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Attending to items in working memory: Evidence that refreshing and memory search are closely related

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Abstract

Refreshing refers to the use of attention to reactivate items in working memory (WM). The current study aims at testing the hypothesis that refreshing is closely related to memory search. The assumption is that refreshing and memory search both rely on a basic covert memory process that quickly retrieves the memory items into the focus of attention, thereby reactivating the information (Cowan, 1992; Vergauwe & Cowan, 2014). Consistent with the idea that people use their attention to prevent loss from WM, previous research has shown that increasing the proportion of time during which attention is occupied by concurrent processing, thereby preventing refreshing, results in poorer recall performance in complex span tasks (Barrouillet, Portrat, & Camos, 2011). Here, we tested whether recall performance is differentially affected by prolonged attentional capture caused by memory search. If memory search and refreshing both rely on retrieval from WM, then prolonged attentional capture caused by memory search should not lead to forgetting because memory items are assumed to be reactivated during memory search, in the same way as they would if that period of time were to be used for refreshing. Consistent with this idea, prolonged attentional capture had a disruptive effect when it was caused by the need to retrieve knowledge from long-term memory but not when it was caused by the need to search through the content of WM. The current results support the idea that refreshing operates through a process of retrieval of information into the focus of attention.

Working memory (WM) is a system dedicated to maintaining a small amount of information over a brief period of time. While the role of attention in WM maintenance has been a matter of considerable debate, there is a growing consensus in the field that the maintenance of information in WM typically relies on attention (e.g., Barrouillet, Portrat, & Camos, 2011; Cowan, 1995; Hudjetz & Oberauer, 2007). The nature of the attention-based mechanism of maintenance, however, is still poorly understood. The current study aims at advancing our understanding of this mechanism, called refreshing (Raye, Johnson, Mitchell, Greene, & Johnson, 2007).

The assumption is that briefly re-attending to the representations of information prolongs their activation and prevents their loss from WM (Barrouillet et al., 2011; Cowan, 1992; Raye et al., 2007). The processes involved are sometimes referred to as reactivation, retrieval and attentional focusing. Consistent with the idea that people use attention to

maintain information in WM, it has been shown that decreasing the proportion of time during which attention can be used for refreshing results in poorer memory. Specifically, a negative linear relationship has been observed between the proportion of time during which attention is occupied by concurrent processing, thereby preventing refreshing, and recall performance (e.g., Barrouillet et al., 2011). In support of the idea that maintenance of information in WM relies on domain-general attention, it has been shown that memory for visual, spatial and verbal material depends on the attentional demands of concurrent processing (e.g., Vergauwe, Barrouillet, & Camos, 2009, 2010).

Behavioural, developmental and neuroimaging research strongly suggests that refreshing is independent from articulatory rehearsal (e.g., Cowan et al., 1998; Camos, Lagner, & Barrouillet, 2009; Hudjetz & Oberauer, 2007; Raye et al., 2007); articulatory rehearsal is assumed to rely on subvocal articulation rather than attentional reactivation. Refreshing and articulatory rehearsal also appear to differ substantially in their estimated speed. In a recent study, Vergauwe, Camos and Barrouillet (2014) showed that, when the use of articulatory rehearsal was prevented by imposing articulatory suppression, response times in an attention-demanding processing task were a linear function of the number of verbal items concurrently maintained; responses took about 40–50 ms longer per additional item in WM (see also Jarrold, Tam, Baddeley, & Harvey, 2011). The authors interpreted this pattern to reflect the fast rate of refreshing, in sharp contrast with the rate of covert speech, estimated at about 150–200 ms per item (Landauer, 1962).

