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Shifting attention among working memory representations: Testing cue type, awareness, and strategic control

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Abstract

It is well known that visual working memory (VWM) performance is modulated by attentional cues presented during encoding. Interestingly, retrospective cues presented after encoding, but prior to the test phase also improve performance. This improvement in performance is termed the retro-cue benefit. We investigated whether the retro-cue benefit is sensitive to cue type, whether participants were aware of their improvement in performance due to the retro-cue, and whether the effect was under strategic control. Experiment 1 compared the potential cueing benefits of abrupt onset retro-cues relying on bottom-up attention, number retro-cues relying on top-down attention, and arrow retro-cues, relying on a mixture of both. We found a significant retro-cue effect only for arrow retro-cues. In Experiment 2, we tested participants' awareness of their use of the informative retro-cue and found that they were aware of their improved performance. In Experiment 3, we asked whether participants have strategic control over the retro-cue. The retro-cue was difficult to ignore, suggesting that strategic control is low. The retro-cue effect appears to be within conscious awareness but not under full strategic control.

Keywords

Working memory; Retro-cue; Attention; Endogenous cue; Exogenous cue

Introduction

Attention generally improves performance. For example, information presented in attended spatial locations is processed more quickly and more accurately than information presented at unattended locations. A vast literature documents the effects of bottom-up (stimulus-driven) and top-down (goal-directed) cues on visual processing (e.g., reviewed in Posner & Petersen, 1990; Wolfe & Horowitz, 2004). The role of attentional selection in visual working memory (VWM) has typically been studied using precue paradigms in which a valid cue is presented before the stimulus array. For instance, Palmer showed that when participants were validly cued to attend to a subset of items in the array, VWM performance improved

because the effective set size was reduced (Palmer, 1990). Other precues, such as abruptly appearing items presented before the stimulus array, have been found to automatically shift spatial attention to the cued location and improve VWM performance when the cued item is tested (e.g., Schmidt, Vogel, Woodman, & Luck, 2002; Woodman, Vecera, & Luck, 2003).

Not only does attention improve perceptual attention, it also improves the selection process leading to VWM encoding. Cues presented concurrently with the sample display (rather than prior to test) can have a similar enhancing effect on VWM performance by allowing participants to select relevant information for encoding (Jiang, Olson, & Chun, 2000). Concurrent cues are less effective when the sample stimuli are presented sequentially and foveated. This indicates that selection mechanisms are linked to spatial selection (Olson, Moore, & Drowos, 2008; see also Hollingworth & Henderson, 2002; Williams, Henderson, & Zacks, 2005; but see Yotsumoto & Sekuler, 2006). In sum, these studies show that at the encoding stage, attentional selection, especially spatial selection, has a robust and predictable effect on VWM performance.

Since attention improves perception and facilitates entry into VWM, does attention also improve our ability to attend to items already in VWM? Recent findings indicate that the answer to this question is a clear “yes”. The paradigm used to investigate this is the retrospective, or retro-cue, paradigm. In the retro-cue paradigm, cues shift, or reorient, internal attention among the representations of items recently encoded in VWM but before a probe display (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003). The cues are spatial (e.g., arrows or pointers) and indicate the location of the previously encoded stimulus that will subsequently be probed. Importantly, the retro-cue effect occurs well outside the limits of iconic memory (.500 ms; Sperling, 1960). Valid retro-cues reliably improve memory accuracy by 5–10%. The retro-cue effect is robust, having been replicated across a range of timing parameters, stimuli, and set sizes (Dell’Acqua, Sessa, Toffanin, Luria, & Jolicoeur, 2010; Griffin & Nobre, 2003; Landman et al., 2003; Lepsien & Nobre, 2006, 2007; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura, Luck, & Vecera, 2007; Nobre, Griffin, & Rao, 2008; Nobre, Rao, & Chelazzi, 2006; Sligte, Scholte, & Lamme, 2008). However, one factor that has received little notice is the influence of cue type on the magnitude of the retro-cue effect.

