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Orienting attention in visual working memory requires central capacity: Decreased retro-cue effects under dual-task conditions

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Abstract

The retro-cue effect (RCE) describes superior working memory performance for validly cued stimulus locations long after encoding has ended. Importantly, this happens with delays beyond the range of iconic memory. In general, the RCE is a stable phenomenon that emerges under varied stimulus configurations and timing parameters. We investigated its susceptibility to dual-task interference to determine the attentional requirements at the time point of cue onset and encoding. In Experiment 1, we compared single- with dual-task conditions. In Experiment 2, we borrowed from the psychological refractory period paradigm and compared conditions with high and low (dual-) task overlap. The secondary task was always binary tone discrimination requiring amanual response. Across both experiments, an RCE was found, but it was diminished in magnitude in the critical dual-task conditions. A previous study did not find evidence that sustained attention is required in the interval between cue offset and test. Our results apparently contradict these findings and point to a critical time period around cue onset and briefly thereafter during which attention is required.

Keywords

Retro-cue; Visual working memory; Attention; Dual task; PRP

Introduction

It is well known that directing attention to particular locations enhances subsequent encoding and performance for targets appearing at the cued locations. A prominent example is spatial precuing, where centrally presented arrows indicate the likely location of the subsequent target (e.g., Posner, 1980). Also, such cues facilitate encoding into visual working memory (VWM)[1] (e.g., Jiang, Olson, & Chung, 2000). Of particular relevance for the present article is the finding that retrospective cues presented *after* encoding and

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[1] Following other authors, we use the terms *working memory* and *shortterm memory* as synonyms.

maintenance improve VWM performance (Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003). Typically, participants encode items into VWM, followed by a retention interval. After this delay, a cue (most often an arrow) indicates one spatial location that is most often probed via change detection. As compared with neutral cues, valid cues enhance performance—the retro-cue effect (RCE). This robust effect consistently reveals a performance benefit of 5 %–15 % in recognition probes using various stimuli, spatial configurations, timing parameters during the retention interval, and so forth (e.g., Berryhill, Richmond, Shay, & Olson, 2011; Griffin & Nobre, 2003; Landman et al., 2003; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura, Luck, & Vecera, 2007; Tanoue & Berryhill, 2012). Importantly, the RCE delay interval between stimulus offset and retro-cue onset is at least 900 ms—thus, well beyond the ~500 ms span of iconic memory (Sperling, 1960). In fact, the RCE persists for delays of up to 9,600 ms without reduction (Astle, Summerfield, Griffin, & Nobre, 2012). However, manipulations of the interval from cue presentation to the test screen show that the RCE increases with time, revealing the time course of the development of the RCE (Pertzov, Bays, Joseph, & Husain, 2013).

To account for the RCE, it has been suggested that attention is allocated to representations of cued items, which are thereby protected from further loss (e.g., via decay or interference) and, consequently, remain more accessible (e.g., Matsukura et al., 2007). A recent study has provided evidence that the allocated attention can even restore information that would otherwise be forgotten (Murray, Nobre, Clark, Cravo, & Stokes, 2013). Several models of VWM describe mechanisms that perhaps can account for the RCE (for a recent summary, see Rerko & Oberauer, 2013). However, in all cases, certain cognitive operations must happen to ensure that protection takes place, which is then evidenced by the presence of the RCE. Here, we investigated whether these operations occurred automatically or were subject to disruption from ongoing concurrent cognitive processing. This is an important and relevant issue in everyday life because it is rare to engage in just a single task—as is the case in most RCE studies. Increasingly, humans are multitaskers. For example, we answer e-mails while speaking to someone and walking across the street. Thus, considering these factors elicits a question regarding the robustness of the RCE in more ecologically valid multitasking situations.

How robust is the retro-cue effect?

Apart from VWM encoding of the to-be-learned material, there are at least four processes that are required to generate and diagnose the RCE: (1) encoding/interpreting the cue, (2) reorienting attention according to the cue, (3) retrieving from VWM the representation of the item associated with the cued location, and (4) comparing the retrieved representation with the test item and selecting the appropriate response. The latter two processes are essential to eventually diagnosing the existence of the RCE. Since response selection proper is typically assumed to be capacity limited and, thus, susceptible to dual-task interference (Pashler, 1994; Pashler & Johnston, 1989; Tombu & Jolicoeur, 2003), there are reasons to expect that dual-task conditions generally hurt performance. The interesting question relates, however, to the size of the RCE under dual-task conditions, as compared with control conditions. Since the processes inducing the RCE can logically begin only with cue onset, manipulating attentional demands around cue onset and in the following period is particularly interesting. What can we expect from increased attentional demands around the time of cue onset?

For one, it is reasonable to assume that the RCE will be reduced under dual-task conditions, since few processes are exempt from central interference in dual-task situations (for reviews, see Janczyk, Pfister, Wallmeier, & Kunde, in press; Lien, Ruthruff, & Johnston, 2006). Still, however, a closer examination is warranted. First, encoding of objects, such as the learned items but also the cue, into VWM suffers from concurrent central processes, at least when the to-be-encoded items are masked (Jolicoeur, 1999; see also Dell'Acqua & Jolicoeur, 2000). Furthermore, symbolic cuing is disrupted by dual-task interference in the precue setting (Du & Abrams, 2010). Yet, precues, particularly arrow cues, have also been shown to effectively bias attention automatically, even when they are uninformative (e.g., Eimer, 1997; Pratt, Radulescu, Guo, & Hommel, 2010). Although one distinction of the retrocue literature from the precue literature is that the nature of the cue is important and neither purely symbolic cues nor purely exogenous cues elicit the RCE (Berryhill et al., 2011), it seems reasonable that arrow retro-cues could *automatically* trigger processes giving rise to the RCE, because arrow cues reliably elicit the RCE (even though there are known differences between external and internal attention; Chun, Golomb, & Turk-Browne, 2011; Makovski & Jiang, 2007; Tanoue, Jones, Peterson, & Berryhill, 2013). Second, the processes triggered by the cue may or may not be susceptible to central interference. The mere fact that the RCE takes a measurable time to develop (e.g., Pertzov et al., 2013; Tanoue & Berryhill, 2012) suggests that these processes are *not* fully automatic: There is no RCE when the cue is presented simultaneously with the test screen (postcue), but only when the cue is presented several hundred milliseconds before the test screen (Makovski et al., 2008; see also Pertzov et al., 2013). However, the processes that are initiated by the cue and that act on the cued item (eventually leading to the RCE) may consist of increasing the cued item's activation. It has been argued that mere code activation is resistant to dual-task interference (see, e.g., Jolicoeur, Tombu, Oriet, & Stevanowski, 2002) and, if true, the size of the RCE should then remain unaffected by the need to perform a concurrent task. In sum, arguments could be made for and against a reduction of the RCE when an attentionally demanding dual task requires processing close in time to the processing of the cue onset.

