Zhang & Luck, 2008). The estimated parameters from the mixture model are used as indices of the degree to which each of these components contributed to the generation of the observed responses.

In the present article, we aimed at testing the contribution of one further component, namely interference from the color wheel. The

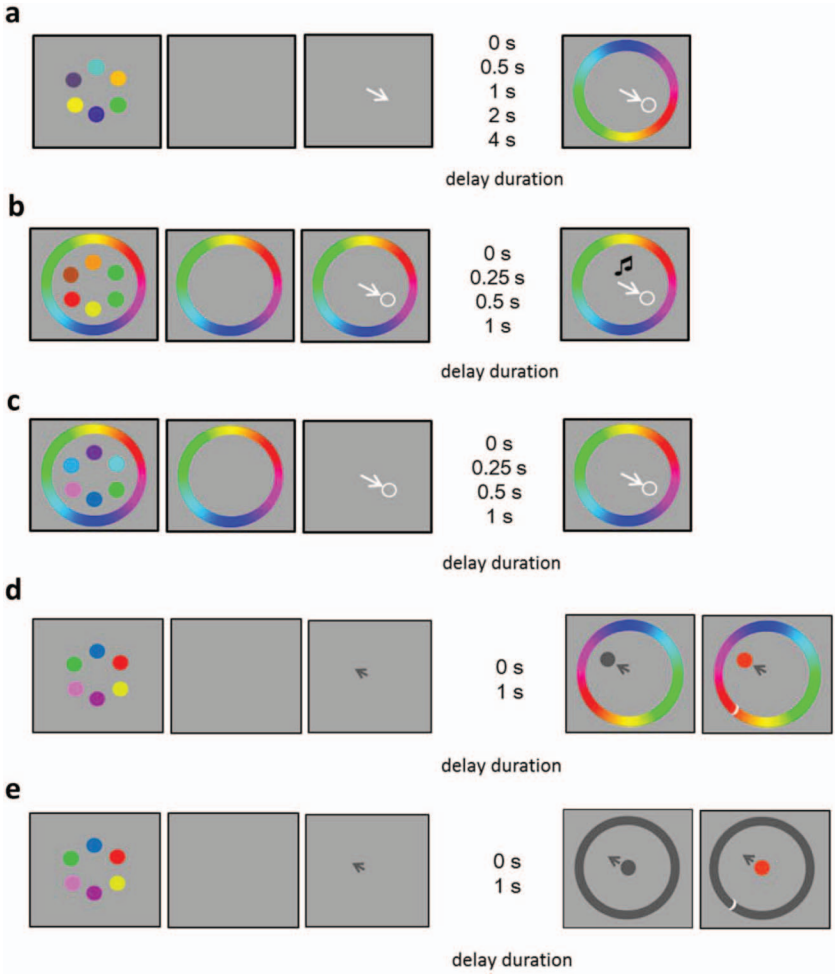

Figure 3. Panel a: Flow of events in E3. Panel b: Flow of events in E4. Panel c: Flow of events in E5. Panel d: Flow of events in the Color Wheel (target location) conditions in E6. Panel e: Flow of events in the Gray Wheel (center location) conditions in E6. See the online article for the color version of this figure.

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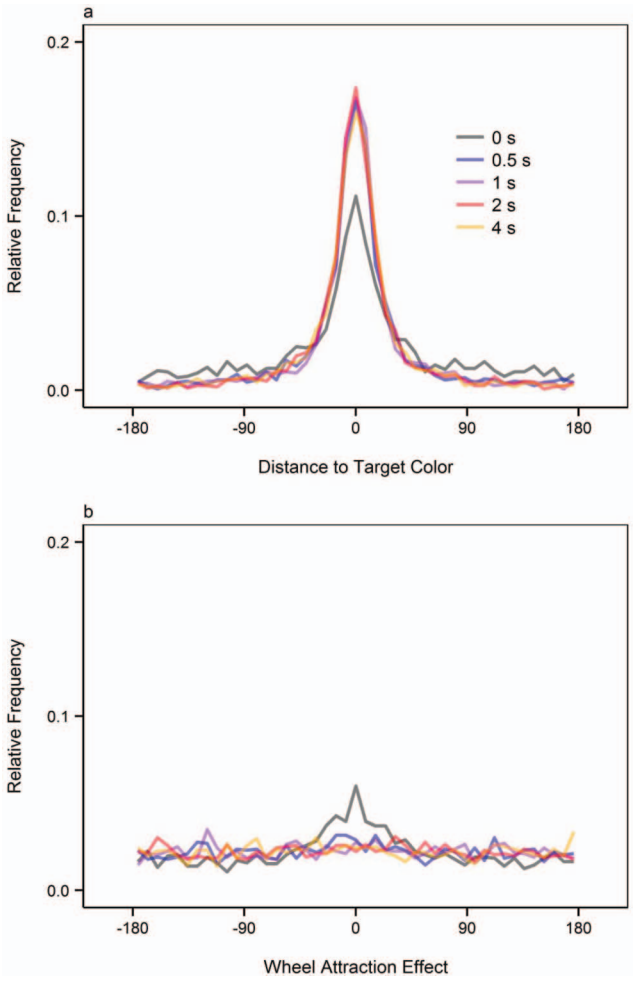

Figure 4. Panel a: Distribution of response deviations centered on the target color in E3. Panel b: Distribution of response deviations centered on the wheel location close to the target in E3. See the online article for the color version of this figure.

color wheel could interfere with retrieval because participants direct their attention to the target location, and the color presented at the wheel location spatially close to it tends to be attended as well. The color at this location, therefore, could replace the target in memory, which translates in responses being attracted (or lured) to wheel locations close to the probed location. To assess whether this was the case, we computed the distance in color space between the response given by the participant and the color on the wheel adjacent in physical space to the location of the target object. For instance, if the target was placed at 90° on the imaginary circle, the color on the wheel at 90° was considered as the center of the lure distribution reflecting color-wheel interference. The lure distribution was defined as the distribution of the deviations of responses from that center, ΔL. Given that the position of the color wheel was randomly selected in each trial, ΔL would be expected to be uniformly distributed if the wheel did not interfere with retrieval (as assumed in the traditional mixture model), and to be centered on 0 if responses were lured to the wheel color proximal to the probed location (hereafter referred to as a *wheel attraction* effect).

Figure 4b illustrates the wheel attraction effect in E3. As can be seen in this figure, a wheel attraction effect was present only in the 0-s Delay condition, and disappeared when a delay of 0.5 s or more was inserted between the recall cue and the presentation of the color wheel. To estimate the contribution of the color wheel interference effect, we entered the ΔL distribution as an additional component in the mixture model. We modeled it similarly to the recall of target and nontarget objects (i.e., with a von Mises distribution; see the online Supplemental Material for a description of the full model probabilities). We were interested in estimating the probability with which responses were lured by the wheel across the different delay conditions, and whether the retro-cue benefit was uniquely because of reductions in this tendency, as would be predicted by the protection from visual interference hypothesis.

We fitted the data of each participant in each condition separately using the modified four-parameter mixture model (and also the standard three-parameter mixture model). The model estimates the *SD* of the von Mises distribution and the probabilities with which each distribution component (target, nontarget, guessing, and wheel attraction) contributed to the observed response distribution. The probability of recalling the target was calculated as 1 - (nontarget + guessing + wheel attraction).

For all continuous color reproduction experiments reported in the present article, response distributions centered on the target color and centered on the wheel attraction point (alongside model predictions derived from the best fitting parameters of standard three-parameter and the extended four-parameter mixture model) are provided in the online Supplemental Material. The four-parameter mixture model provided a better fit of the data whenever responses were affected by color-wheel interference, and the fit was about equally good in the absence of wheel interference (comparison of the fit of the two models can be found in the online Supplemental Material). For all experiments and conditions, we report the estimates of the four-parameter mixture model.