This above estimate of the rate of refreshing in WM lends some support to a hypothesis put forward by Cowan (1992). According to this hypothesis, scanning through a set of items represented in WM for the purpose of retrieval of a particular item can serve to reactivate these representations, suggesting that refreshing and scanning might be similar. Memory scanning has historically been studied using the Sternberg paradigm (Sternberg, 1966) and its estimated speed is very similar to the estimated refreshing speed. In the Sternberg paradigm, a list of items is presented, followed by a single probe item for which participants need to judge whether the probe is a member of the study list. The classic result is that response times to the probe are a linearly increasing function of list length, with responses taking about 40 ms longer for each additional verbal memory item (Sternberg, 1966). Based on the similarity of the estimated refreshing speed and scanning speed, we recently pointed out that refreshing of items in WM might be closely related to memory search, both processes being instances of a basic covert memory process that quickly retrieves the memory items into the focus of attention, thereby reactivating the information (Vergauwe & Cowan, 2014; see also Cowan et al., 1998; Jarrold et al., 2011).

The present study aimed at providing a first direct test of the hypothesis that memory search causes refreshing. Therefore, our goal was to examine how recall performance is affected by prolonged attentional capture caused by memory search. The research of Barrouillet and colleagues has shown that the disruptive effect of processing on maintenance does not depend on the nature of the processes capturing attention but on the proportion of free time during which they capture attention, thereby impeding refreshing; i.e., the cognitive load (Barrouillet et al., 2011). For example, in one study, participants were presented with series of letters to be maintained, followed by a number of digits to be processed at a fixed pace.

Participants were instructed to judge either the location of the digits on screen or their parity status (odd vs. even). The rationale was that the parity task involved prolonged attentional capture, relative to the location task, because it requires retrieving knowledge from long-term memory (LTM) on top of response selection. Accordingly, it was found that, at equal pace, the parity task resulted in slower reaction times and induced commensurately lower memory performance (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007).

In the current study, we made use of these findings regarding cognitive load. In our task, short series of red letters were presented for subsequent recall and four successive black letters were presented at a fixed pace between the letters to be remembered (Figure 1). Participants were instructed to ignore the black letters (Ignore condition), judge their spatial location (Location condition), judge their alphabetic position (Alphabet condition), or judge them as present in or absent from the list of red letters presented so far (Memory condition). The assumption was that, relative to the Location task, the Alphabet task will result in prolonged attentional capture caused by the requirement to retrieve knowledge from LTM. Thus, in line with Barrouillet et al. (2007, 2011), we expected that the Alphabet task would result in poorer recall. If memory search and refreshing are both relying on retrieval from WM, then prolonged attentional capture caused by memory search should not lead to such forgetting because memory items are assumed to cycle through the focus of attention during memory search and thus, memory items are assumed to be reactivated during that period of time, in the same way as they would if that period of time were to be used for refreshing directly. Thus, in contrast to the expected difference in recall performance between Location and Alphabet, we did not expect recall performance to suffer from prolonged attentional capture caused by memory scanning in the Memory task, relative to Location.

Method

Participants and Design

Thirty-two undergraduate psychology students (16 females, mean age = 21.22) enrolled at the University of Missouri-Columbia and were paid \$15 for their participation. They were native speakers of English and had normal or corrected-to-normal vision. Task (Ignore, Location, Alphabet or Memory) was manipulated within subjects.

Materials, Tasks, and Procedure

Participants were presented with series of 4, 5 or 6 red letters to be remembered. The presentation of each red letter was followed by the successive presentation of 4 black letters. Red letters were presented at the center of the screen, whereas black letters were presented either in the lower part or the upper part of the screen.

A set of 18 consonants was used as stimuli; half of the consonants occur before the letter “O” in the alphabet (D, F, G, H, J, K, L, M and N) and half of the consonants occur after the letter “O” in the alphabet (P, Q, R, S, T, V, W, X and Z).

Each series began by a screen announcing the number of letters that was to be maintained. Participants were required to press a button to start the trial. First, a fixation cross (+) was centrally displayed (750 ms), followed the first red letter. Red letters were presented for

1000 ms, followed by a 6-s processing phase after a 500-ms delay. In each processing phase, each black letter was displayed for 1000 ms and was followed by a delay of 500 ms.