One recent study is particularly relevant regarding the attentional requirements of the RCE. Hollingworth and Maxcey-Richard (2013) introduced a visual search task in the time interval between cue offset and test. Across several experiments, they found that the secondary task induced a general performance decrement (in comparison with the retro-cue task alone), but they found no evidence showing a reduced RCE despite the concurrent visual search task. From these results, the authors concluded that sustained attention is not necessary for the RCE in the time interval *following* cue offset. Note, however, that in this study, the secondary task display was presented 500 ms (or even 700 ms) after cue offset and remained visible for an extended period (2,000 ms) until the memory test screen appeared. One possibility is that attentional processing had already been accomplished by the time the secondary task initiated.

What about the time closer to and briefly before the cue? There appears to be no study explicitly targeting this time point, but one study by Makovski (2012) provides some insight.

Makovski (2012, Experiment 2) reported no reduction of the RCE following interference from a secondary task, but note that this particular experiment was not explicitly designed to test for central interference. In this study, during the retention interval of the visual retro-cue task, participants indicated manually whether or not a visually presented number was odd or even. However, although these data provide support for an automatic RCE, two concerns make this conclusion premature. First, the particular combination of visual stimuli and manual responses has been described as favorable for successful dual-task performance with minimal interference (e.g., Hazeltine, Ruthruff, & Remington, 2006). Consequently, dual-task effects may have been minimized. To enhance the potential for interference, we presented an auditory stimulus (which is more compatible with a verbal than with a manual response). Second, Makovski imposed a long delay between the secondary task number onset to retro-cue onset (1,550 ms). The mean response time (RT) to the number, however, was only 663 ms. Thus, because participants had already responded to the number at the time of cue onset, it is unlikely that there was any remaining potential for central interference when the cue was eventually presented. Thus, these results cannot provide a clear answer to the question of whether the size of the RCE is affected by dual-task interference or not.

The present experiments

Here, we report two experiments meant to fill the gap of whether the retro-cue benefit requires attention around the time of cue onset, cue encoding, and briefly thereafter. Experiment 1 used a classical approach where we compared single- and dual-task conditions. In Experiment 2, we replicated the results with a design borrowed from research on the psychological refractory period (PRP; e.g., Pashler, 1994), where two tasks were performed on each trial but the degree of temporal overlap varied from trial to trial.[2] We first expected a general decline in performance in the dual-task conditions. Such a finding would reveal the efficiency of the procedure. The critical question concerns the size of the RCE, and two scenarios are possible. First, the size of the RCE might remain unaffected. This outcome would support the argument that attention is not necessary in the period immediately surrounding cue presentation (see Hollingworth & Maxcey-Richard, 2013, for such an outcome concerning the time window 500 ms *after* offset of the retro-cue). Second, the RCE might become smaller. This observation would support the view that attention in and around cue encoding is crucial.

Experiment 1

In Experiment 1, we compared a standard retro-cue condition (single task) with two conditions where participants were to simultaneously perform a secondary task (dual task). This secondary task was binary tone discrimination; that is, participants responded to the pitch of a tone with a manual keypress. We expected performance to be better in the single-task condition and worse overall in dual-task conditions (see also Hollingworth & Maxcey-Richard, 2013). The critical issue, however, was whether the size of the RCE would be reduced under dual-task conditions. Furthermore, we distinguished between two dual-task

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[2] Strictly speaking, both of the latter conditions are dual tasks. Hereafter, however, when talking about dual-task situations, we refer to the high task overlap condition, whereas we subsume the low task overlap condition under the term *single task*.

conditions. In one, the secondary task tone occurred *before* the retro-cue was presented; in the other, it occurred simultaneously with retro-cue offset (but still, in both conditions, the tone was presented close to cue onset).

Method

Participants—Thirty-six undergraduate students from the University of Würzburg participated in this experiment (32 female; mean age: 20.9 years). All participants gave informed consent, were naïve regarding the hypotheses underlying this experiment, and reported correct or corrected-to-normal vision. Participants signed informed consent documents.

Stimuli and apparatus—Experimental protocols were presented by a standard PC via a 17-in. CRT monitor. VWM and test stimuli in the retro-cue task were circles (radius: 1.7 cm) of nine different colors (blue, brown, yellow, gray, green, purple, orange, red, and pink). Cues were white arrows (2.1 cm long) pointing up-left, up-right, down-left, or down-right in the valid cue conditions and a white X (0.8 cm high) in the neutral cue conditions. Filler stimuli on the test screen were white annuli. All visual stimuli were presented against a black background. Stimuli in the tone task were two sinusoidal tones (300 or 900 Hz; 50 ms) presented via headphones. Responses were collected via four external response keys, two located on the left side of the participants (for the tone task), the other two located on the right side (for the retro-cue task).

Procedure—All participants were tested individually in a single 1-h session. A trial started with a fixation cross (200 ms) followed by the VWM array (300 ms) with four circles, each filled with one of four randomly drawn colors (see Fig. 1). No color was repeated within a trial. After a first delay period, indicated by a blank screen (1,000 ms), a valid (arrow) or neutral (X) cue was presented (100 ms). Following a second delay period, again shown as a blank screen (400 ms), the test screen appeared (until response), consisting of one colored circle and three white annuli. In the event of an error in the tone task, an error message appeared for 1,000 ms; the next trial started following an intertrial interval of 1,000 ms.