Results

We removed one participant in E3 because of experimenter error that led this participant not to contribute data for some of the conditions in this experiment. We analyzed the obtained parameters of the mixture model across the different delay conditions. Delay was entered in a BANOVA model as a categorical predictor with five levels (0, 0.5, 1, 2, and 4 s). When necessary, we followed up on this analysis by performing paired-samples Bayesian *t* tests. Figure 5a shows the *SD* (precision) parameter, and Figure 5b shows the probability of correctly retrieving the target object and the probabilities of different kinds of errors (i.e., recalling a nontarget, guessing a random color, or being lured by the wheel) in E3 as a function of delay. We will describe the effects of delay on each of these parameters next.

Precision. The *SD* parameter provides an index of the precision of the memory representations: the smaller the *SD*, the higher the precision. Overall, there was no evidence that allowing more time to focus attention changed precision in E3 (see Figure 5a). The BANOVA model having Delay as a categorical predictor yielded a BF = 0.17 in comparison to a Null model without that predictor. By reversing this ratio (i.e., computing 1/BF), one can get the evidence in favor of the Null hypothesis that was 5.88. We

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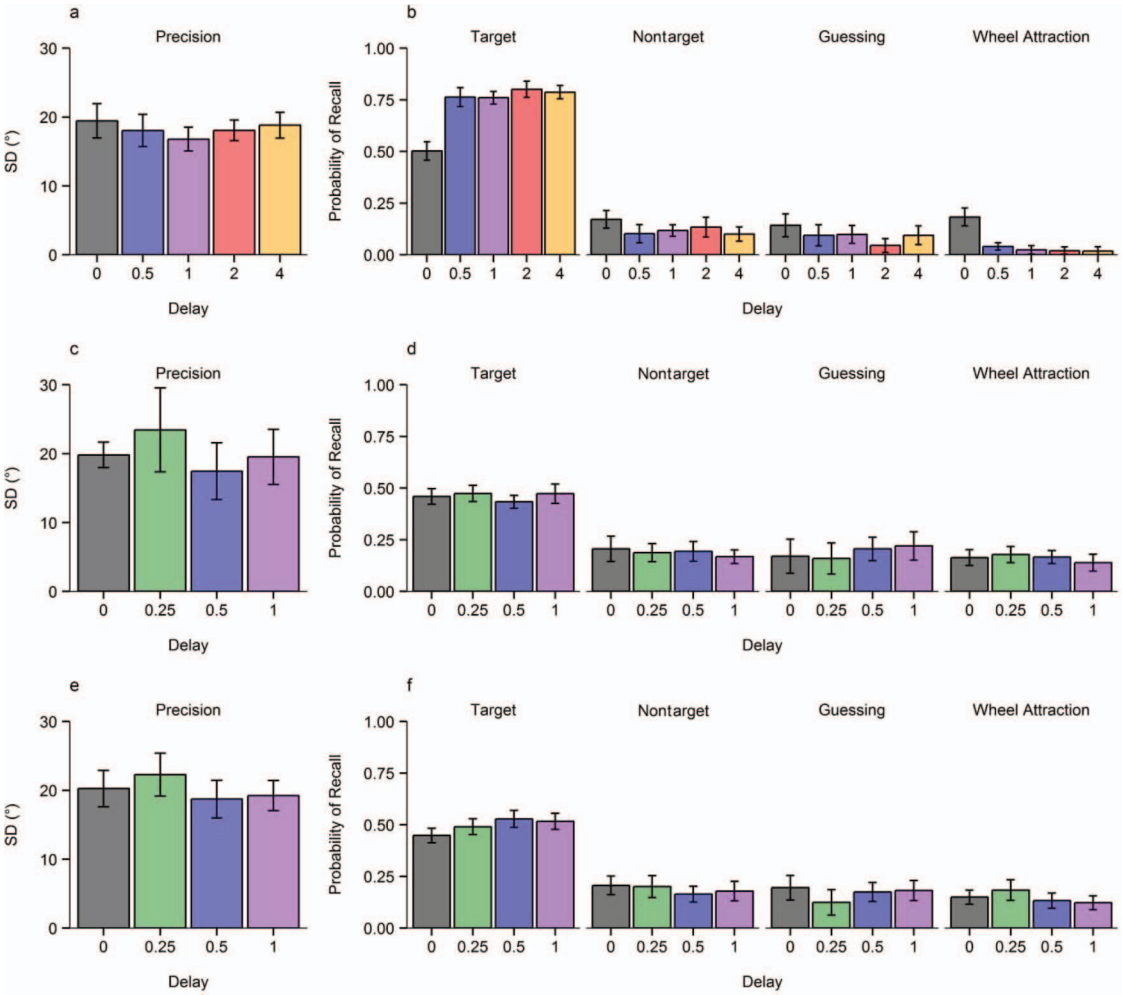

Figure 5. Mixture model results. Panels a, c, and e show the estimated *SD* reflecting precision across the delay conditions in E3 to E5, respectively. Panels b, d, and f show the estimated probability of correctly retrieving the target (Target), and of each possible type of error: retrieval of a nontarget object (nontarget), guessing (guessing), and wheel interference (wheel attraction) across delay conditions in E3 to E5, respectively. Error bars depict 95% within-subjects confidence intervals (Cousineau, 2005). See the online article for the color version of this article.

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also compared the 0-s Delay condition to the 1-s Delay condition (that numerically had the smallest *SD*), which still yielded a BF = 0.92, indicating that even in this condition the evidence does not support a delay benefit.

Probability of target recall. As shown in Figure 5b, the probability of correctly retrieving the target object was larger in all delay conditions compared to the 0-s Delay condition. Entering Delay in a BANOVA using target recalls as the dependent variable yielded a BF = 7.6. We followed up on this analysis to assess which delays differed from each other, using *t* tests. The 0 versus 0.5 s Delay comparison yielded a BF = 1.3×10^6 (and comparing all delays as one category against the 0-s Delay condition yielded a BF = 1.15×10^{18}). Comparison of all subsequent delays with each other yielded BFs supporting the Null hypothesis: 0.5 versus 1 s, BF = 0.24; 1 versus 2 s, BF = 0.79; 2 versus 4 s, BF = 0.29. Hence 0.5 s was a sufficiently large delay to yield a retro-cue benefit, and increasing the delay further hardly improved performance.

Probability of nontarget recall. As shown in Figure 5b, all delay conditions in E3 yielded smaller proportions of nontarget responses than the 0-s Delay condition. Entering Delay as a predictor in the BANOVA only yielded a BF = 0.9, which is ambiguous because it provides no evidence in favor of either model. However, in comparing all delay conditions to the 0-s Delay, there was some evidence for a delay benefit, BF = 5.88. Comparison of all subsequent delays with each other always provided evidence favoring the Null (BF = 0.27, 0.29, and 0.43 for the comparison of: 0.5 vs. 1 s, 1 vs. 2 s, and 2 vs. 4 s, respectively).

Probability of guessing. Figure 5b shows that guessing was somewhat reduced in the delay conditions compared with 0-s Delay. The effect of Delay yielded an ambiguous BF = 1.13 overall. However, when all delays larger than 0.5 s were pooled together against the 0-s Delay condition, the evidence for a delay benefit was BF = 3.45. Note that the 2-s Delay condition was the one yielding most of the effect (comparison of the 0-s and 2-s Delay condition yielded a BF = 4.3). The evidence for a benefit

for the other conditions individually pitched against the 0-s Delay favored the Null (0.5 s, BF = 0.58; 1 s, BF = 0.5; 4 s, BF = 0.5). Hence, this set of findings only hints at a reduction in guessing as a function of delay.