Previous work demonstrates that both bottom-up and top-down attentional cues improve perception and facilitate entry into VWM. Is this flexibility special to perceptual attention or do bottom-up and top-down attentional effects exist among representations of items in VWM? In this context, the terms bottom-up (stimulus-driven) and top-down (goal-directed) are applied to the retro-cue. In other words, we investigated whether bottom-up and top-down retro-cues can redirect internal attention to representations of items in VWM. Retro-cue studies have tested single retro-cue types, typically arrows or line segment (Landman et al., 2003; Lepsien & Nobre, 2006, 2007; Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007; Nobre et al., 2008; Nobre et al., 2006; Sligte et al., 2008; for use of symbolic cues see Lepsien & Nobre, 2007); for use of a bottom-up cue see Experiment 2A in Makovski and Jiang (2007). Furthermore, arrow cues may be a special case since they are processed using both bottom-up and top-down attention (Hommel, Pratt, Colzato, & Godijn, 2001; Ranzini, Dehaene, Piazza, & Hubbard, 2009; Ristic & Kingstone, 2006). Arrow cues,

as a “hybrid” cue capitalizing on multiple attentional resources, may maximize the retro-cue benefit. In Experiment 1, we investigated whether the nature of the cue type—top-down, bottom-up, and hybrid—had an effect on the magnitude of the retro-cue benefit.

The second goal of this study was to assess conscious awareness of the retro-cue benefit and the strategic control over the retro-cue. There is reason to believe that the retro-cue may be explicitly conscious and under strategic control. Attentional cueing can occur without awareness (McCormick, 1997), although in other cases it is probably present, such as the classic Posner cueing paradigm (Posner, 1980). In the retro-cue paradigm, the magnitude of the retro-cue benefit is large, and the cue is unmasked. This points toward the prediction that participants should be aware of the retro-cue benefit. On the other hand, participants are not given information about the purpose of the retro-cues. There is no clear reason why a cue presented after encoding would be interpreted as task relevant. This perspective leads to the counter prediction that participants should not be aware of the retro-cue benefit.

The issue of strategic control is distinct from awareness; one can be aware of something yet unable to control reactions to it. We previously found that the degree to which control can be exerted over the contents of VWM depended on the ability to use spatial attention to select (and suppress) items for VWM (Olson et al., 2008). This finding predicts that the influence of attentional retro-cues on VWM will not be entirely under strategic control.

EXPERIMENT 1: IS THE RETRO-CUE BENEFIT DUE TO SHIFTS OF TOPDOWN AND/OR BOTTOM-UP ATTENTION?

In the small retro-cue literature, there has been no comparison of retro-cue magnitude as a function of retro-cue type. The purpose of Experiment 1 was to assess what type of attentional manipulation most effectively redirects internal attention in a retrocue paradigm. The present task used retro-cues that clearly relied on bottom-up or top-down attention. The top-down retro-cue was a digit that mapped onto the location of one item. The bottom-up cue was an abrupt onset cue appearing at the location of the cued item. The third cue type was the “hybrid” arrow cue, which may be processed by both bottom-up and top-down attention. Performance for each retro-cue was compared with an uninformative neutral cue control condition. We predicted that we would replicate the retro-cue effect on arrow retro-cued trials. Significant retro-cue effects from bottom-up and top-down cueing were also anticipated. The size of the retro-cue effect for each cue condition would indicate that the retro-cue effect depended primarily on top-down (number retro-cue), bottom-up (a dash serving as an abrupt onset retro-cue), or a mixture of top-down and bottom-up attention (arrow retro-cue).

Method

Participants—Twenty-five volunteers from Temple University psychology pool participated (ages 18–25 years, 4 male) in exchange for one course credit or for \$5 (their choice). The Internal Review Board of Temple University approved all experimental protocols. One participant was excluded for chance performance.

Equipment—In every experiment, participants were tested individually in a room with dimmed lighting. They sat approximately 57 cm from a 22'' computer monitor. The experiment was programmed in E-prime (Psychology Software Tools, PA, USA).

Stimuli—All stimuli and cues were presented on a uniform black background. The memory display consisted of four unique colour discs (3.8° diameter). Colours were chosen randomly from a pool of nine colours on each trial. Colour discs were displayed equidistantly (6.5°) from fixation in a square pattern. The cue screen consisted of one of the four possible cues. These cues were a neutral cue (“X”, 4° Å~ 4°), an arrow cue (4.5° Å~ 4°), a dash cue (white bar, 2° Å~ 0.7°), and a number cue (“1” upper left, “2” upper right, “3” lower left, “4” lower right, 2° Å~ 0.7°). The neutral, arrow, and number cues appeared at fixation; the dash cue appeared at the same location as the colour disc stimuli. The probe screen consisted of three empty annuli as placeholders that appeared in the same locations as the colour discs on the memory display, thus preserving the spatial arrangement of the memory display. The fourth space was always filled with a colour stimulus from the memory array.