All participants performed in three tone conditions in this experiment. In the *no-tone* condition, there was no tone task, and the VWM trial proceeded as described above. The participants' task was to decide whether the same color as that for the test screen stimulus had been presented at this position or not in the VWM array (in Fig. 1 a positive answer would be required). Participants pressed a response key with their right index finger if the answer was *yes* and with their right middle finger in the case of a *no* answer. This condition served as the baseline single task. In two other conditions, the presence of a tone produced a dual-task situation. Participants had to respond as quickly as possible to the pitch of the tone (high or low) by pressing the designated response key with their left index or middle finger. In the *early-tone* condition, the tone was presented 150 ms before the retro-cue onset; in the *late-tone* condition, it was presented at retro-cue offset. In all other aspects, these two conditions were similar. The tone-pitch-response mapping was counterbalanced across participants.

The experiment started with a brief practice block of 20 early-tone trials to familiarize participants with the dual task. The experiment proper consisted of twelve 32-trial blocks, four blocks per tone condition. These four blocks were presented in succession, and the order was counterbalanced across participants. For the no-tone condition, there were 2 repetitions of the 16 trial types resulting from the combination of 2 responses (yes, no) × 2 cue types (valid, neutral) × 4 locations of the test stimulus. For the tone conditions, additionally 2 tone stimuli (300 vs. 900 Hz) were combined with the 16 trial types, resulting in the 32 trials. To prevent phonological encoding and rehearsal, participants performed an auditory suppression task and spoke the word “cola” throughout the experiment. The experimenter stayed in the room to monitor compliance.

Design and analyses—The *retro-cue type* (valid vs. neutral) and the *tone condition* (no vs. early vs. late) were varied within subjects, resulting in a 2 × 3 factorial design. Analyses focused on accuracy and RT in the retro-cue task.[3] On the basis of the motivation for the present experiment, we calculated a set of Helmert contrasts on the factor *tone condition*. Thus, contrast 1 compared the no-tone condition with the combined two tone conditions; contrast 2 compared the two tone conditions. Paired *t*-tests evaluated the existence of an RCE proper separately for the three (tone) conditions. Performance in the tone task was analyzed by means of a 2 (retro-cue type: valid vs. neutral) × 2 (tone condition: early vs. late) repeated measures ANOVA. RTs were deemed outliers when they deviated by more than 3 standard deviations from their respective cell means (1.5 % for tone RTs, 1.6 % for retro-cue RTs). For analyses of the retro-cue task, trials with erroneous tone task responses and RT outliers to the tone were excluded. For the respective RT analysis, outliers in the retro-cue task were excluded as well. For analyses of tone RTs, only trials associated with correct responses to the tone were considered, and outliers were excluded. A significance level of $\alpha = .05$ is adopted throughout this article.

Results

Retro-cue task—Accuracy (mean percent correct) and mean RTs are illustrated in Fig. 2. The results in terms of d' are very similar (see the Appendix). As was expected, participants demonstrated superior accuracy with a valid retro-cue, as compared with a neutral retro-cue. In other words, the RCE was present, $F(1, 35) = 45.72$, $p < .001$, $\eta_p^2 = .57$. Furthermore, there was a significant effect of the dual-task condition. Contrast 1 showed that performance was better in the single-task no-tone condition, as compared with the collapsed dual-task conditions, $F(1, 35) = 38.99$, $p < .001$, $\eta_p^2 = .53$. This contrast also revealed a smaller magnitude of the RCE in the dual-task conditions, as compared with the single-task condition, $F(1, 35) = 5.34$, $p = .027$, $\eta_p^2 = .13$. Contrast 2 investigated the differences between the dual-task conditions: There was no performance difference depending on whether the tone in the secondary task was presented early or late, $F(1, 35) = 0.84$, $p = .366$, $\eta_p^2 = .02$, and there was no difference in the size of the RCE, $F(1, 35) = 0.36$, $p = .553$, $\eta_p^2 = .01$. When tested separately, the RCE was evident across all conditions [no tone, $t(35) = 6.79$, $p < .001$; early tone, $t(35) = 3.65$, $p = .001$; late tone, $t(35) = 4.42$, $p < .001$].

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[3] Although the RCE is typically reported in terms of accuracy, we report RTs as well to exclude any concerns regarding speed–accuracy trade-offs in the present data.

A relatively similar picture emerged for RTs. Participants responded more quickly after a valid than after a neutral retro-cue, $F(1, 35) = 46.14$, $p < .001$, $\eta_p^2 = .57$. Responses were also faster in the single-task condition, as compared with the collapsed dual-task conditions (contrast 1), $F(1, 35) = 134.31$, $p < .001$, $\eta_p^2 = .79$. Also, the difference between the two cue conditions was larger in the single-task condition, $F(1, 35) = 25.81$, $p < .001$, $\eta_p^2 = .42$. Furthermore, contrast 2 showed that responses were slower in the late- than in the early-tone condition, $F(1, 35) = 9.31$, $p = .004$, $\eta_p^2 = .21$. The magnitude of the RT difference due to the different retro-cue types was constant across the two tone conditions, $F(1, 35) = 0.38$, $p = .543$, $\eta_p^2 = .01$.

Tone task—Mean correct RTs in the tone task were 1,326 ms for both the neutral and valid retro-cues for the early-tone condition and 1,360 and 1,318 ms (neutral and valid retro-cue, respectively) for the late-tone condition. There were no significant effects, all Fs ≤ 1.86, all ps ≥ .182. Participants committed errors on 2.7 % and 4.3 % of the trials in the early-tone condition, and on 2.7 % and 3.3 % of the trials in the late-tone condition (neutral and valid cue, respectively). Thus, overall, participants made (significantly) more errors when encountering a valid, as compared with a neutral, retro-cue, $F(1, 35) = 6.85$, $p = .013$, $\eta_p^2 = .16$. This difference was slightly larger in the early-tone condition, as reflected by a marginally significant interaction, $F(1, 35) = 3.67$, $p = .063$, $\eta_p^2 = .10$. Tone condition (early, late) itself exerted no significant effect on error percentages, $F(1, 35) = 0.86$, $p = .360$, $\eta_p^2 = .02$.