There were four experimental conditions (Figure 1): (1) In the Ignore condition, participants were instructed to ignore the black letters and to keep their index fingers on the buttons until they were prompted to use the keyboard for recall at the end of a series, (2) In the Location condition, participants were instructed to judge the location of each black letter (i.e., upper part vs. lower part of the screen), (3) In the Alphabet condition, participants were instructed to judge the alphabetic position of each black letter (i.e., before vs. after the letter “O”), and, (4) In the Memory condition, participants were instructed to judge the status of each black letter (i.e., present in or absent from list presented so far). All decisions were to be made as fast as possible without making errors.

For half of the participants, the responses “up” (location), “present” (memory) and “before” (alphabet) were made by pressing the right button and the responses “down”, “absent” and “after” by pressing the left button. This stimulus-response mapping was reversed for the remaining participants. Responses and reaction times were recorded. At the end of the series, the black outline of a rectangle appeared on screen, prompting participants to recall the red letters in order of appearance by using the keyboard. Each letter that the subject typed was echoed on screen. The participant pressed ENTER to finish recall.

The experiment started with a visualization of a trial. Next, four blocks of 9 trials were presented. Each block corresponded to one of the four Task conditions and started with instructions, followed by two practice trials in which auditory feedback was given for processing responses. Next, 9 experimental trials followed within the block; 3 series of 4 red letters, 3 series of 5 red letters and 3 series of 6 red letters were presented in random order. The assignment of materials to the four different task conditions were counterbalanced across participants, as was the order in which the different tasks (trial blocks) were presented to participants.

Four sets of 9 series were created. Across participants, these were rotated among the four Task conditions. Within a set of 9 series, red and black letters per series were selected so that, for each of the processing tasks requiring responses, the two response options were balanced. For the target-present black letters, all red letters presented so far in the series had equal chances of being used and care was taken to limit repetitions of the same target within one processing phase. Target-absent black letters never corresponded to a red letter that was going to be used as a memory item later in the trial¹.

Recall performance was scored by calculating PCU scores (i.e., partial-credit unit scoring; Conway et al., 2005), expressing mean proportion of letters that were recalled correctly with respect to serial order within a series.

¹Due to a programming error, this condition was not fulfilled on two trials in the Memory search condition for eight participants. Removing these trials from further analyses did not change the observed pattern of recall performance; there was a significant difference between Location and Alphabet, $p < .01$, but not between Location and Memory, $p = .82$.

Results and Discussion

To ensure that participants paid attention to the processing task, only trials with processing accuracies of at least 80% were included in the following analyses (9% of the trials were discarded). The data of one participant were excluded because the participant did not have any trials in the Alphabet task that reached this criterion. The data of one additional participant was discarded because no recall responses were recorded. For the remaining 30 participants, mean processing accuracies were 97%, 89% and 93% for the Location, Alphabet, and Memory tasks, respectively. As expected, correct response times (RTs) were longer in the Alphabet task ($M=686$ ms, $SD=70$ ms) and the Memory task ($M=628$ ms, $SD=79$ ms), relative to the Location task ($M=441$ ms, $SD=79$ ms), $t(29)=23.26$, $p<.001$, and $t(29)=16.80$, $p<.001$, respectively. Comparable results were obtained when we used processing accuracy criteria of 70% or 90% instead of 80%.

Analysis of recall performance

A repeated-measures ANOVA on the PCU scores with Task (Ignore, Location, Alphabet, or Memory) as within-subject variable revealed a significant effect of Task on recall performance, $F(2.33,67.50)=12.84$, $p<.001$, $\eta_p^2=0.31$, Greenhouse-Geisser corrected². A planned comparison (Ignore vs. all other conditions) showed that recall performance suffered from the requirement to perform a secondary task during the 6-s delays in between the presentation of the memory items, $F(1,29)=16.81$, $p<.001$, $\eta_p^2=0.37$. Importantly, in line with our main prediction, recall performance was disrupted by the prolonged attentional capture induced by retrieval of knowledge from LTM (Location vs. Alphabet, .86 vs. .76), $F(1,29)=11.69$, $p<.01$, $\eta_p^2=0.29$, but not by prolonged attentional capture induced by memory search (Location vs. Memory, both .86), $F<1$.

