Probabilistic retro-cues do not determine state in visual working memory

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Abstract

The effective use of our capacity-limited visual working memory (VWM) requires mechanisms that govern how it represents information. Validly cueing an item in VWM after encoding, for instance, enhances memory performance for that item and biases its state in VWM, bringing its representation to an active state such that attentional selection is biased towards perceptually similar inputs. Critically, when the retro-cue is less than 100% valid (i.e., probabilistic rather than deterministic), the effect of the cue on memory performance varies. Here we investigated whether deterministic and probabilistic retro-cues also differ in their influence over item state in VWM. Participants encoded two colored squares, and a retro-cue indicated which item was most likely to be probed in a subsequent memory test. Across blocks, we manipulated cue validity to be deterministic (100% valid) or probabilistic (70% valid). On a subset of trials, no memory probe was presented and the trial ended with a visual search task in which a colored distractor – matching the cued memory item, the non-cued item, or neither – was presented. Predictably, in the deterministic condition, the presence of a singleton distractor matching the cued item reliably slowed reaction times during visual search. In the probabilistic condition, however, there were no differences in reaction times when the singleton matched the cued item or the non-cued item, despite a reliable benefit to memory performance on valid memory trials. We suggest that, while probabilistic retro-cues improve memory of the cued item, they are not sufficient to bias its state in VWM.

Keywords Visual working memory · Visual search · Attention

Visual working memory (VWM) – our “online” storage system for visual information – is highly capacity limited. As such, a number of attentional mechanisms exist that control what, and how, information is stored in memory, to ensure that the most useful information is available to guide subsequent behavior. For example, an important representation in VWM can be reinforced by retroactively cueing it (i.e., pointing to the location in which it previously appeared) during the retention interval of a VWM task (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003). By indicating which item in memory is most likely to be probed in the upcoming memory test, such retro cues can enhance recall of the cued item. Moreover, the effect of retro-cues varies with perceived cue reliability when retro-cues are probabilistic in nature:

Retro-cues that indicate which item in memory will be tested with 80% validity, for instance, have a greater effect on recall than those that indicate the to-be-tested item with 50% validity (Gunseli, van Moorselaar, Meeter, & Olivers, 2015). Thus, the effect of retro cues on recall varies with their *reliability*, and deterministic (i.e., 100% valid) and probabilistic retro-cues differ with respect to their effects on memory performance.

In addition to enhancing recall, retro-cues – specifically deterministic retro-cues – have also been shown to alter the state of item representations in VWM, making the cued representation “active” (Olivers, Meijer, & Theeuwes, 2006; van Moorselaar, Theeuwes, & Olivers, 2014). Given that deterministic and probabilistic retro cues have variable effects on VWM recall, here we seek to determine whether probabilistic and deterministic retro-cues also differ in their influence over item state in VWM.

According to the dual-state model (Olivers, Peters, Houtkamp, & Roelfsema, 2011), items in VWM are represented in either of two functionally different states, and the state of a representation determines how it will guide behavior. This model draws from visual search studies: While searching for a

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particular object in the environment, we often maintain the identity of our search target in VWM (Carlisle, Arita, Pardo, & Woodman, 2011; Woodman & Arita, 2011; Woodman, Carlisle, & Reinhart, 2013). This representation, known as the attentional template, interacts with attentional selection to provide a competitive advantage to perceptual inputs sharing its features (Desimone & Duncan, 1995; Duncan & Humphreys, 1989). The dual-state model (Olivers et al., 2011) was proposed to account for the observation that the attentional template can guide selection, while other items concurrently stored in VWM do not (Houtkamp & Roelfsema, 2009; Judith C. Peters, Goebel, & Roelfsema, 2009). According to this model, at most one item in memory can be represented in an *active* state and will consequently bias attention towards perceptually similar inputs; all other items are represented in an *accessory* state and are shielded from perceptual inputs, preventing them from biasing selection.