Discussion

Clearly, VWM performance worsened under dual-task conditions and the magnitude of the RCE became smaller. This outcome suggests that around the time of cue onset and encoding, attention is required to induce an RCE. There was, furthermore, no difference in the size of the RCE between both tone conditions.[4] This finding suggests that it is not cue encoding but the subsequent processes of reorienting attention and reorganizing VWM contents that are affected by the dual task. Finally, performance on the tone task was worse in the case of valid, as compared with neutral, retro-cues. Thus, there was an effect of retro-cue type on tone task performance showing that the occurrence of valid arrow retro-cues attracted attention. One potential concern relates to the fact that the RCE might have been scaled to the overall performance level. In fact, even for neutral cues, performance was clearly worse in dual- than in single-task conditions.

Therefore, before drawing conclusions from these findings, we strove to replicate them in Experiment 2, which was also designed to overcome shortcomings of Experiment 1.

Experiment 2

Experiment 1 showed that the RCE was reduced in size by an attentionally demanding dual task around cue presentation. There were, however, two shortcomings in this experiment.

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[4] The difference in RTs in the retro-cue task between the two dual-task conditions results from the fact that participants typically first responded to the tone and then to the VWM task but RT measurement in the retro-cue VWM task began with the onset of the test screen.

First, the single- versus dual-task variation was confounded with the absence or presence of a tone in the course of each trial. Second, the blocked design invites strategic preparation, which may differ across the different block conditions. Experiment 2 addressed these shortcomings. Here, we presented a tone stimulus on each trial and instantiated a critical manipulation from the PRP paradigm (see, e.g., Janczyk, 2013; Pashler, 1994; Tombu & Jolicoeur, 2003). In the PRP paradigm, two tasks are performed on each trial. However, the respective stimuli are presented with a varying stimulus onset asynchrony (SOA). At short SOAs, task overlap is high, whereas at long SOAs, task overlap is low—with the advantage that task overlap can be varied randomly across trials. This also eliminates confounds related to stimulus presence or variable instructions.

We incorporated the early-tone condition from Experiment 1. In the low task overlap condition, the tone was presented 850 ms prior to the retro-cue. In the high task overlap condition, the tone was presented only 150 ms prior to the retro-cue (see Fig. 1 for an illustration). We predicted that the results of Experiment 1 would be replicated—in particular, a reduced RCE in the high task overlap condition, as compared with the low task overlap condition.

Method

Thirty-six new undergraduate students participated in this experiment (27 female; mean age: 22.4 years). The paradigm followed the procedure described for Experiment 1, the main difference being that there was always a tone and it was presented with an SOA of either 850 or 150 ms prior to the retro-cue, thereby creating the low and high task overlap conditions, respectively.

A practice block (20 trials) preceded the five experimental blocks. Within each experimental block, the 64 trial types resulting from 2 tones (300 vs. 900 Hz) × 2 task overlap conditions (low, SOA = 850 ms; high, SOA = 150 ms) × 2 responses (yes, no) × 4 test locations × 2 retro-cue types (valid, neutral) were randomly intermingled. The tone-pitch-response mapping was counterbalanced across participants. Data were analyzed by an ANOVA with retro-cue type and task overlap as repeated measures. As outliers, 1.7 % (tone task) and 1.5 % (retro-cue task) of the trials were identified according to the same criteria as in Experiment 1.

Results

Retro-cue task—Accuracy (mean percent correct) and mean RTs are illustrated in Fig. 3. The results in terms of d' are very similar (see the Appendix). First, the RCE remained present across task overlap conditions, and accuracy was higher with a valid than with a neutral retro-cue, $F(1, 35) = 44.27$, $p < .001$, $\eta_p^2 = .56$. Also, accuracy was higher in the low task overlap condition than in the high task overlap condition, $F(1, 35) = 9.31$, $p = .004$, $\eta_p^2 = .21$. Finally, the RCE was smaller with high task overlap than with low task overlap, $F(1, 35) = 5.01$, $p = .032$, $\eta_p^2 = .13$. Tested separately, an RCE was still evident in both task overlap conditions [low, $t(35) = 6.66$, $p < .001$; high, $t(35) = 3.62$, $p = .001$]. There was no difference for the neutral cues between the two task overlap conditions, $t(35) = 1.05$, $p = .300$.

Responses were given faster following valid than following neutral cues, *F*(1, 35) = 29.90, $p < .001$, $\eta_p^2 = .46$, and for the low, as compared with the high, task overlap condition, *F*(1, 35) = 160.38, $p < .001$, $\eta_p^2 = .82$. The RT difference between valid and neutral retro-cues was observed only with low task overlap, *F*(1, 35) = 27.74, $p < .001$, $\eta_p^2 = .44$.

Tone task—Mean correct RTs for the high task overlap condition were 960 and 1,071 ms with a neutral and a valid cue, respectively. The corresponding values for the low task overlap condition were 1,031 and 1,019 ms. Thus, overall, RTs were shorter in the neutral retro-cue than in the valid retro-cue condition, *F*(1, 35) = 19.64, $p < .001$, $\eta_p^2 = .36$, but the degree of task overlap had no impact on RTs, *F*(1, 35) = 0.10, $p = .757$, $\eta_p^2 < .01$. The RT difference due to retro-cue type was evident only in the high task overlap condition and was absent in the low task overlap condition, *F*(1, 35) = 27.79, $p < .001$, $\eta_p^2 = .46$. A similar picture emerged for mean error percentages in the tone task (high task overlap, 4.1 % and 6.5 %; low task overlap, 4.6 % and 5.1 %; neutral and valid retro-cue, respectively). More errors were made with a valid than with a neutral retro-cue, *F*(1, 35) = 8.43, $p = .006$, $\eta_p^2 = .19$, but this difference was larger in the high task overlap condition, *F*(1, 35) = 7.28, $p = .011$, $\eta_p^2 = .17$. The main effect of task overlap condition was not significant, *F*(1, 35) = 1.53, $p = .224$, $\eta_p^2 = .04$.