Experimental design and trial sequence—Four randomly interleaved cue conditions were tested: neutral cue, arrow retro-cue, dash retro-cue, and number retro-cue. The arrow, dash, and number cues were 100% informative cues. The neutral cue, which consisted of 50% of all trials, was uninformative and served as a baseline condition. The choice of neutral cue was determined by a pilot study (N = 16 participants), in which a series of neutral cues were tested: dashes appearing simultaneously at each location, the number “9” at central fixation, four central arrows pointing to each location, and an X at central fixation. The first three neutral cues shared features with the valid cues, and the fourth cue did not. No significant differences in terms of performance accuracy were found between these cue types, $F(3, 45) = 1.71$, $p = .18$. As such, we decided to use the neutral cue, which shared no feature with the valid cue: the X symbol. Participants were instructed to remember the colour and location of each colour disc. No specific instructions were given regarding speed or accuracy. They were informed that the X cues were not informative but that the other cues would tell them which item would be probed. Each trial began with the presentation of a fixation cross for 200 ms followed by a memory display for 300 ms. This was followed by a 1,000-ms blank retention interval, then a cue screen for 100 ms, then a second delay period for 400 ms. This was followed by the probe screen (the experimental design is shown in Figure 1). The probe screen for all tasks and conditions preserved the spatial arrangement of the memory display by indicating stimulus locations with empty annuli as placeholders. At retrieval, one space was filled with a colour from the memory array. The task was to decide whether it matched the colour that had previously resided in that position. Participants responded by pressing the “Y” key if the colour–location conjunction matched that of the original memory display and by pressing the “N” key if it did not match. Responses were unspeeded. Trials were equally likely to match or mismatch (chance = 50%). Participants completed four 50-trial blocks separated by rest breaks.

Articulatory suppression—In all experiments, participants were instructed to repeat a three-letter word throughout the experiment to avoid verbal encoding of the colours. A

different word was specified at the beginning of each block. The participants were instructed to speak sufficiently loudly that the experimenter could hear them through the door.

Results and discussion—A repeated measures analysis of variance (ANOVA) evaluated the effect of cue condition (neutral, arrow, dash, number) on VWM raw accuracy. Data are depicted in Figure 2 and Table 1. There was a significant main effect of cue condition, $F(3, 69) = 8.97$, $p = .001$, driven by the significantly greater performance when the arrow served as the retro-cue than in the other cue conditions (all pairwise comparisons are Bonferroni corrected: neutral: $p = .002$; dash: $p = .012$; number: $p = .003$). There was no significant difference between the neutral and dash cues ($p = 1.0$), the neutral and number cues ($p = 1.0$), or the dash and number cues ($p = .27$). The same analysis was conducted using the d' values. The results were generally consistent with the raw accuracy data. There was a significant main effect of cue condition, $F(3, 69) = 5.76$, $p = .001$, driven by significantly greater discrimination when the arrow served as the retro-cue than for the neutral cue ($p = .007$) or the number cue ($p = .03$). Consistent with the accuracy data, the pairwise comparisons between the neutral, dash, and number cues did not reach statistical significance (all p s = 1). One difference was that there was no significant difference in the discrimination values between the arrow and the dash cues ($p = .10$).

Reaction time analyses also revealed a significant main effect of cue condition, $F(3, 69) = 59.73$, $p = .001$. Pairwise comparisons found significant pairwise differences between all conditions (all p s, $.005$). Participants were fastest when responding to the dash retro-cues and second fastest in responding to the neutral retro-cues. Responses to arrow and number retro-cues ranked third and fourth, respectively.

In sum, in Experiment 1 we investigated whether the retro-cue effect is largely dependent on top-down or bottom-up attention. We examined three behavioural measures of performance: raw accuracy, discrimination (d'), and reaction time. The raw accuracy and d' data revealed that the retro-cue effect was strongest on trials presenting the arrow retro-cue. These data suggest that the retro-cue benefit is sensitive to the attentional nature of the cue itself. The reaction time data shade these findings by demonstrating that the presence of the dash or neutral retro-cues was faster than the response to the arrow retro-cue.