Some of the evidence supporting the dual-state model has come from studies using deterministic retro-cues to manipulate whether items are represented in an active or an accessory state. Olivers et al. (2006, Experiment 6), for instance, instructed participants to remember the colors of two sequentially presented circles for a later memory test. One of these two circles was then retroactively cued, indicating with 100% validity that it would be tested at the end of the trial. A visual search task intervening in the memory test required participants to locate a shape singleton presented among distractors, one of which was an additional singleton that carried a color that was related to the cued item in memory, related to the non-cued item in memory, or unrelated to either memory item. Reaction times to locate the target were significantly longer when the singleton distractor was related to the cued item in memory than when it was related to the non-cued item or unrelated to either, suggesting that only the cued representation was maintained in a state that actively biased attention. In a follow-up study, van Moorselaar et al. (2014, Experiment 4) confirmed that non-cued items did not capture attention by virtue of being represented in an accessory state, rather than because they were removed from memory, by testing both memory items (the retro-cue indicated which item would be tested first). Thus, deterministic retro-cues that identify a memory item as being more immediately relevant also determine the representational fate of all items in VWM: The cued item occupies the active position, while the non-cued item is held as accessory.

Do probabilistic retro-cues exert the same influence over item state in VWM? It is tempting to assume that their influence is the same; however, probabilistic and deterministic retro-cues *do not* exert the same influence over recall performance in VWM tests. In an experiment that focused on the costs of invalid retro-cues in a probabilistic design, Gunseli et al. (2015) manipulated the reliability of a retro-cue across

two different conditions: 80% and 50%. The retro-cue benefited performance on valid trials in both conditions; however, a cost on invalid trials was only observed with a highly reliable cue (i.e., when there was a low probability the non-cued item would be tested). The authors reasoned that observers adjusted the mechanisms underlying the retro-cue effect in response to perceived cue reliability, suggesting that retro-cue reliability plays an important role in *how* the cues are utilized, and how they affect recall performance. If the mechanisms that underlie the retro-cue effect are, indeed, flexible, it is reasonable to question whether a probabilistic retro-cue would have the same influence over item state in VWM as a deterministic retro-cue.

Here we directly compare the effects of deterministic and probabilistic retro-cues on the state of items in VWM. We use a paradigm modeled after Hollingworth and Hwang (2013), in which participants complete a visual search during the retention interval of a retro-cue VWM task. However, we adjusted this task such that trials end *either* in a visual search *or* a VWM recall probe, as in Kiyonaga, Egner, and Soto (2012), in order to reduce the motivation to re-sample the cued item when it appears as a distractor during search (known as *perceptual resampling*; Woodman & Luck, 2007). To preview our results, we find that, although probabilistic retro-cues influence subsequent recall in our memory task, we show no differences in reaction times on the search task when a color singleton in the search array matches the cued versus the non-cued memory item. In contrast, we provide evidence that, following a deterministic retro-cue, reaction times are significantly lengthened when the singleton matches the color of the cued item relative to when it matches the color of the non-cued item. Thus, we conclude that probabilistic retro-cues are insufficient to determine the state of representation in VWM.

Methods

Participants

Thirty-five undergraduate students from the University of Guelph between the ages of 18 and 23 years ($M = 19.29$) participated for partial course credit. All participants reported having normal or corrected-to-normal vision and no color blindness.

Stimuli and apparatus

Experimental stimuli were viewed on a $1,280 \times 1,024$ CRT monitor using a 75-Hz refresh rate with black background (3.2 cd/m^2), and responses were made via a standard keyboard. Participants sat in a dimly lit room, and viewing distance was fixed at 57 cm using a head and chin rest. The colors of the memory items on each trial were randomly selected from a

360° color wheel (created in CIELAB color space such that experimental stimuli were isoluminant at 47.5 cd/m²; as used in Dube, Emrich, & Al-Aidroos, 2017) with the constraint that they were separated by a minimum of 50° on the wheel. Search stimuli were white Landolt squares.