Discussion

In Experiment 2, participants performed two tasks during each trial, but the degree of task overlap varied between high and low. This design borrows from the PRP paradigm (e.g., Pashler, 1994). Performance was generally worse with high task overlap than with low task overlap (an instance of the PRP effect), but much less so than in Experiment 1. Moreover, performance in the neutral cue condition was comparable. Still, however, the RCE was again reduced in size with high task overlap. These findings replicate and extend the results from Experiment 1, where the comparison was made between classical single- and dual-task conditions. Also similar to Experiment 1, performance in the secondary tone task was worse when encountering valid, as compared with neutral, retro-cues, and this was particularly true with high task overlap, which was comparable to the early-tone condition in Experiment 1.

General discussion

In two experiments, participants performed a retro-cue VWM task (Astle et al., 2012; Berryhill et al., 2011; Griffin & Nobre, 2003; Landman et al., 2003) in combination with a secondary task, and we investigated whether the RCE would remain stable or would be reduced in size under attentionally demanding dual-task conditions.

The results were consistent across both of the present experiments, despite their procedural and design differences. First, similar to what has been observed by others (Hollingworth & Maxcey-Richard, 2013), performance was worse in dual- than in single-task conditions (Experiment 1) and with high than with low task overlap (Experiment 2). Unlike in the work of Hollingworth and Maxcey-Richard—where the dual task was applied in the interval between cue offset and test—the RCE was reduced in size when the attentional demands were imposed briefly before/around the time of cue onset.[5] Thus, our outcome extends—and also contradicts—previous research and gives a hint as to where to locate the attentional demands giving rise to the RCE. Second, there was no performance difference between the early- and the late-tone conditions in Experiment 1. Although more research is needed, this finding suggests that the secondary tone task affected processes after cue encoding, most likely during the reorientation of attention required by the cue. Third, in both experiments, performance on the secondary tone task was worse when the retro-cue was valid. Thus, it seems as if encountering a valid retro-cue temporarily disrupts other processes that currently require attention—for example, the concurrent tone task. This is consistent with prior findings demonstrating the difficulty participants have in ignoring retro-cues (Berryhill et al., 2011). In this work, it was found that even when instructed to ignore the retro-cues, the RCE remained robust.

The type of task we used deserves further consideration. First, it should be noted that we observed a significant decrement in the size of the RCE even though our tone task could be considered quite simple—at least when compared with more challenging visual search tasks that were used in other studies. On the other hand, the RCE remained evident across all conditions. Logically, it can be predicted that the reduction in RCE should become even more apparent when a more complex, more attention-demanding task is used. It might even be the case that under such challenging conditions, the RCE would be eliminated. Second, unlike previous studies, we did not use a *visual* secondary task. Such avoidance of input modality overlap is common in PRP research to circumvent and exclude any modality-specific processing problems. Still, however, this task had an impact on the size of the RCE. But this reduction cannot be attributed to mere visual interference. Instead, the kind of interference imposed by the tone task is typically attributed to central attention, such as that necessary for response selection or decision making (e.g., Pashler, 1994). Thus, it seems as if, at the time point considered here, central attentional processes are required to initiate those actions within VWM that give rise to the RCE. Future research may carefully isolate the demands imposed by using a task of the visual modality and those resulting from more central requirements.

More broadly, it seems worthwhile to fully and precisely characterize which working-memory-related processes are capacity limited and susceptible to dual-task interference. First, it is well established that encoding involves central processes and suffers in dual-task situations (Dell’Acqua & Jolicoeur, 2000; Jolicoeur, 1999). Second, retrieving (long-term) memory content seems to be a process that can run in parallel with other processes (Green, Johnston, & Ruthruff, 2011; Logan & Delheimer, 2001; Logan & Schulkind, 2000; but see also, e.g., Healey & Miyake, 2009). Third, it appears that processes that reorganize and/or protect working memory content in some way (for example, by directing attention toward cued items, as in the present experiments) are not automatic and are, therefore, susceptible to dual-task interference. There is also evidence demonstrating that switching attention between items in working memory is time-consuming (e.g., Garavan, 1998; Janczyk & Grabowski, 2011; Janczyk, Wienrich, & Kunde, 2008). It seems likely that this kind of

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[5] As has already been noted in the respective “Discussion” section, in Experiment 1 the RCE was smaller in size in the dual-task conditions, but overall performance was also worse. Thus, one might argue that the RCE was scaled to overall performance in this experiment, which limits the conclusions. Note that this does not apply to Experiment 2. Here, performance in the neutral cue condition was not affected by the task overlap manipulation.

working memory manipulation and reorganization also suffers from dual-task interference and requires a common central processing capacity.

Conclusions

Retro-cues that successfully orient attention among items held in VWM improve performance long after encoding ends—the retro-cue effect (cf. Griffin & Nobre, 2003; Landman et al., 2003). Previous research did not find a reduction of the RCE when an attention-demanding dual task is applied long after cue offset and encoding (Hollingworth & Maxcey-Richard, 2013). In contrast, the present experiments show that the RCE indeed suffers and becomes smaller when the dual task occurs close to cue onset and cue encoding.

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Appendix d′ results

In addition to the analyses reported in the main text, analyses for the retro-cue task were carried out on the basis of d'. In general, the emerging picture is qualitatively the same as for accuracy and RTs.

Experiment 1

We calculated d' and submitted it to the same analyses as we did for accuracy and RTs. Values for 2 participants were corrected using the log-linear rule (cf. Hautus, 1995). The d' values for the no-tone condition were 0.91 and 1.56; for the early-tone condition, 0.51 and 0.88; and for the late-tone condition, 0.52 and 0.96 (neutral and valid cues, respectively).

The main effect of cue type was significant, $F(1, 35) = 51.72$, $p < .001$, $\eta_p^2 = .60$. Contrast 1 showed a decrease of detection from the single- to the dual-task conditions, $F(1, 35) = 37.55$, $p < .001$, $\eta_p^2 = .52$. The difference between the two cue conditions was smaller under dual-task conditions, $F(1, 35) = 5.62$, $p = .023$, $\eta_p^2 = .14$. Contrast 2 revealed no significant performance differences between the two dual-task conditions, $F(1, 35) = 0.67$, $p = .417$, $\eta_p^2 = .02$, and the retro-cue effect was of the same size, $F(1, 35) = 0.30$, $p = .586$, $\eta_p^2 < .01$. Aretro-cue effect was evident in all tone conditions [no tone, $t(35) = 6.76$, $p < .001$; early tone, $t(35) = 3.80$, $p = .001$; late tone, $t(35) = 4.64$, $p < .001$].