Wheel attraction. The wheel attraction parameter indexes the amount of color wheel interference. There was substantial evidence for a delay benefit in E3: only in the 0-s Delay condition, a substantial proportion of responses were lured by the wheel. Overall, the effect of Delay yielded a modest BF = 1.96. However, comparing the 0-Delay condition against all other delays yielded BF = 3.77×10^6, providing unambiguous evidence for an effect of delay. This finding was consistent in individual comparisons of each delay against the 0-s Delay. There was no evidence that increasing the delay beyond 0.5 s reduced the wheel attraction effect further (all BFs < 0.48).

Discussion

In a nutshell, in E3 we observed a substantial increase in the probability of retrieving the target object when a delay of half a second or more was inserted between the retro-cue and the test display. Memory precision, however, remained unchanged. The increase in correct retrieval was brought about at the expense of several types of errors. First, participants were less likely to confuse memory objects with each other. This finding suggests that focusing attention on the target enhances retrieval by reducing the competition of nontarget objects for recall. Guessing was also somewhat reduced in the current study, albeit the evidence for such an effect was only robust in one delay condition. Lastly, focused attention reduced color interference: participants were lured in some proportion of the trials to select the color in the wheel next to the target location. This wheel-attraction effect completely disappeared when attention was focused on the target object for at least half a second before the onset of the wheel.

Our findings are consistent with both a role of protection from visual interference and retrieval Head Start in bringing about retro-cue benefits in a cued reproduction task. We showed that presenting the color wheel too early during the retrieval processes impairs retrieval. On the one hand, we showed for the first time that the wheel has a center of attraction (i.e., the point next to the target object) that tends to replace the target color in memory, thereby luring responses to it, and a retro-cue protects from this interference. This finding is consistent with the protection from visual interference hypothesis. On the other hand, we also observed reductions in other types of errors besides wheel attraction that contributed to the retro-cue benefit (reductions in nontarget recalls and, to a smaller extent, of guessing). These effects leave room for additional mechanisms contributing to the delay benefit over and above visual interference. One such mechanism is a Head Start for retrieval. Experiments 4 and 5 aimed to disentangle the effects of (protection from) visual interference and of providing a Head Start for retrieval by selectively delaying response execution (E4) or response selection and execution (E5) while holding visual interference constant (see Figure 1).

Experiments 4 and 5

E3 showed that protection from visual interference at tests contributes to the retro-cue benefit in a continuous-reproduction task, and leaves open the possibility of an additional contribution from retrieval Head Start. Our goal in E4 and E5 was to determine whether retrieval Head Start does contribute to the retro-cue benefit in this task independently of protection from visual interference. To attain this goal, in E4 and E5 the color wheel was present throughout the trial, so that the retro-cue does not delay the onset of color-wheel interference (see Figure 3b and 3c). Therefore, the retro-cue cannot enable participants to protect the cued object from color interference before that interference occurs. In E4, we manipulated the delay between the location cue and a response signal indicating that a response could be entered. Hence, the delay conditions in this experiment are akin to the Delay Execution condition of E1 in that they only delay execution of the physical response. In E5 the wheel was kept onscreen throughout the trial except during the delay between the location cue and the response signal. Our reasoning was that removing the wheel during the delay prevents participants from selecting a response during this period, but arguably does not reduce color-wheel interference: In all conditions the color wheel was present during the entire retention interval up to the onset of the location cue, during which it could interfere with the memory representations. Note that in E5, removal of the wheel from the screen during the delay actually yields a larger visual change than in the 0-s Delay condition and hence, from a pure visual-interference standpoint, one could expect lower (or at least not better) performance in the delay conditions than in the no-delay condition. This is the opposite of what is predicted by the retrieval Head Start hypothesis: The delay conditions in E5 are akin to the Delay Selection condition in E2 in that they delay response selection and execution while holding color interference constant. The head-start hypothesis implies that this condition should improve memory performance by enabling more complete retrieval before response selection commences (as outlined in Figure 1).

To foreshadow our results, delaying response execution in E4 did not yield a benefit, consistent with the results from E1. Delaying response selection in E5 yielded a benefit, but it did not reduce the amount of visual interference as indexed by the wheel-attraction effect, consistent with the results from E2. These results extend our previous findings with the recognition task by showing that retrieval Head Start contributes to the retro-cue benefit in a continuous-reproduction task even in the presence of color interference.

Method

E4: Delay response execution. This experiment ($n = 24$, see Table 1) was similar to E3 with the following exceptions. The color wheel (randomly rotated from trial to trial) was shown together with the memory array and remained onscreen until the end of the trial (see Figure 3b). At the end of the 1-s RI, the location cue (white circle frame and white central arrow) was shown, and after a delay (0, 0.25, 0.5, or 1 s), the mouse cursor (center of the screen) and a tone were presented indicating that a response could be made. Therefore, in this experiment, we forced participants to delay response execution until a response signal (mouse + tone) was presented. Each delay condition occurred in a separate block of trials (order counterbalanced across participants). There were 120 test trials and 10 practice trials per block.

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E5: Delay of response selection. This experiment ($n = 24$) was similar to E4 with the difference that during the delay period (0, 0.25, 0.5, or 1 s), the color wheel was removed from the screen (see Figure 3c), hence allowing retrieval of the target, but no response selection. When the wheel reappeared on the screen again, it was oriented in the same way as when it appeared for the first time during that trial (i.e., with the onset of the memory array).

The samples of participants in E4 and E5 were independent and nonoverlapping. Note that we have changed the delays in E4 and E5 because the values used in E3 had no visible effect on performance. Therefore we reduced the number of delay levels and inserted one further interval between 0 and 0.5 to give us the chance of observing a gradual increase in performance, in case there was one, over the first 500 ms following the cue.

Results and Discussion

Figures 5c and 5e show the average estimated *SD* parameter as a function of delay in E4 and E5. Figures 5d and 5f show the probabilities of correctly retrieving the target and of making one of three errors: nontarget recalls, guessing, and responding to wheel attraction.

Precision. Similarly to E3, there was no evidence that delay had an effect on precision in E4 or E5. The BANOVA model including Delay as a categorical predictor yielded a BF = 0.31 and 0.30 in E4 and E5, respectively, showing that the Null hypothesis should be preferred by a factor of about 3. Comparison of individual delays against each other always yielded BFs below 1.

Probability of target recall. The probability of correctly retrieving the target object did not vary as a function of delay in E4 (see Figure 5d), but ramped up with delay in E5 (see Figure 5f). The overall effect of delay in E4 yielded a BF = 0.16 (favoring the Null by a factor of about 6). Individual comparisons of conditions with *t* tests all yield BFs < 0.83, supporting the Null hypothesis. The evidence for an effect of delay in E5 was BF = 2.71. In E5, the comparison of the 0 s to the 0.25 s delay favored the Null (BF = 0.71), but comparison of the 0 s to the 0.5 s delay (BF = 10.37), and of the 0 s to the 1 s condition (BF = 4.11) yielded evidence supporting an improvement in the probability of recalling the target by inserting a delay.

Probabilities of errors. As shown in Figure 5d and 5f the probability of making errors by recalling a nontarget, guessing, or because of wheel attraction was not substantially modulated by delay in E4 and E5.