Procedure

Each trial began with the 360-ms presentation of a memory array comprising two squares (1.2° in width and height) placed randomly in two of eight possible positions equally spaced around an invisible circle with a 5.5° diameter, all centered on a central fixation point with 0.07° radius (see Fig. 1). After the removal of the array and a delay of 400 ms, a line cue extended from fixation and pointed to the location previously occupied by one of the memory items, retroactively indicating it to be the most important item on that trial. This retro-cue remained on-screen for 200 ms and, following another 400-ms delay, the trial ended in one of two ways: a memory test or a visual search. We used memory trials to assess the retro cue effect on memory retrieval, and visual search trials to assess its effect on memory state – the division of these trials removed the motivation to resample the color on search trials (Woodman & Luck, 2007). On memory trials (55% of trials), the items presented in the initial memory array were re-drawn to the screen, but only one was colored in. Its color was either the same as at initial presentation (50% of memory trials) or it differed by 30° on the color wheel, and participants were instructed to use their left hand on the keyboard to press the letter “s” to indicate that it was the same, or “d” to indicate that it was different. On search trials, eight Landolt squares (0.44° in width and height) were drawn to the screen, spaced equally around fixation with the same eccentricity as the memory array. Search distractors were presented with the gap on either the top or the bottom of the square, and participants searched for a single target with the gap on the left or right side. Participants were instructed to use their right hand on the keyboard to press the right arrow key if the gap appeared on the right, or the left arrow key if the gap appeared on the left, as quickly as possible. On each search trial, one of the search distractors (chosen randomly) was uniquely colored. On a third of search trials, the color of the singleton matched that of the cued memory item (match cued), on another third the singleton color matched that of the non-cued memory item (match non-cued), and on the remaining trials the color of the singleton did not match either item in memory (novel).

Participants completed six blocks of trials (95 trials per block: 50 memory and 45 search in each), across which we alternated between two cue validity conditions: 70% and 100%. Participants were explicitly told at the beginning of the experiment that the validity conditions would alternate, and an instruction screen at the beginning of each block

reminded them of their current condition. Cue validity was described as *how often* the cue would correctly predict the tested item (i.e., seven out of ten trials will probe the cued item vs. *all* trials will probe the cued item). In blocks with 70% cue validity, the retro-cue validly cued the to-be-tested memory item 35 of the 50 memory trials, whereas blocks with 100% cue validity correctly indicated the to-be-tested item on all 50 memory trials. Cue validity of the initial block of trials was pseudo-counterbalanced across participants. In total, participants completed 545 experimental trials: 300 memory and 245 search, randomly intermixed.

Results

We removed participants with a greater than 50% error rate on either the memory test or the search task, resulting in the removal of five participants from the data set and a final sample of 30 participants.

Memory test

In probabilistic (i.e., 70% valid) retro-cue blocks, mean change detection accuracy was statistically significantly higher in the valid cue condition (68.5%) than in the invalid condition (64.73%), $t(30) = -2.53$, $p = .017$, suggesting that participants effectively used the cue to prioritize the relevant item for retention. Mean change detection accuracy did not differ between the valid probabilistic retro-cue condition and the deterministic retro-cue condition (69.53%), $t(30) = .869$, $p = .392$. Thus, although participants used the cue to effectively prioritize the cued item, there was no statistically detectable difference in performance when the valid cue was 70% versus 100% reliable (see Fig. 2).