Experiment 2

We calculated d' and submitted these values to the same analyses as we did for accuracy and RTs. The d' values were 0.46 and 0.72 with high task overlap (SOA = 150 ms) and 0.57 and 1.02 with low task overlap (SOA = 850 ms; neutral and valid, respectively).

Detection was better with a valid than with a neutral cue, $F(1, 35) = 41.69$, $p < .001$, $\eta_p^2 = .54$, and with low than with high task overlap, $F(1, 35) = 9.57$, $p = .004$, $\eta_p^2 = .22$. The difference between cue types was larger with low task overlap, and the interaction approached significance, $F(1, 35) = 3.14$, $p = .085$, $\eta_p^2 = .08$. The retro-cue effect was, however, significant for both task overlap conditions [150 ms, $t(35) = 3.36$, $p = .002$; 850 ms, $t(35) = 5.94$, $p < .001$].

References

Astle DE, Summerfield J, Griffin I, Nobre AC. Orienting attention to locations in mental representations. Attention, Perception, & Psychophysics. 2012; 74:146–162.

Berryhill ME, Richmond LL, Shay CS, Olson IR. Shifting attention among working memory representations: Testing cue types, awareness, and strategic control. The Quarterly Journal of Experimental Psychology. 2011; 65:426–438. [PubMed: 21846267]

Chun MM, Golomb JD, Turk-Browne NB. A taxonomy of external and internal attention. Annual Review of Psychology. 2011; 62:73–101.

Dell’Acqua R, Jolicoeur P. Visual encoding of patterns is subject to dual-task interference. Memory & Cognition. 2000; 28:184–191. [PubMed: 10790974]

Du F, Abrams RA. Endogenous orienting is reduced during the attentional blink. Experimental Brain Research. 2010; 205:115–121. [PubMed: 20625704]

Eimer M. Uninformative symbolic cues may bias visual-spatial attention: Behavioral and electrophysiological evidence. Biological Psychology. 1997; 46:67–71. [PubMed: 9255432]

Garavan H. Serial attention within working memory. Memory & Cognition. 1998; 26:263–276. [PubMed: 9584434]

Green C, Johnston JC, Ruthruff E. Attentional limits in memory retrieval – Revisited. Journal of Experimental Psychology: Human Perception and Performance. 2011; 37:1083–1098. [PubMed: 21517217]

Griffin IC, Nobre AC. Orienting attention to locations in internal representations. Journal of Cognitive Neuroscience. 2003; 15:1176–1194. [PubMed: 14709235]

Hautus MJ. Corrections for extreme proportions and their biasing effects on estimated values of d’. Behavior Research Methods, Instruments, & Computers. 1995; 27:46–51.

Hazeltine E, Ruthruff E, Remington RW. The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. Cognitive Psychology. 2006; 52:291–345. [PubMed: 16581054]

Healey MK, Miyake A. The role of attention during retrieval in working-memory span: A dual-task study. The Quarterly Journal of Experimental Psychology. 2009; 62:733–745. [PubMed: 18720294]

Hollingworth A, Maxcey-Richard AM. Selective maintenance in visual working memory does not require sustained visual attention. Journal of Experimental Psychology: Human Perception and Performance. 2013; 39:1047–1058. [PubMed: 23067118]

Janczyk M. Level-2 perspective taking entails two processes: Evidence from PRP experiments. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2013; 39:1878–1887.

Janczyk M, Grabowski J. The focus of attention in working memory: Evidence from a word updating task. Memory. 2011; 19:211–225. [PubMed: 21287425]

Janczyk M, Pfister R, Wallmeier G, Kunde W. Exceptions to the PRP effect? A comparison of prepared and unconditioned reflexes. Journal of Experimental Psychology: Learning, Memory, & Cognition. (in press).

Janczyk M, Wienrich C, Kunde W. On the costs of refocusing items in working memory: A matter of inhibition or decay? Memory. 2008; 16:374–385. [PubMed: 18432482]

Jiang Y, Olson IR, Chun MM. Organization of visual short-term memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2000; 26:683–702.

Jolicoeur P. Dual-task interference and visual encoding. Journal of Experimental Psychology: Human Perception and Performance. 1999; 25:596–616.

Jolicoeur, P.; Tombu, M.; Oriet, C.; Stevanovski, B. From perception to action: Making the connection – A tutorial. In: Prinz, W.; Hommel, B., editors. Attention and performance XIX: Common mechanisms in perception and action. Oxford, UK: Oxford University Press; 2002. p. 558-586.

Landman R, Spekreijse H, Lamme VA. Large capacity storage of integrated objects before change blindness. Vision Research. 2003; 43:149–164. [PubMed: 12536137]

Lien M-C, Ruthruff E, Johnston JC. Attentional limitations in doing two tasks at once: The search for exceptions. Current Directions in Psychological Science. 2006; 15:89–93.

Logan GD, Delheimer JA. Parallel retrieval in dual-task situations: II. Episodic memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2001; 27:668–685.

Logan GD, Schulkind MD. Parallel retrieval in dual-task situations: I. Semantic memory. Journal of Experimental Psychology: Human Perception and Performance. 2000; 26:1072–1090. [PubMed: 10884010]

Makovski T. Are multiple visual short-term memory storages necessary to explain the retro-cue effect? Psychonomic Bulletin & Review. 2012; 19:470–476. [PubMed: 22415524]

Makovski T, Jiang YV. Distributing versus focusing attention in visual short-term memory. Psychonomic Bulletin & Review. 2007; 14:1072–1078. [PubMed: 18229477]

Makovski T, Sussman R, Jiang YV. Orienting attention in visual working memory reduces interference from memory probes. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2008; 34:369–380.