There was some concern that the dash retro-cue's appearance at the same location as the stimulus might have produced masking. However, the retro-cue appears 1,000 ms after the offset of the stimulus array. The forward masking literature suggests that masking effects are greatest within 100 ms and fall off quickly thereafter (reviewed in Breitmeyer & Ganz, 1976). Backward masking might also raise concerns in the dash retro-cue condition since the dash and the subsequent probe occupy the same location. The backward masking literature suggests that visual recognition performance reaches 97% accuracy with temporal offsets between the stimulus and mask of only 40 ms (Rolls & Tovee, 1994). In the present study, the separation was 400 ms, making backward masking an unlikely explanation for the absent retro-cue effect under the dash retro-cue condition. Secondly, there was concern that the number retro-cue might not have been processed due to insufficient time. We previously found that healthy young adults can view, interpret a numerical digit, and make a verbal response at reaction times around 420 ms when digits 1–4 were possible answers (Berryhill,

Kveraga, Webb, & Hughes, 2005). Since the current task did not require a motor response within this window, we are confident that participants were able to interpret the meaning of the digit in the 400 ms after retro-cue presentation.

An additional concern was that inhibition of return might have inhibited the bottom-up retrocue effect by delaying the response to the cued location (reviewed in Dukewich, 2009). However, this possibility is minimized by the fact that inhibition of return is significantly reduced when cues are always valid (Wright & Richard, 2000), as in the current study.

EXPERIMENT 2: IS THERE CONSCIOUS AWARENESS OF THE RETRO-CUE BENEFIT?

In Experiment 1, the presence of an arrow retrocue improved participants' performance by 7% even though no additional information was provided to VWM. This kind of VWM performance improvement is striking, yet our introspective sense was that the retro-cue trials did not seem qualitatively easier. Furthermore, previous work suggests that use of an arrow cue does not require conscious awareness to influence behaviour (e.g., Bartolomeo, Decaix, & Sieroff, 2007). In the present experiments, participants were clearly conscious of the explicit retro-cues, but we were not sure if they were aware of the beneficial effect on their performance. In Experiment 2, we investigated this question by asking whether participants' were consciously aware that the arrow retro-cue was providing them with a performance boost. To assess this, participants provided confidence ratings after each trial. If participants were aware of the retro-cue benefit, we expected to observe significantly higher confidence ratings for trials with the arrow retro-cue. In contrast, if the participant ratings perceived the arrow retro-cue, but did not believe that the cue is improving their performance we expected to see no difference in confidence between the arrow and neutral retro-cues.

Method

Participants—A new group of 20 Temple University undergraduates (ages 20–26 years, 8 male) participated for course credit or \$5. An additional participant was excluded from analyses for chance performance across conditions.

Materials and trial sequence—The experimental procedure remained the same as above with two exceptions: (a) Only two cues were used: a valid arrow cue and a neutral cue; and (b) confidence ratings were collected after each trial. The arrow cue was selected because it was the only cue that successfully elicited a retro-cue effect. After participants made their unspeeded yes/no response, a new screen appeared. Participants were asked to make a button press response using numbers 1–6, where the number 1 indicated very low confidence, and the number 6 indicated complete confidence. There were four blocks of 50 trials each. In 5 participants, the experimenter accidentally ended the program early.

Results and discussion—Repeated measures ANOVAs evaluated how performance was modulated by cue condition (neutral, arrow); see Figure 3 and Table 1. As in Experiment 1, arrow retro-cues helped participants respond more accurately, $F(1, 19) = 63.43$, $p < .001$. The discrimination and reaction time (RT) data were consistent with the raw accuracy data;

arrow retro-cues improved performance discrimination and RT: d' , $F(1, 19) = 55.59$, $p < .001$; RT, $F(1, 19) = 10.22$, $p = .005$. There were no significant main effects of block (1–4) on performance accuracy or d' (p s $> .51$). However, reaction time performance improved in a significant linear fashion across block, $F(1, 14) = 35.70$, $p < .001$. There were no significant interactions between block and cue condition in accuracy, d' , or RT (all p s $> .15$).

Confidence ratings were analysed using a repeated measures ANOVA comparing factors of cue condition (neutral, arrow) and response accuracy (correct, error). Participants were more confident on trials answered correctly (M correct = 4.48, M error = 3.91), $F(1, 19) = 59.95$, $p < .001$. Of interest to the main question of Experiment 2 was the finding that participants had confidence ratings that were significantly higher in the arrow retrocue condition than in the neutral condition ($M_{\text{neutral}} = 3.53$, $M_{\text{arrow}} = 4.86$), $F(1, 19) = 73.41$, $p < .001$. This boost was apparent on both correct trials ($p < .001$) and incorrect trials ($p < .001$); as such, the interaction of retro-cue and accuracy was not significant ($F(1, 19) = 1.12$, $p = ns$). Confidence ratings also increased linearly as a function of block, $F(1, 14) = 12.39$, $p = .003$. These findings indicate that participants were sufficiently aware of the retro-cue benefit to feel more confident in their performance on the trials with an informative cue. Indeed, participants were more confident on arrow retro-cue trials even when they supplied an incorrect answer.