In E4, for nontarget, guessing, and wheel attraction the effect of delay yielded BFs of 0.10, 0.12, and 0.14, respectively, showing that the Null hypothesis should be preferred by a factor of at least 7. Likewise comparisons of individual delay conditions with each other always yielded BFs favoring the Null in E4 (largest BF = 0.42).

For E5, a similar pattern was observed: BFs of 0.13, 0.25, and 0.51 were obtained for an effect of delay on nontarget, guessing, and wheel attraction errors, respectively. Comparison of individual delay conditions against each other also favored the Null (largest BF = 0.75). In sum, the results of our analysis showed that there was not enough evidence to ascribe a benefit of delay to reductions to any of the error categories of the mixture model in E4 or E5.

In summary, focusing attention on retrieving an object from VWM in the absence of the opportunity to select a response yielded a retro-cue benefit in E5 even in the presence of color interference, hence replicating the findings of E2 with a different paradigm. Furthermore, corroborating the results of E1, in E4 we observed that it is not sufficient to ask participants to delay response execution to obtain a retro-cue benefit, because the presence of the color wheel during the delay allows people to carry out response selection even when they have to withhold motor execution.

The retro-cue benefit in E5 was modest, and there was not enough evidence to ascribe it to any particular error component. This benefit came about even though the delay did not reduce the color-wheel attraction effect. Note that there were a substantial proportion of responses to wheel attraction both in E4 and E5, and that the estimates of color-wheel attraction were similar to the one obtained in the 0-s Delay condition in E3. Hence, presentation of the color wheel during the maintenance phase was sufficient to induce color wheel interference. Critically, removal of the wheel during the delay in E5 did not substantially reduce this tendency. For example, in E5, the BF for the effect of Delay on the size of the wheel-attraction effect was 0.51, supporting the Null by a factor of 2. Comparison of each delay against the 0-s Delay showed again evidence supporting the Null: 0 versus 0.25 s, BF = .42; 0 versus 0.5 s, BF = 0.26; and 0 versus 1 s, BF = .39.

By holding all potentially interfering visual input constant across conditions, E4 and E5 served to isolate the contribution of other mechanisms to the delay benefit. One such mechanism could be a Head Start for retrieval before making a decision for a response. A small delay benefit was obtained when response selection and execution are delayed, as predicted from the retrieval head-start hypothesis. The finding that the wheel-attraction effect—a direct indicator of one form of visual interference—remained unaffected by the delay manipulations corroborates the assumption that visual interference was held constant in these experiments, and that the delay benefit observed in E5 came about independently of protection from color interference, at least as far as that interference is reflected in the wheel-attraction effect.

Experiment 6

In E3 to E5 we observed that color retrieval from VWM is susceptible to interference from the color wheel as indexed by the color-wheel attraction effect. This effect is reduced by a retro-cue if time is provided to protect the target from interference (as in E3). When color interference already occurred before the cue, a retro-cue benefit is still obtained, albeit to a much smaller degree, as long as retrieval can proceed ahead of response selection (as in E5). The Head Start for retrieval ensures that when participants start using the retrieved object to make a decision, retrieval is sufficiently advanced.

In our final experiment, we aimed at providing further support for the above conclusions. First, we wished to show that retro-cues protect from interference but also allow for a retrieval Head Start, with both processes independently contributing to the retro-cue benefit. So far, we only demonstrated retro-cue benefits in conditions in which color interference was high because of the use of a color wheel. However, it is important to know whether the focusing benefits yielded by a retrieval Head Start can be observed in

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conditions without color-wheel interference. Such a finding would underscore the importance of focused attention for enhancing retrieval from VWM even in conditions of low visual interference. Second, although the wheel attraction effect was consistently found in the previous experiments, so far we cannot rule out the possibility that selecting the color at this location is a guessing strategy. Evidence ruling out a guessing strategy would be an important validation of our measure of color interference, and to our contention that retro-cues protect memory from it.

In E6 we created two wheel conditions (Color and Gray) and two delay conditions (0 and 1 s). In the new Gray Wheel condition, the color wheel was hidden by a dark gray ribbon, thereby eliminating interference from the colors in the color wheel. In the Color Wheel condition, retro-cueing one object for 1 s allows focused attention to protect memory from color interference and for retrieval to start ahead of response selection. In the Gray Wheel condition, there was no color interference, so retro-cueing could not protect memory from it, but it could still provide a Head Start for retrieval, because retrieval could start ahead of response selection. Comparison of retro-cue benefits across these two conditions will allow us to estimate the degree to which retro-cue benefits are because of protection from color interference at test and from retrieval Head Start. Moreover, this manipulation allowed us to assess whether the wheel attraction effect is indeed because of color interference or because of a guessing strategy (i.e., clicking on the wheel at a point close to the probed location). If the latter is true, then similar levels of wheel attraction should be observed in both wheel conditions. In contrast, if the wheel attraction effect indeed reflects color interference, then we should observe it only in the 0-s Delay in the Color Wheel condition.

Method

In E6 ($n = 24$), participants completed a version of our continuous color reproduction task. We modified our basic paradigm in several ways. First, we wished to created conditions with and without color interference. We took inspiration from the study of van den Berg, Shin, Chou, George, and Ma (2012), in which participants were cued to reproduce the color of one object, and across two conditions, responses were entered either through a color wheel or through a scrolling bar. In the scrolling-bar method, participants initially saw one arbitrarily chosen color displayed at the probe location. They used left and right buttons to scroll through circular color space until the color displayed in the probe matched that of the color they had in mind. VWM performance was better in the scrolling condition than in the Color Wheel condition. Hence the findings of van den Berg et al. (2012) are consistent with our assumption that the presentation of the wheel significantly impairs retrieval. There was, however, a number of differences between the two conditions in terms of modus of response (using the mouse or buttons), and feedback (presentation of the color at the location of the target or not), besides the difference in terms of wheel presentation. Therefore, we decided to adapt the scrolling method in a way that makes the conditions with and without the color wheel equivalent in all other regards but the presence of color interference.

Accordingly, we created two wheel conditions: a Color Wheel condition (see Figure 3d) and a Gray Wheel condition (see Figure 3e). Color and Gray Wheel trials were similar; the only difference between them being that the true color wheel was hidden under a dark-gray ribbon in the Gray Wheel condition. As for the other experiments, in the beginning of the trial, an array of six colored dots was shown, followed by 1-s RI. Next, a central dark gray arrow was shown pointing to one of the objects in the array, and 0 or 1 s thereafter the test display appeared, consisting of the wheel (randomly rotated from trial to trial), mouse cursor, and a dark-gray probe dot (radius 1.16°). Participants had to move the mouse cursor to the wheel. When the cursor entered the wheel, the cursor was replaced by a white dot in the wheel, and the color at that wheel location was shown in the probe dot. Participants could then use the mouse to move the white dot through the wheel, and to see the corresponding wheel color being displayed in the probe dot. This procedure was the same in the Color and Gray Wheel conditions. When participants were satisfied with the color of the probe dot, they pressed the left mouse button to confirm their response.

Because presenting a colored probe in the location of the target could produce probe interference (Pinto et al., 2013), we also created two probe location conditions: in the *Target* condition, the probe was shown in the target location, and in the *Center* condition, the probe dot appeared in the center of the screen.

Participants completed two sessions, one with the Color Wheel and one with the Gray Wheel, in counterbalanced order. The delay durations (0 or 1 s) and the probe location (target or center) were fully crossed and varied across different blocks of trials (order also counterbalanced across participants) in each session. Participants completed 120 test trials and 5 practice trials per test block (480 trials per session).