Matsukura M, Luck SJ, Vecera SP. Attention effects during visual short-term memory maintenance: Protection or prioritization? Perception & Psychophysics. 2007; 69:1422–1434. [PubMed: 18078232]

Murray AM, Nobre AC, Clark IA, Cravo AM, Stokes MG. Attention restores discrete items to visual short-term memory. Psychological Science. 2013; 24:550–556. [PubMed: 23436786]

Pashler H. Dual-task interference in simple tasks: Data and theory. Psychological Bulletin. 1994; 116:220–244. [PubMed: 7972591]

Pashler H, Johnston JC. Chronometric evidence for central postponement in temporally overlapping tasks. Quarterly Journal of Experimental Psychology. 1989; 41A:19–45.

Pertzov Y, Bays PA, Joseph S, Husain M. Rapid forgetting prevented by retrospective attention cues. Journal of Experimental Psychology: Human Perception and Performance. 2013; 39:1224–1231. [PubMed: 23244045]

Pfister R, Janczyk M. Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. Advances in Cognitive Psychology. 2013; 9:74–80. [PubMed: 23826038]

Posner MI. Orienting of attention. Quarterly Journal of Experimental Psychology. 1980; 32:3–25. [PubMed: 7367577]

Pratt J, Radulescu P, Guo RM, Hommel B. Visuospatial attention is guided by both the symbolic value and the spatial proximity of selected arrows. Journal of Experimental Psychology: Human Perception and Performance. 2010; 36:1321–1325. [PubMed: 20873941]

Rerko L, Oberauer K. Focused, unfocused, and defocused information in working memory. Journal of Experimental Psychology: Learning, Memory, and Cognition. 2013; 39:1075–1096.

Sperling G. The information available in brief visual presentations. Psychological Monographs. 1960; 74:1–29.

Tanoue RT, Berryhill ME. The mental wormhole: Internal attention shifts without regard for distance. Attention, Perception, & Psychophysics. 2012; 74(6):1199–1215.

Tanoue RT, Jones KT, Peterson DP, Berryhill ME. Pre- and retro-cueing differentially rely on prefrontal activations: A tDCS investigation. Brain Stimulation. 2013; 6:675–682. [PubMed: 23266133]

Tombu M, Jolicoeur P. A central capacity sharing model of dual-task performance. Journal of Experimental Psychology: Human Perception and Performance. 2003; 29:3–18. [PubMed: 12669744]

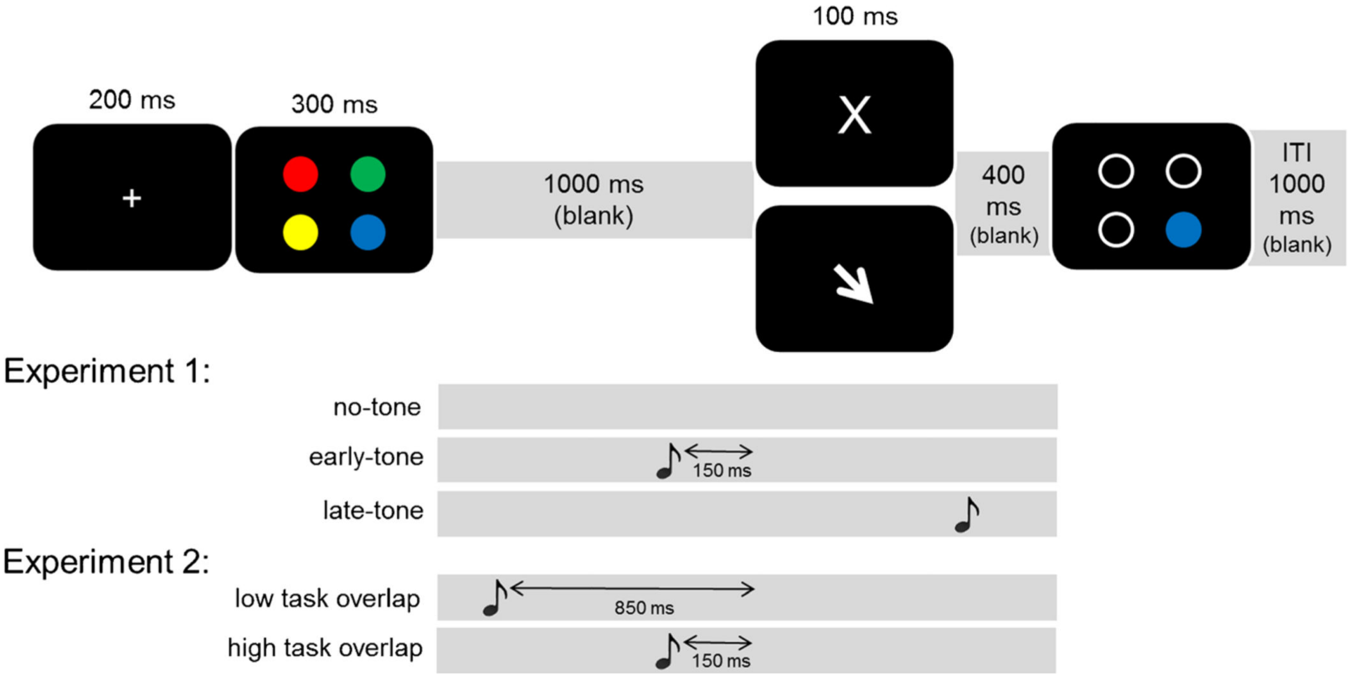

Fig. 1.