EXPERIMENT 3: IS THE RETRO-CUE BENEFIT UNDER STRATEGIC CONTROL?

In Experiment 2, participants were aware of their superior performance when they saw an informative retro-cue. However, even if subjects are aware of the performance benefit provided by the arrow retro-cue, it does not necessitate that the cue effects are fully under strategic control. We predicted that if the retro-cue effect were under strategic control, then participants would be able to follow directions to disregard arrow retro-cues. Consequently, performance would not be affected by the presence of invalid arrow retro-cues. If the retro-cue effect is not subject to strategic control, then participants will not be able to ignore arrow retro-cues. If participants cannot ignore the arrow retro-cues, performance will be impaired. Two experimental conditions were included to parametrically assess participants' degree of strategic control. In the ignore inaccurate condition, the arrow retro-cue was always inaccurate. We expected that if there were even a modest degree of strategic control, participants would be able to categorically ignore the arrow retro-cue. In the ignore mixed condition, the arrow retro-cue was occasionally accurate. If participants have incomplete strategic control over the attentional redirection prompted by the arrow retro-cue, performance will be affected by the arrow retro-cue.

Method

Participants—A group of 22 Temple students (ages 19–31 years, 5 male) participated. Two participants were excluded for chance performance.

Materials and trial sequence—The experimental procedures remained the same as those used in Experiment 2, with two changes. First, confidence ratings were not collected. Second, at the beginning of each block, participants were given written and verbal

instructions to attend or ignore the retro-cues. These instructions depended on the block condition: attend (arrow retro-cues were 100% accurate), ignore mixed (arrow retro-cues were accurate on 25% of the arrow retro-cue trials, equivalent to 12.5% of trials overall), and ignore inaccurate (arrow retro-cues were 0% accurate). For the attend block, participants were instructed that the arrow retro-cue was always accurate and that they should attend to the cue. For the ignore mixed and ignore inaccurate conditions, participants were instructed that the retro-cues would not be helpful because the cue was not always accurate and that they should ignore the arrow retro-cues. They were told that they might notice that the cues were occasionally accurate in some blocks of trials. There were one attend block, two ignore mixed blocks, and two ignore inaccurate blocks; the attend block was presented first, and the remaining blocks were pseudorandomly presented—the conditions could have followed each other, or they could have been interleaved. There was only one attend block because it demonstrated that this group of participants also exhibited a retro-cue effect for informative cues. In 2 participants, the final block of trials was lost due to programming error.

Results and discussion—Raw accuracy was analysed using a repeated measures ANOVA comparing the factors of retro-cue condition (arrow, neutral) and block condition (attend, ignore mixed, ignore inaccurate); see Figure 4 and Table 1. Raw accuracy was higher when there was an arrow retro-cue, $F(1, 19) = 19.39$, $p = .001$. The most relevant finding with regard to strategic control was the fact that the interaction of retro-cue and block condition was significant, $F(2, 38) = 10.45$, $p = .001$, due to the absence of a retro-cue effect in the ignore inaccurate block. Interestingly, the retro-cue benefit persisted in the ignore mixed condition even though the arrow retro-cue was rarely valid, $t(19) = 2.66$, $p = .016$. To examine performance in the ignore mixed condition in more detail, we compared performance on the arrow retro-cues that were valid versus when they were invalid. When retro-cues were valid, performance was 5% more accurate, but this effect only reached borderline significance, $t(19) = 1.94$, $p = .07$. In the ignore inaccurate block, accuracy did not differ based on the neutral or misleading arrow retro-cue, $t(19) = 1$, $p = \text{ns}$, suggesting that there was no cost in accuracy associated with the presence of completely invalid retro-cues.

To examine the possibility that the retro-cue effect varied as participants learned more about the statistics of the arrow-cue validity we compared separately or the ignore inaccurate and ignore mixed conditions. There was no main effect of block in the ignore inaccurate, $F(1, 19) = 1.7$, $p = .21$, or in the ignore mixed condition ($F(1, 19) = 1$, $p = \text{ns}$).