Results

Because of experimenter error, four participants had missing data in several design cells and hence were excluded, leaving a final sample of 20 participants in E6. Figure 6 presents the average estimated parameters of the four-parameter mixture model in each condition of E6. For each measure, we ran linear Bayesian regression models having Wheel (Color or Gray), Delay (0 or 1 s), and Probe Location (center or target) as categorical fixed effects (predictors), and participant as random effect on the intercept and the slopes of the main effects of each predictor. To assess the evidence for interactions and main effect of our predictors, we compared models including or omitting these terms in a top-down fashion. First, we computed the BF of a full model including all main effects and interactions for our fixed effects, which was taken as the current best model. Next, we computed the BF for a reduced model omitting the three-way interaction term. By diving the BF of the current best model (in the current step the full model) over the BF of the reduced model one can gauge the evidence for the removed term: $BF < 1$ indicated that the reduced model explained the data better, and hence that the excluded term was not necessary to account for the data; $BF > 1$ indicated that removal of the term in the reduced model impaired its ability to account for the data, and hence the current best model was a better account of the data. If the current best model was inferior to the reduced model, the reduced model took the place of the current best model, and we moved on to remove the next term (e.g., one two-way interaction) from updated current best model. We successively assessed the evidence for each term in the model through this top-down

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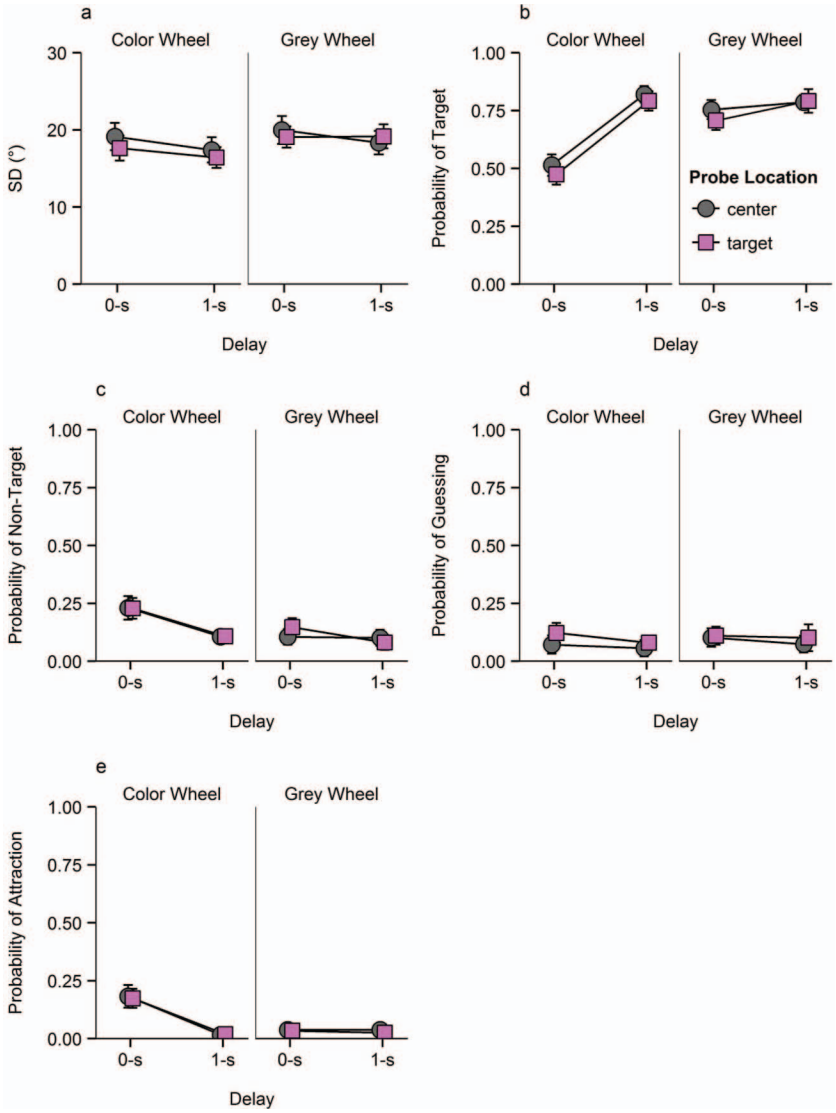

Figure 6. Mixture model results as a function of Delay, Probe Location, and Wheel condition in E6. Panel a: memory precision. Panel b: probability of recalling the target object. Panel c: probability of responding with a nontarget. Panel d: probability of guessing. Panel e: probability of responding to wheel attraction. Error bars depict 95% within-subjects confidence intervals (Cousineau, 2005). See the online article for the color version of this figure.

method. Table 2 shows the evidence for each predictor and interactions thereof. The order of terms shown in Table 2 is the one used in proceeding through the top-down sequence of model comparisons. BFs presented in bold indicate predictors necessary to account for the data, and hence indicate terms maintained in the best model at each step.

Precision. Figure 6a shows the *SD* across experimental conditions in E6. Overall, there was no evidence that precision varied across conditions. Table 2 shows the evidence for main effects and interactions in the data. In accordance with the visual inspection of Figure 6a, there was no evidence supporting an effect of either variable manipulated in the experiment.

Probability of target recall. As can be seen in Figures 6b, target recalls increased as a function of Delay in both Wheel conditions. Moreover, recall in the Gray Wheel conditions was better than in the Color Wheel condition. There was also an interaction between Delay and Wheel condition: The delay effect was larger in the Color Wheel condition than in the Gray Wheel condition, showing that retro-cue benefits were larger in the presence of color-wheel interference. The results of the Bayesian analysis confirm this pattern by showing large evidence for main effects of Delay and of Wheel condition, and for an interaction between them. Given the interaction, we assessed the amount of evidence for the delay benefit in the Gray Wheel condition, which was BF = 2.75, hence providing only weak support for a delay benefit in this condition. Lastly, Probe Location had no substantial impact on target recalls, and there was no evidence supporting interactions with this variable.

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Table 2
Bayes Factors Quantifying the Strength of Evidence for the Interactions and Main Effects of the Variables Manipulated in E6

Evidence for	*SD*	Target	Nontarget	Guessing	Attraction
Three-way interaction	.35	.47	.83	.39	.34
Wheel × Probe Location	.49	.27	.25	.38	.26
Delay × Probe Location	.43	.51	.51	.23	.23
Delay × Wheel	.29	**8.92**	**233.65**	.25	**6.58×10^{14}**
Probe location	.36	.81	.24	.67	.26
Wheel	1.71	**4,285**	**16.94**	.33	**1,740**
Delay	.80	**1.1×10^{6}**	**3,044**	.54	**3,595**

Note. Evidence was assessed in a top-down fashion by starting with a full model including all interactions and main effects of our manipulated variables, which was taken as the best model. Next, a reduced model was run without one of the terms of interest (starting with the three-way interaction and moving down as indicated in the left-most column). The Bayes factor (BF) of the current best model against the reduced model reflects the strength of evidence for the removed term: BF $<$ 1 favors the reduced model as the current best model; BF $>$ 1 favors the maintenance of the current best model. In the next step, another term was removed from the current best model, the evidence for this term was assessed by comparison of the reduced and current best model, and the current best model was updated accordingly. BFs presented in bold indicate terms that were maintained in the final best model.

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Probability of nontarget recall. As can be seen in Figures 6c, nontarget recalls decreased with Delay. There was a smaller proportion of nontarget recalls in the Gray Wheel condition than the Color Wheel condition. There was also an interaction between Delay and Wheel condition: The delay effect was larger in the Color Wheel than in the Gray Wheel condition. The results of the Bayesian analysis (see Table 2) confirm this pattern by showing strong evidence for main effects of Delay and Wheel condition, and for an interaction between them. In light of the interaction, we tested the evidence for an effect of delay in the Gray Wheel condition, BF = 2.76, which again only hints at an evidence for a benefit of delay. Probe Location had no substantial effect, and there was no evidence for interactions with this factor.