Illustration of trials in Experiments 1 and 2. Low task overlap refers to a stimulus onset asynchrony of 850 ms, whereas it was 150 ms in the high task overlap condition

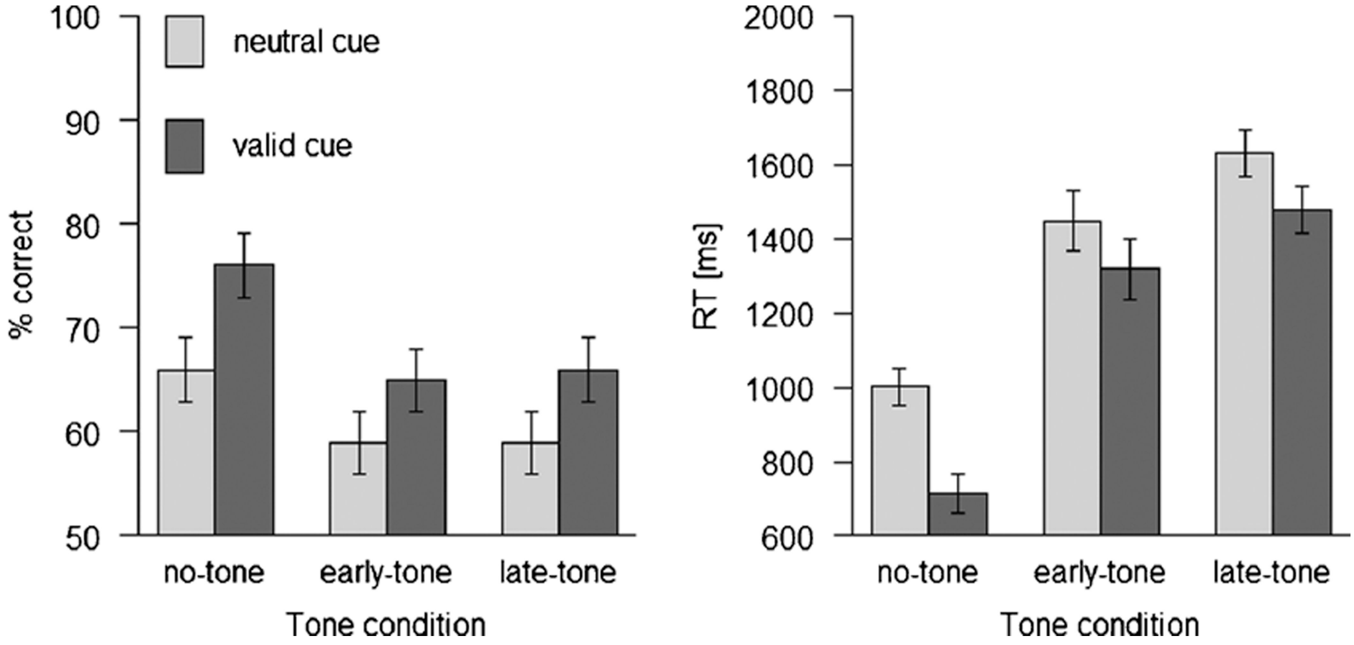

Fig. 2.

Results of the retro-cue task in Experiment 1 as a function of cue type and tone condition. Left panel, mean percentage correct; right panel; mean reaction times (RTs). Errors bars are 95 % within-subjects confidence intervals calculated separately for each tone condition (Pfister & Janczyk, 2013)

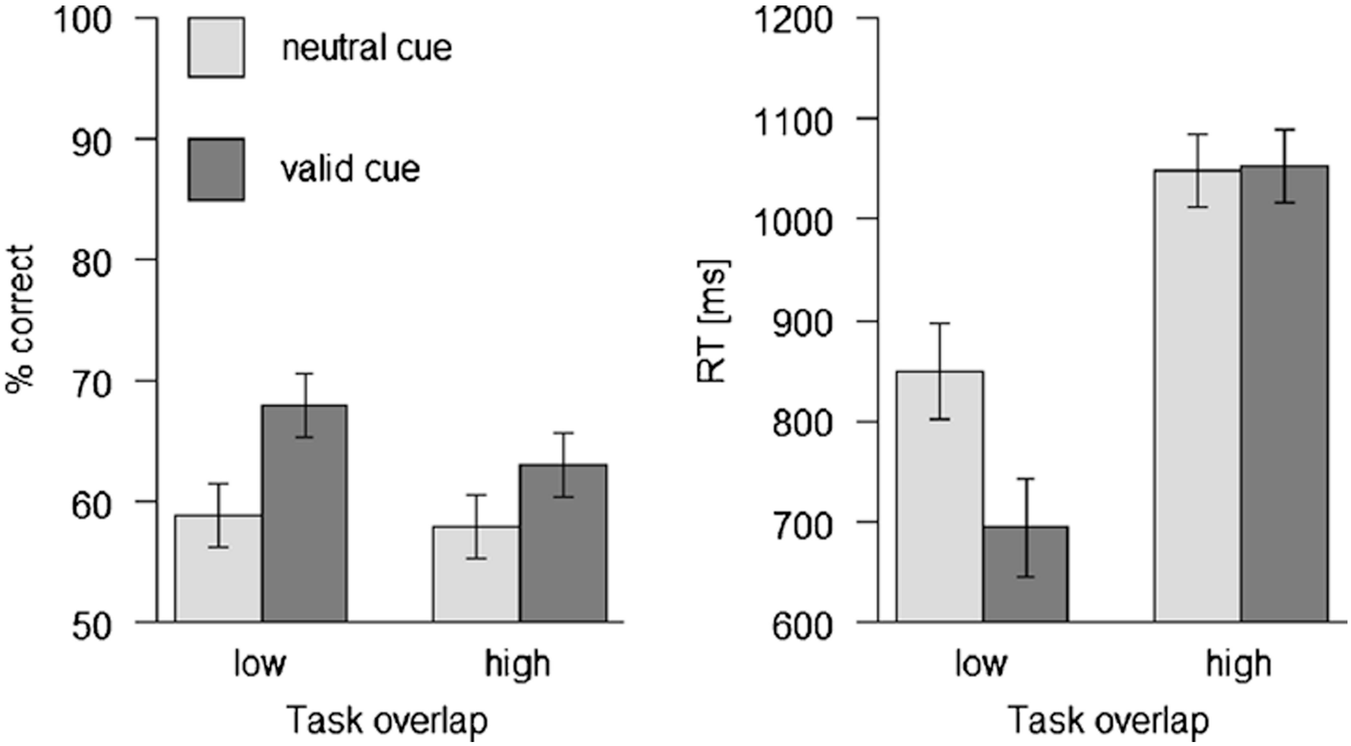

Fig. 3.

Results of the retro-cue task in Experiment 2 as a function of cue type and task overlap. Left panel, mean percentage correct; right panel, mean reaction times (RTs). Errors bars are 95 % within-subjects confidence intervals calculated separately for each task overlap condition (Pfister & Janczyk, 2013)