The d' data were consistent with the raw accuracy data as d' was greater when an arrow retro-cue appeared, $F(1, 19) = 15.78$, $p = .001$. The interaction of cue condition and block condition was significant, $F(2, 38) = 8.23$, $p = .001$, as there was no retro-cue effect present in the ignore inaccurate condition, $t(19) = 1.26$, $p = .22$. In the ignore mixed condition, the retro-cue benefit only reached borderline significance, $t(19) = 1.85$, $p = .08$. The analysis of performance across time found no main effect of block (first, second) in the ignore inaccurate condition, $F(1, 19) = 2.41$, $p = .14$, and no interaction of retro-cue and block ($F(1, 19) = 1$, $p = \text{ns}$). In the ignore mixed condition, there was no main effect of block, $F(1, 17) = 2.97$, $p = .10$, but the interaction of retro-cue and block did reach significance, $F(1, 17) = 6.67$, $p = .019$. The interaction was characterized by smaller d' values in the second block for the arrow retro-cue trials (first block, $M = 2.40$; second, $M = 1.69$), which was not found in the

neutral retro-cue trials (first, $M = 1.74$; second, $M = 1.72$). As in accuracy and d' , the reaction time analysis revealed a main effect of cue, $F(1, 19) = 20.07$, $p = .001$, and a significant Cue $\times$ Condition interaction, $F(2, 38) = 38.08$, $p = .001$. The interaction was due to the arrow retro-cue speeding responses in both the attend, $t(19) = 7.15$, $p = .001$, and the ignore mixed conditions, $t(19) = 6.31$, $p = .001$. However, in the ignore inaccurate condition, the arrow retro-cue significantly slowed responses, $t(19) = 3.14$, $p = .005$. We also compared performance on the arrow retro-cues that were valid versus when they were invalid. When the cues were valid, performance was 235 ms faster, $t(19) = 3.92$, $p = .001$. In the analysis of reaction time across block, reaction times sped up significantly during the second block in the ignore inaccurate condition, $F(1, 19) = 4.94$, $p = .04$, and there was no interaction of cue and block ($F(1, 19) = ns$). In the ignore mixed conditions, the speeding of reaction times reached borderline significance, $F(1, 17) = 4.10$, $p = .06$, and the interaction was not significant, $F(1, 17) = 2.10$, $p = .17$.

The results of Experiment 3 support the hypothesis that the retro-cue effect is not fully under strategic control. In the ignore inaccurate condition, the arrow retro-cues were never informative. In this condition, participants have sufficient strategic control to prevent the uninformative arrow retro-cues from lowering performance accuracy, although reaction times are slower. This provides one piece of evidence indicating that strategic control is imperfect. The finding that there was no difference between the neutral and invalid arrow retro-cues also shows that participants did not benefit by eliminating the cued item from VWM. When participants were instructed to ignore retro-cues that were generally misleading in the ignore mixed condition, a retro-cue effect persisted that diminished across the first and second blocks. These data indicate that the arrow retro-cue could not be ignored in cases when it was occasionally accurate, but that the ability to ignore the retro-cue improved over time. This provides a second piece of evidence to suggest that strategic control is not perfect. These implications of these findings are discussed below.

GENERAL DISCUSSION

The retro-cue effect refers to the improvement in VWM performance provided by an informative cue presented after encoding and maintenance that indicates which item will be subsequently probed. It is of theoretical interest because it opens a window into the internal attentional operations of VWM and because it is one of the few manipulations known to improve VWM performance. We tested several factors that influence attentional shifting in the perceptual realm including cue type, conscious awareness, and strategic manipulation of attention.

In Experiment 1, we investigated whether the magnitude of the retro-cue effect depended primarily on bottom-up (abrupt onset), or top-down (number) attentional cueing. Each of these cue types is effective at shifting perceptual attention in precueing paradigms. Therefore, we predicted that each of these cues would shift attention in VWM and result in a retro-cue effect. However, a robust retro-cue effect was observed only for the arrow retro-cue. Arrow retro-cues do not fit neatly within the top-down/bottom-up dichotomy because they are a highly overlearned symbol. Arrows are better described as a “hybrid” cue tapping into both bottom-up and top-down attention (Hommel et al., 2001; Ranzini et al., 2009;

Ristic & Kingstone, 2006). Purely bottom-up and top-down cues failed to evoke a retro-cue benefit. Previous retro-cue studies have overwhelmingly used arrow cues (Landman et al., 2003; Lepsien & Nobre, 2006, 2007; Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007; Nobre et al., 2008; Nobre et al., 2006), which turns out to be fortuitous, given the null effects we observed with other retro-cue types.