Probability of guessing. Figure 6d shows the estimated guessing proportion across conditions. Guessing was not substantially affected by any of the manipulations. As shown in Table 2, the evidence for each of the predictors always yielded BFs $<$ 1.

Wheel attraction. Figure 6e shows the probability of responses being attracted by the wheel. As shown in Table 2, there was evidence for a main effect of Delay and of Wheel, and for an interaction between these terms. This is because only in the 0-s Delay of the Color Wheel condition, a substantial proportion of responses were attracted by the wheel. Retro-cueing an object for 1 s reduced this tendency, and so did the use of a gray wheel. Probe Location had no impact on the attraction effect and did not interact with any of the other predictors.

Discussion

The results of E6 showed again that retro-cuing an object improves retrieval from VWM. In E6 we manipulated color interference and delay independently. Moreover, we also manipulated the location of a probe dot that served to display the candidate response color for the participants during response selection. There was no evidence that the location of the probe dot had an effect. Apparently, presenting a colored probe in the location of the target introduced no additional interference compared with a central colored probe.

More germane to our research question, in the Color Wheel condition we again observed a tendency to respond with the color in the wheel that happened to be spatially close to the target. Retro-cues reduced the tendency to fall prey to wheel attraction. There was no wheel-attraction effect in the Gray Wheel conditions, showing that responding to the wheel locations close to the target was not a guessing strategy adopted by participants, but indeed reflected color interference, or in other words, confusion of the color in memory with the color in the wheel in a spatially close location. These results corroborate the assumption that the color wheel creates interference, and part of the retro-cue benefit arises through protection of the target from this interference.

Retro-cuing an object also reduced the probability of recalling a nontarget color, suggesting that it does more than just protecting memory from color-wheel interference. The effect of a retro cue over and above protection from color interference can be directly observed in the Gray Wheel condition, which minimized color interference. In this condition we still observed a benefit of the retro cue (i.e., of delaying response selection after the location cue) on the probability of target recall and on the proportion of nontarget errors. The evidence in support of these effects (BF ~3) was only tentative in supporting a benefit. Therefore, these results are consistent with the retrieval Head Start hypothesis, but cannot unambiguously pinpoint a role of retrieval Head Start in enhancing VWM performance in the absence of visual interference. One reason for the weakness of the retro-cue benefit in the Gray Wheel condition could be that nothing prevented participants in the 0-s Delay of this condition from self-imposing a delay to enhance retrieval. Such a strategy would dilute any differences between the 0 and 1-s Delay conditions. We looked at reaction time (RT) to get a hint of how people paced themselves in the experiment: participants took almost twice as long to respond in the Gray Wheel conditions (M = 3.8 s) than in the Color Wheel conditions (M = 2.1 s), a difference that yielded a BF = 49′610. This finding is compatible with the hypothesis that taking more time to respond could be one of the factors that contributed to the higher performance of participants in the Gray versus Color Wheel conditions.

In summary, the results of E6 do not unambiguously support a role of retrieval Head Start independently of color interference, but they provide tentative evidence in favor of it.

Continuous Reproduction Task: Overview of Results Across Experiments

Across E3 to E6, we tested 87 individuals in a continuous color-reproduction task. Across these experiments, we manipulated whether the color wheel was presented together with the memory array (E4 and E5) or not (E3 and E6), and whether participants simply clicked on the wheel to indicate a color (E3, E4, or E5) or could adjust the color of a probe stimulus (E6). One may wonder how these manipulations impacted performance in our baseline (0-s Delay) condition. Inspection of Figures 5 and 6 indicates that baseline performance across experiments was remarkably similar: the mean *SD* was around 20°, and probability of recalling the target was around 0.5 (with exception of the Gray Wheel conditions), which is consistent with a WM capacity estimate of about three items (cf. Zhang & Luck, 2008). Moreover, estimates of nontarget recalls, guessing, and wheel attraction were again of similar magnitude across experiments.[2] This invariance shows that changing the response mode (from clicking to scrolling) does not impact performance. Perhaps more importantly, it shows that color wheel interference occurs with comparable strength whenever it is not preceded by the cue, regardless of whether the wheel is present already during encoding (E4 and E5) or only at test (E3). Even presenting the identical color wheel twice, once at encoding and once at test (E5), did not result in measurably more interference. This finding is consistent with the idea that estimates of VWM are relatively stable after onset of interference (Pinto et al., 2013; Sligte et al., 2008).

Across E3 to E6, however, there were substantial differences regarding how well people could make use of the delay to improve their VWM performance, particularly regarding the probability of recalling the target. Figure 7 shows a box-plot of the delay benefits in target recall probability across experiments. The data in this figure are plotted according to what processes we assumed to be postponed during the delay: only *Execution* of the response (E4), or execution + *Selection* of the response (E5 and Gray Wheel condition of E6), or both decision components + *Interference* (E3 and Color Wheel condition of E6). As shown in this figure, delay increased target-recall probability by 1% in E4, by about 5–6% in E5 and Gray Wheel condition of E6, and by 26–31% in E3 and the Color Wheel condition of E6. As this figure shows, the benefits of delaying response selection are modest compared with the benefits of postponing color interference. This figure clearly shows that more information is available from VWM than accessed under traditional testing conditions, and focused attention can be used to pull out this information. Although focusing benefits are larger when one can protect representations from visual interference, our results suggest that there is also a benefit yielded by providing enough time to retrieve a representation before making use of it for decision making.

General Discussion

The main goal of the current study was to test the predictions of two hypotheses about focusing benefits in VWM: the *protection from visual interference hypothesis*, stating that focusing attention protects the focused object in VWM against interference arising from subsequent visual input, and the *retrieval Head Start hypothesis*, which states that allocating time for retrieval before decision allows more information to be extracted from VWM.

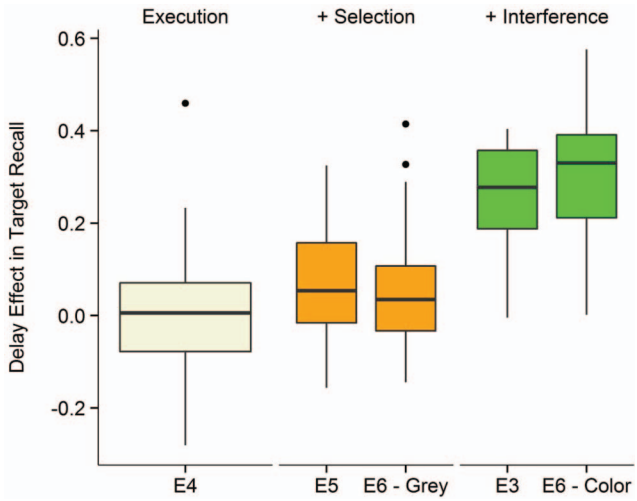

Figure 7. Box-plot of the size of the delay effect (1-s Delay condition – 0-s Delay condition) in the estimate of the probability of recalling the target across E3 to E6. Note that experiments were organized according to the processes that were (in an incremental fashion) postponed during the delay by design in each experiment. See the online article for the color version of this figure.

Evidence for Visual Interference

Several authors have proposed that attention protects the focused representation from interference (Makovski & Pertzov, 2015; Makovski et al., 2008; Matsukura et al., 2007; Sligte et al., 2008). This hypothesis has been tested mainly by presenting irrelevant stimuli during the RI (e.g., masks or secondary tasks). The impact of visual interference that is relevant to the task (such as interference produced during tests of VWM) and the protection thereof by retro-cues remained an uncharted area so far. In the present study we filled this gap by providing direct evidence that retro-cues protect color memory from color interference in both recognition and continuous reproduction.