Search task

Reaction times For each participant, reaction times in each condition were trimmed to 2.5 standard deviations, resulting in the loss of, on average, 7% of trials. We subjected reaction times on correct trials to a 3 (Singleton Condition: Match Cued, Match Non-Cued, Novel) $\times$ 2 (Cue validity: 70%, 100%) within-subject ANOVA, yielding no significant main effect of singleton condition or cue validity, $F(2,58) = 1.206$, $p = .307$, and, $F(1,29) = 2.42$, $p = .131$, respectively, and a significant interaction, $F(2,58) = 3.677$, $p = .031$ (see Fig. 3). Looking at probabilistic (i.e., 70% valid) retro-cue conditions only, we again observed no effect of singleton condition on search reaction times, $F(2,58) = .517$, $p = .599$, suggesting that, with a probabilistic retro-cue, there are no differences in attentional capture between any of the singleton conditions. Looking, however, at deterministic (i.e., 100% valid) retro-cue conditions only, we observed a reliable effect of singleton

Fig. 1 Example trial sequence. Example memory test shows a no-change trial, and example visual search task shows a match-cued singleton distractor. Actual background color was black

condition on search reaction times, $F(2,58) = 3.977$, $p = .024$, $\eta_p^2 = .121$. Further paired samples t-tests revealed statistically significantly longer reaction times in the match cued singleton condition relative to both the match non-cued condition, $t(29) = 2.484$, $p = .019$, and the novel singleton condition, $t(29) = 2.400$, $p = .023$. Reaction times in the match non-cued and novel conditions did not differ significantly, $t(33) = -0.35$, $p = .73$. Thus, when a retro-cue is probabilistic, although observers effectively use it to prioritize the cued item for retention, the cue does not determine which VWM representation will interact with selection during a subsequent visual search task. When a retro-cue is deterministic, however, search times are significantly lengthened when a singleton is present in the display that matches the cued item, suggesting that deterministic retro-cues do cause the cued item to be maintained in an active state that interacts with selection during visual search.

Fig. 2 Change detection accuracy across experimental conditions. Error bars in this figure are adjusted within-subject standard error (Morey, 2008)

Accuracy See Table 1 for a full list of accuracies. Overall, target discrimination accuracy was high ($M = 90.6\%$). To assess the contribution of speed-accuracy trade-offs to the observed reaction times, we subjected target discrimination accuracy scores to a 3 (Singleton Condition: Match Cued, Match Non-Cued, Novel) $\times$ 2 (Cue Reliability: 70%, 100%) repeated-measures ANOVA. Results revealed a significant main effect of singleton condition, $F(2,58) = 4.138$, $p = .021$, but no main effect of cue reliability and no significant interaction, $F(1,29) = .160$, $p = .692$, and $F(2,58) = .628$, $p = .537$, respectively. To directly compare accuracy scores in the critical conditions, we performed two separate paired samples t-tests comparing accuracies in the match cued and match non-cued conditions within each cue reliability condition (70% and 100%). There was no significant difference between accuracy scores in the match cued and match non-cued conditions when the cue was 70% reliable, $t(30) = -0.27$, $p = 0.79$,

Fig. 3 Search response times across experimental conditions. Error bars in this figure are adjusted within-subject standard error (Morey, 2008)

Table 1 Target detection accuracy across conditions (%)

	Match cued	Singleton conditions Match non-cued	Novel
70% Valid cue	90.04	89.75	91.90
100% Valid cue	89.18	90.25	91.61

nor when it was 100% reliable, $t(30) = 0.81$, $p = 0.42$. Thus, the critical differences in response times between the match cued and match non-cued conditions cannot be explained by related differences in target discrimination accuracy.

General discussion

Here we demonstrate an important functional difference between probabilistic and deterministic retro-cues. Despite both being an effective means of prioritizing an item in VWM to benefit a subsequent VWM task, only deterministic – *not* probabilistic – retro-cues bring the cued item into an active state. That is, probabilistic retro-cues are not sufficient to make a VWM representation active: With a probabilistic retro-cue, no memory-driven biases are observed during perception.