A second goal was to gauge participants' awareness and strategic control over the retro-cue benefit. In Experiment 2, we asked whether participants were consciously aware of the retro-cue benefit. Since the retro-cues were clearly visible, we knew they were aware of the presence of the retro-cue, but perhaps they did not feel that they influenced their performance. We reasoned that if they were consciously aware, they should display higher confidence levels on retro-cue trials. Consistent with this, participants had higher confidence on retrocue trials than on neutral trials, regardless of accuracy, suggesting that participants were aware of the benefits derived from the retro-cue.

In Experiment 3, we investigated whether participants had strategic control over the use of retro-cues or whether attentional shifts prompted by cueing could be detrimental to performance. We predicted that if the retro-cue effect was under strategic control, then participants should be able to ignore the retro-cue when it was uninformative. Conversely, if the effect is not under strategic control, then participants should not be able to ignore uninformative retro-cues, and they may incur a performance cost. The results showed that the effect is not entirely under strategic control. Instead of a performance cost when arrow retrocues were occasionally accurate, participants accrued speed and accuracy benefits. Participants were slowed in blocks in which the arrow retrocue was never valid.

In summary, the retro-cue benefit seems to require retro-cues that can tap into both top down and bottom-up attention. The beneficial effect of the retro-cue is sufficiently salient that participants become consciously aware of the effects exerted on behaviour. Although participants were aware of these effects, they could not effectively limit the influence of the retro-cue. Rather, the presence of an arrow retro-cue appears to force an obligatory shift of attention to the cued item in VWM even when participants are instructed to ignore the cue, and the retro-cue harms performance.

Prioritization or protection?

Matsukura and colleagues conducted an elegant series of retro-cue studies in which they compared two possible mechanisms of the retro-cue effect: prioritization and protection (Matsukura et al., 2007). According to a prioritization mechanism, the probe item would first be compared to the representation of the cued item. In other words, if there were a queue of representations in VWM, the retro-cue promotes one to the head of the line with the other representations behind it. A protection mechanism suggests that the cued item becomes resistant to decay and interference. To continue our analogy, the item at the head of the line quickly becomes the only representation in line as the other items decay. Matsukura et al. used a double retro-cue paradigm in which an initial retro-cue was followed by second retro-cue that might prompt a different item. They hypothesized that if the prioritization account were true, the second retro-cue would reshuffle the line again but have no effect on performance because the second item in line could be compared after the cued (prioritized)

item. Instead, they found that performance fell if the second retro-cue was inconsistent with the first retro-cue, a result they interpreted as consistent with the protection account. They concluded that the first retro-cue protected the cued items, and the uncued items decayed without protection. However, the drop in performance accuracy is rather modest: 84% to 81% for a set size of 4 items (Experiment 3, Matsukura et al., 2007). Because this change in performance accuracy is relatively small, it suggests that the decay rate of unprotected items is relatively slow. In this example, the slow decay rate afforded a second comparison process, and performance remained highly accurate. In practice, such a mechanism seems to be more like a prioritization account since there appears to be sufficiently slow delay of uncued items to allow a second comparison process.

Although there are many experimental differences between the double retro-cue tasks employed by Matsukura and colleagues (2007) and our single retro-cue tasks, our data appear to better support the prioritization account. In Experiment 3, our participants benefited from an arrow retro-cue that was only infrequently accurate (ignore mixed). According to a prioritization account, the retro-cues prioritized the cued item for comparison. In the ignore mixed case, when the retro-cue was accurate, the appropriate comparison was made first, and there was a significant retro-cue effect for the arrow retro-cues. When the retro-cue was inaccurate, the uncued VWM representations remained sufficiently vivid to permit a second comparison process, and performance did not drop sufficiently to cancel out the retro-cue effect. We interpret these findings as evidence of a mechanism in which the representation of the cued item is prioritized for comparison and is likely to be protected from decay, but secondary comparisons remain possible.