In recognition, visual interference arises from the recognition probe. We demonstrated this effect by contrasting the standard Retro-Cue condition to the Response-Selection Delay condition. These conditions were equated in all respects except the timing of the probe: In the Retro-Cue condition, onset of the probe was delayed relative to the cue, together with response selection and execution. In the Response-Selection Delay condition the probe was presented at the same time as the retro-cue in the Retro-Cue condition, but response selection was postponed. Hence partici-

[2] We assessed evidence for performance differences in the 0-s Delay conditions in E3 to E6 with a between-subjects BANOVA. The evidence always favored the Null for any of the parameter of the mixture model (see online Supplemental Material for the BFs), whether we used encoding condition, response mode, or experiment as independent variables.

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pants could use the location of the probe as a cue to retrieve the memory object presented at that location but they could not avoid the interference yielded by the color of the probe. The resulting impairment of recognition in the comparison of these two conditions, therefore, can unambiguously be attributed to probe interference.

In a continuous-reproduction task, interference arose from the color wheel in the test display. We were able to measure the interference yielded by one aspect of the test display—the color wheel—directly: People tend to choose the color in the wheel that happened to be spatially closest to the target. This wheel-attraction effect can be explained as follows: At test, attention is directed to the target's location, from which it spreads to nearby locations, including nearby sections of the color wheel. As a consequence, nearby colors in the color wheel replace the target representation in VWM, or are confused with the target representation. This wheel-attraction effect disappeared when the onset of the color wheel was delayed relative to the onset of the cue, and when the color wheel was replaced by a gray wheel. We conclude that the wheel attraction effect is because of color interference, and that attention can be used to protect memory from this interference.

In the present study, we assumed that testing memory introduces interference because of the requirement to process stimuli at test that are similar to the items that participants have to maintain in memory. This assumption is substantiated by the findings, for example, of Pinto et al. (2013) which indicate that interference arises from objects that share the same features and locations as the memoranda. The impact of visual interference can also be detected in studies varying the amount of visual input presented at test. For example, in the study of Makovski et al. (2010) VWM performance was worse when testing memory with two probes (for a forced choice comparison) compared with presentation of one probe (for a match-mismatch decision). This is consistent with the idea that the requirement to attend to two colors instead of one increases interference and impairs VWM retrieval. Makovski et al. also compared performance in both task versions with and without a retro-cue, and already observed that retro-cue benefits were larger for the two-probe task. This is consistent with the idea that retro-cues protect from visual interference arising at test, as we have observed in the present series of experiments.

All in all, these results combined show that the information that we can keep as accessible in mind is prone to interference at several levels. On the one hand, there is interitem interference: representations in VWM compete for being represented and retrieved. On the other hand, there is perceptual interference, by which labile representations are distorted or replaced by perceptually available stimuli. Focused attention helps people to reduce interference both by protecting the focused representation from competition from other memory items (as implied by the observed reductions of nontarget recalls) and by shielding it against additional visual input (as implied by a reduction in the wheel attraction parameter).

Delay Effects and the Retrieval Head Start Hypothesis

Our experiments provided evidence that there is more to the focusing benefit than protection from color interference: Introducing a delay between a cue indicating the target object and the time at which a decision is made about that object enhances VWM performance even when color interference is held constant. To achieve this benefit it is not enough to force participants to delay response execution. Participants have to be prevented from using the retrieved representation to select a response for at least 0.5 s to fully benefit from the delay.

The benefits of inserting a delay were observed in a recognition task by comparing a standard No-Cue condition to a Response-Selection Delay condition: in both conditions a probe stimulus was shown at the end of the RI (hence equating these conditions in terms of probe interference), but whereas probe onset in the No-Cue condition allowed participants to start comparing the probe to the retrieved representation and selecting a response, in the Response-Selection Delay condition response selection was postponed for 1 s (see E2). Performance in the Response-Selection Delay condition improved compared to the No-Cue condition, showing a benefit of focusing the target over and above its protection from visual interference.

In a continuous-reproduction task, we observed that delaying the test by at least half a second while removing the color wheel from the screen to prevent response selection (E5) increased the probability of retrieving the target object. In this experiment the opportunity for interference from the color wheel was equated across all conditions: The wheel could interfere during the retention interval preceding the cue, and at test. Therefore, the benefits of the delay cannot be attributed to protection from color interference. If anything, in this experiment there was more potential for visual interference in the Delay conditions than in the 0-s Delay condition because in the Delay conditions the color wheel was reintroduced at test with a sudden onset, which arguably attracts attention to it. The color-wheel attraction effect was not reduced by the delay, confirming that the delay did not reduce color-wheel interference. The Head Start for retrieval hypothesis predicts that removing the opportunity to respond during retrieval (thereby delaying response selection) does confer a benefit, and this is what we observed in this experiment.

Moreover, in E6, we reduced color interference by using a gray wheel. Again, inserting a delay tended to improve retrieval from VWM. The residual retro-cue benefit in the Gray Wheel condition is consistent with a retrieval head-start hypothesis. When retrieval and response selection can be carried out concurrently, a less then optimal memory trace (possibly one that has not been retrieved to the fullest) may be used in selecting a response, leading to errors. Separating retrieval and response selection in time confers the necessary time for retrieval to be completed ahead of making a decision.

Can All Retro-Cue Benefits Be Explained by Interference?

One may wonder whether we need a Head Start for retrieval hypothesis to account for the present data, or whether protection from interference may be a sufficient (and perhaps more parsimonious) explanation of all the retro-cue benefits we observed. This is a possibility that we cannot entirely rule out, but we find it unattractive, because an explanation of all the delay benefits observed across our six experiments requires several implausible assumptions.

First, we would have to explain the benefit of delaying response selection—but not the onset of the probe—in the Delay Selection

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condition of E2. One possibility is that the presentation of the printed question ("identical?" or "different?") contributes to visual interference with VWM, so that delaying it yields a benefit for recognition. This explanation requires the assumption that white letters interfere with color representations in VWM. This possibility is not supported by our data. If presenting the question "identical?" or "different?" introduced additional interference, then performance in the No-Cue condition of E1 should be better than in the No-Cue condition of E2. Inspection of Figure 2c shows that, if anything, recognition accuracy was numerically larger in the No-Cue condition of E2. The BF for the between-subjects comparison was 0.4, hence supporting the Null.

Second, we would have to explain the delay benefit in E5, where the potentially interfering visual input was the same in all delay conditions: The color wheel was present during encoding, during the precue retention interval, and during test (see Figure 3c). The only difference between the 0-Delay condition and the conditions with a postcue delay consisted in the insertion of a blank-screen interval between cue and test in the latter. Temporarily removing the color wheel during the postcue delay produced a larger visual change in the delay conditions, and hence had a larger potential to induce interference, than in the 0-s Delay condition (in which the wheel never left the screen). It is unclear how removal of the wheel could reduce color interference. Unsurprisingly, we did not observe a reduction of the color interference effect indexed by the wheel attraction parameter of the mixture model as a function of delay. Nevertheless, a delay improved performance.

Third, in the Gray Wheel condition of E6 we removed the colors from the wheel, which eliminated the wheel-attraction effect and resulted in a substantial improvement of VWM performance. Arguably, the Gray Wheel condition still involved some visual input, including the color in the probe dot. It is possible that the small delay benefit in the Gray Wheel condition reflects protection from interference from that input. If the color in the probe dot created visual interference, however, we should expect interference to be larger when it appears in the location of the target than when it appears centrally, and no such difference was observed.