Evaluating an alternative to the dual-state model

Research suggests that intentionally classifying an item as “active” inherently grants it a special status in VWM that allows it to interact with perceptual representations (Olivers & Eimer, 2011; Peters, Roelfsema, & Goebel, 2012). Subsequent investigations of the dual-state model, however, have assessed an alternative theory: Namely, that greater importance placed on the “active” item causes it to be maintained with greater representational quality than the remaining items in VWM (Hollingworth & Hwang, 2013; van Moorselaar et al., 2014). By this account, the observed effects on attention are a byproduct of the quality of the representation in VWM rather than functionally different states. Hollingworth and Hwang (2013) directly tested this account by assessing the relationship between the quality of a VWM representation and its biasing affect over attention during visual search. They reported evidence in support of the dual-state account, demonstrating that a cued item may still exert a bias over attention despite being maintained with precision comparable to the other, non-cued item in memory. The results of the current experiment strengthen this conclusion: Here we provide evidence that a cued item may be better remembered but that this does not translate to an automatic biasing effect over attention. Simply prioritizing an item for a subsequent memory test using a probabilistic retro-cue will not bring that item

into an active state, despite enhancing memory performance for that item.

Though we agree with the conclusions of Hollingworth and Hwang it is worth mentioning that the retro-cue employed in their paradigm was, in fact, probabilistic in nature. They observed no evidence to suggest that the non-cued item in memory exerted any bias over attention, suggesting that it had effectively moved into an accessory position and that the remaining cued item in memory occupied the active position. They did not, however, include a condition to directly test the biasing effect of the cued item during search. The results of the current experiment suggest that a probabilistic retro-cue is not sufficient to move an item into an active state and, thus, it is not likely that they would have observed any bias towards a search item matching the cued memory representation during search. This is an important point for future work that intends to use retro-cues to intentionally characterize items in VWM.

Why is VWM state not automatically biased by a probabilistic retro-cue?

The results reported here highlight the influence of strategy on the fate of items in VWM. That is, simply reallocating attention within VWM is not sufficient to characterize an item’s representation – with more than one item in VWM, there is something inherently strategic about the active/accessory distinction. When one memory item is strongly prioritized (as was the case with a deterministic retro-cue signaling irrelevancy of the non-cued item in the current experiment), this may cause the observer to drop the remaining item(s) from VWM completely, resulting in only a single item occupying VWM – a circumstance that is conducive to its automatic classification as active. In this case, the classification of the cued representation as active is not a direct consequence of the cue, rather it is a direct consequence of that item being the only item represented in memory. Indeed, Gunseli et al. (2015) attributed enhanced costs of invalid cues at higher cue reliabilities to the likely removal of the non-cued item from memory. When the non-cued item in the memory array remains relevant to the task, however, additional control may be required to move the cued item into an active state, a move that bears no strategic advantage for the task. It is worth noting, however, that an aspect of our data makes this interpretation unlikely: If the non-cued item was removed from memory following a deterministic retro-cue, greater resources would be allocated to the cued representation in this condition relative to the probabilistic retro-cue condition (i.e., resources would not be divided among two representations). Here we observed no significant differences between memory performance on tests of the cued representations in the 70% and 100% conditions, suggesting that the same number of items are present in memory in both conditions. The mechanism by which deterministic retro-cues cause the cued representation to be classified as active is still

unknown, and more research is required in order to understand it. Despite this, the relevant behavioral effects of deterministic and, perhaps more importantly, probabilistic retro-cues are clear. While it cannot be determined whether probabilistic retro-cues can *never* influence the state of items in VWM (perhaps, for instance, probabilistically cueing a *target* for an upcoming visual search task would be sufficient for its activation), it is certainly not the case that probabilistic retro-cues signaling relative priority for recall are sufficient to bring the cued representation into an active state.

Conclusion

The results reported here define important limitations to the utility of probabilistic retro-cues in VWM tasks: Probabilistic retro-cues can improve memory retrieval without altering state. The implications of this finding are both practical and theoretical in nature: It highlights the importance of considering strategy when interpreting retro-cue effects and, perhaps more importantly, it supports the claim that item state in VWM is separable from its precision. That is, it is not simply an item's precision in memory that underlies its biasing effect over attention; rather, there is something deliberate and unique about the active distinction.

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