Contrasting internal and perceptual attention

Although it is parsimonious to assume that perceptual and internal shifts of attention reflect a single process, there is some evidence to suggest that there are differences. In two cases, perceptual and internal VWM attentional cueing paradigms have produced different patterns of results. Notably, Makovski and Jiang investigated the flexibility of internal attentional shifts by retro-cueing one or more target locations (Makovski & Jiang, 2007). They only observed a significant retro-cue benefit when a single location was cued. When they supplied the cue before the stimulus array, they found a benefit when up to three locations were cued. From these data they concluded that shifting internal attention is less flexible than shifting perceptual attention because it appears to be restricted to a single item. In a similar vein, the data from Experiment 1 indicate that the retro-cue benefit, reflecting shifts of internal attention, does not generalize across various cue types as readily as in perceptual attention tasks.

Terminology

In the interest of clarity we note that there are at least two distinct retro-cue paradigms in common use. One task compares retro-cue performance with performance on a postcue trial, in which a valid cue appears at the same time as test (Makovski & Jiang, 2008; Makovski et al., 2008). In these experiments, the retro-cue trials are presented after the delay and are followed by a second, shorter, delay period to offset the presentation of the retro-cue from the appearance of the test array. The postcue trials present the cue and the test array

simultaneously. A second retro-cue paradigm compares neutral and informative retrocues, as we did here (paradigms reviewed in Lepsien & Nobre, 2006). The distinction between these two different paradigms has not been discussed explicitly, and comparisons across conventions may be misleading. During pilot testing, we ran a series of studies comparing valid retro-cues with valid postcues. In contrast to the current findings reported in Experiment 1, we observed a robust retro-cue benefit across all cue types. One possibility is that in these preliminary experiments, the offset between the presentation of the retro-cue and the test array permitted participants to attend first to the cue and then to the test array in a stepwise manner. It is unclear why this offset would lead to significantly improved performance. Furthermore, in spite of the performance benefit offered by the retro-cue, participants rated these trials with lower confidence ratings. The discrepancy between the preliminary and the current findings signals that the different retrocue paradigms may be testing different things. For the sake of clarity, we suggest that future investigators refer to the paradigm tested here, which is the more commonly used paradigm, as the standard retro-cue task and devise a different term for the task used by Jiang and colleagues (Makovski & Jiang, 2008; Makovski et al., 2008).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Experimental design. Experiment 1: After stimulus presentation and a delay, a single cue appeared. The cue was either neutral (X) or informative (number, dash or arrow). Following the cue was a second brief delay after which a probe item appeared. The recognition task was to indicate whether the probe item was in the correct location (conjunction task).

Figure 2.

Experiment 1 results. Performance accuracy for each retrocue condition: neutral (X), arrow, abrupt onset (-), and number (#). The asterisks indicate the presence of a significant difference between conditions. Error bars indicate 95% confidence intervals.

Figure 3.

Experiment 2 results: (A) Performance accuracy for each retro-cue condition: neutral (X), arrow. (B) Confidence for errors and correct answers for each retro-cue condition. The asterisks indicate the presence of a significant difference between conditions. Error bars indicate 95% confidence intervals.

Figure 4.

Experiment 3 results: Performance accuracy for each retrocue condition—neutral (X), arrow—and for each block condition—attend (arrow retro-cues are informative), ignore mixed (arrow retro-cues are informative on a portion of trials), and ignore inaccurate (arrow retro-cues are never accurate). The asterisks indicate the presence of a significant difference between conditions. Error bars indicate 95% confidence intervals.

Table 1.

Accuracy and correct reaction time data for each experiment and retro-cue condition

Experiment	Condition	Raw accuracy	Reaction time (ms)	d'
Experiment 1	Neutral	.75 (.10)	818 (164)	1.53 (0.65)
	Arrow	.82 (.09)	942 (207)	2.07 (0.85)
	Dash	.76 (.11)	717 (258)	1.66 (0.78)
	Number	.73 (.13)	1,013 (220)	1.44 (0.99)
Experiment 2	Neutral	.74 (.07)	1,532 (390)	1.54 (0.48)
	Arrow	.87 (.07)	1,268 (358)	2.50 (0.65)
Experiment 3				
Attend	Neutral	.70 (.11)	883 (175)	1.31 (0.77)
	Arrow	.83 (.11)	1,089 (212)	2.26 (1.11)
Ignore mixed	Neutral	.75 (.09)	1,053 (210)	1.60 (0.72)
	Arrow	.81 (.08)	914 (185)	1.94 (0.72)
Ignore inaccurate	Neutral	.73 (.09)	1,087 (208)	1.39 (0.53)
	Arrow	.71 (.08)	1,177 (289)	1.24 (0.72)

Note: Standard deviation values appear parentheses.