In summary, it would be possible to explain all the delay benefits in our experiments by protection from visual interference, but such an explanation would require additional assumptions that make it less parsimonious than a combination of two mechanisms, protection from visual interference and a Head Start for retrieval.

Finally, we believe that the Head Start for retrieval hypothesis is plausible in the context of accumulator models of memory-based decision making, such as the diffusion model. Although little work has been done on how information is retrieved and used for decisions in VWM tasks, some recent studies point to the plausibility of using such a model to understand decision making in VWM tasks as well. For example, Pearson, Raskevicius, Bays, Pertzov, and Husain (2014) examined the dynamics of retrieval in tasks assessing VWM with a sequential-sampling model that assumes gradual accumulation of evidence from memory over time (see also Donkin, Nosofsky, Gold, & Shiffrin, 2013). So far, applications of evidence-accumulation models to VWM have blended target retrieval and decision making into a single process, tacitly assuming that information accruing from memory is immediately fed forward into the decision process. Such a continuous flow of information from memory to decision is arguably nonoptimal when target information is retrieved from VWM only gradually, so that the initial input from memory is very noisy. It might be more advantageous to delay the onset of decision until a sufficiently clear and accurate representation of the target has been retrieved from memory. To the extent that retrieval and decision processes are not sufficiently separated in standard VWM testing conditions, imposing such a separation externally could improve performance.

Other Explanations of the Retro-Cue Benefit

In the present article we tested two hypotheses of retro-cue benefits. However, there are other hypotheses aiming at explaining this benefit in the literature. For example, there has been some evidence that retro-cues free VWM capacity by allowing removal of the noncued objects (Kuo, Stokes, & Nobre, 2012; Souza, Rerko, & Oberauer, 2014; Williams, Hong, Kang, Carlisle, & Woodman, 2013). There is also evidence that focusing attention on an object in a location strengthens the bindings between that object and its location (Rerko & Oberauer, 2013; Souza, Rerko, & Oberauer, 2015). Our findings are not inconsistent with these hypotheses.

The *protection from visual interference* and the *binding strengthening* hypotheses fit together well: Strengthening the bindings of the cued object to its location could protect that object from interference. The strengthening effect of focusing on object-location bindings outlasts the time during which an object is focused, so that bindings remain strengthened while the focus of attention moves elsewhere, and bindings are strengthened in a cumulative fashion when the focus returns to an object several times. This assumption has been supported by the finding that cueing an object multiple times leads to better recognition (Rerko & Oberauer, 2013) and less error in reproducing it from memory (Souza et al., 2015) compared with cueing it only once. At present it is unclear whether the cumulative benefit of multiple cueing arises from cumulative protection of an object against visual interference—such that focusing an object twice protects it better from interference than focusing it once. Alternatively, the cumulative benefit of multiple cueing could arise through another effect of focusing.

The *retrieval Head Start* hypothesis meshes well with the *removal* hypothesis. Retrieval requires selection of the target over other objects in VWM (i.e., using the target representation and not a nontarget for determining the response), and this selection could be facilitated by (partial or complete) removal of nontarget representations. Supporting this idea, in at least two experiments we found evidence that the delay reduced the probability of erroneously retrieving nontargets (E3 and E6), whereas only one experiment showed evidence for a reduction in guessing (E3).

However, a retrieval Head Start is not the same as removal of nontargets: Memory performance could benefit from a longer retrieval time during which evidence from the target accumulates even if nontargets remain in VWM unchanged. One difference between the retrieval head-start hypothesis and the removal hypothesis is that a retrieval Head Start is beneficial only for the just retrieved object. The retrieval Head Start hypothesis, therefore, cannot explain the beneficial effect of a retro-cue in conditions where the cued object is not immediately tested after being cued.

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For instance, Rerko et al. (2014) cued object A, then tested object B, followed by testing object A, and showed a retro-cue benefit for A. This effect cannot be explained by a Head Start for retrieval of A, but it can be explained by (partial) removal of other objects, or by strengthening of the bindings of A to its location. A Head Start for retrieval also cannot explain the retro-cue effects in the experiments of Souza et al. (2014), who asked people to remember two arrays presented one after the other. In between the two arrays, one object in the first array could be retro-cued. A retro-cue benefit was observed for that object even though encoding of a second array, and in one experiment even testing an object in the second array, intervened between the retro cue and the test of the target in the first array. Retro-cueing an object in the first array even helped memory for the second array, as predicted from the assumption that noncued objects in the first array were removed from VWM. Future studies should aim to distinguish between the retrieval head-start hypothesis and the removal hypothesis to assess what is the contribution of bringing one object to the focus of attention (or retrieving it) versus getting rid of noncued objects from VWM.

Do Retro-Cues Improve Memory Precision?

In all experiments reported in the current article, retro-cue benefits were found in estimates of the probability of retrieving the target from VWM, whereas estimates of precision were unaffected by our focusing manipulation (all BFs favored the Null). This finding meshes well with previous studies reporting that retro-cues make items accessible that will be otherwise lost to VWM (Murray et al., 2013; Souza, Rerko, Lin et al., 2014). Some studies, however, have observed that retro-cueing an item also improves memory precision (Gunseli, van Moorselaar, Meeter, & Olivers, 2015; van Moorselaar et al., 2015; Williams et al., 2013). At present, it is not clear why some studies do find effects on precision whereas others do not.

One striking difference between studies that did and studies that did not observe retro-cue benefits on precision is memory set size: Improvements in precision are usually observed for smaller arrays ($n \leq 4$), but not for larger ($n \geq 6$). In a recent study, Souza (2015) tested young and old adults in a retro-cue paradigm embedded in a continuous-reproduction task. Retro-cues improved overall performance for both young and old adults with set sizes of 3 and 5 items, but the retro-cue effect on estimates of memory precision was more reliable with small than with larger set sizes. One reason why this may be the case is because parameters in the mixture model tend to trade off against each other, leading to unreliable estimation at low levels of performance (i.e., low memory precision, high guessing, or both; Lawrence, 2010).

Further Implications for the Study of VWM

The present experiments show that color information displayed at test interferes with VWM for colors. We isolated one source of visual interference—the color wheel attraction effect. Incorporating this component to the well-established mixture model (Bays et al., 2009; Zhang & Luck, 2008) enabled us to estimate the probability that responses were "lured" by the color wheel. Because the color wheel is usually rotated from trial to trial, responses that are lured by the wheel will be uniformly distributed in relation to the target color, and hence will be captured by the guessing parameter in the traditional mixture model. The proportion of guessing responses has been used to inform debates about VWM capacity (discrete-capacity or slot models vs. continuous resource models). Our study shows that the proportion of guessing responses can be overestimated when VWM is tested with a color wheel.

More generally, our study shows that VWM capacity is limited by interference, not only between items in memory but also from additional visual input. In the presence of visual interference, estimates of VWM capacity underestimate how much information can be maintained in VWM. When visual interference is reduced, either by minimizing interfering stimuli at test (e.g., by using a gray wheel) or by directing attention to the target before the onset of interfering stimuli, a more accurate assessment of VWM can be obtained.

Conclusion

Across six experiments, we have shown that focusing attention on the relevant representation for the test improves retrieval from VWM in both recognition and reproduction tasks. This benefit occurred whenever a delay was inserted that allowed retrieval to proceed for at least 0.5 s in the absence of the opportunity to select a response. Focusing attention on one object also protected this representation from interference from the stimuli used in testing memory. Our findings therefore underscore the power of guiding attention to the relevant representation before test as a means of getting the most out of VWM.

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