Temporal analysis

Following Barrouillet et al. (2007, 2011), we estimated the cognitive load (CL) involved in the different processing tasks by calculating the ratio between the total processing time of the black letters presented in the processing phases and the total time available to process them (6500 ms). Cognitive load was set to 0 for the Ignore condition and was calculated, for the Location, Alphabet and Memory tasks, by adding up the response times within processing phases and dividing the sum by 6500. CL was lowest in the Location condition ($M=.27$) and was significantly higher in the Alphabet condition ($M=.42$), $t(29) = 22.39$, $p<.001$, and in the Memory condition ($M=.38$), $t(29) = 16.17$, $p<.001$. If memory search does not cause refreshing, then recall performance should be a direct function of CL calculated in this way. However, if memory search causes refreshing, then recall performance in the Memory condition should be better than expected from the CL calculated in this manner.

We plotted recall performance as a function of CL, for the non-Memory conditions (i.e., Ignore, Location and Alphabet), to obtain a function relating recall performance to approximated CL for those conditions in which attentional capture was not induced by memory search (Figure 2). Slopes and intercepts of this function were calculated for each

²Including List length as a second within-subjects variable revealed significant main effects of Task and List length but no interaction.

individual. Next, to examine whether recall performance is affected differentially by prolonged attentional capture caused by memory search, the expected PCU score for the Memory condition was calculated based on the parameters of this linear function for each individual. Observed recall performance in the Memory condition ($M=.86$) was significantly higher than what would be expected from the linear function ($M=.79$), $t(29) = 3.67$, $p < .001$. This strongly suggests that attentional capture caused by memory search is different from attentional capture caused by other attention-demanding processes.

The current study is the first to provide direct evidence for the hypothesis that refreshing and memory search are closely related (Cowan, 1992; Vergauwe & Cowan, 2014). Consistent with the idea that both processes rely on retrieval of information into the focus of attention, we observed that prolonged attentional capture induced by memory search did not lead to forgetting while prolonged attentional capture induced by retrieving knowledge from LTM did lead to forgetting. This is exactly what we expected; decreasing the proportion of time during which refreshing is impeded by concurrent processing has no disruptive effect on recall when the process that is capturing attention reactivates the memory items.

Our assumption was that judgments in the Memory task were based on memory search, the process by which the content of WM is scanned (Sternberg, 1966). One could, however, argue that the decision is not based on the result of an active search in the central region of WM, but rather on familiarity that arises from activated representations in LTM. It has been proposed that set-size effects can be used to differentiate between these possibilities. Specifically, the presence of set-size effects (increasing response time as a function of the number of items in WM) is assumed to be a behavioral marker of the list items being represented in the central, capacity-limited component of WM, as opposed to LTM (e.g., Burrows & Okada, 1975; Souza, Rerko, & Oberauer, 2014). We can examine this. In our Memory task, the number of items in WM increases across the different processing phases, i.e., one item is in WM in the processing phase following the presentation of the first memory item, two items following the presentation of the second memory item, and so on. Using the serial position of the first four processing phases in our Memory task as a proxy for the number of items represented in WM, we observed that RT increased in a linear way with set-size (mean slope of 35 ms/item for target-absent probes, $R^2 = .996$; mean slope of 37 ms/item for target-present probes, $R^2 = .98$)³. This is very similar to the classic Sternberg (1966) finding and suggests that participants engaged in an active search in the central component of WM, rather than making a decision based on familiarity. As we expected, prolonged attentional capture caused by this process did not result in forgetting. Note, however, that this does not mean that the Memory task did not lead to any forgetting at all; recall in the Memory condition was poorer than in the Ignore condition. Some forgetting is to be expected because attentional capture in the Memory task is not only caused by the process of memory search; attention is probably also needed for other processes such as stimulus encoding and response selection.

³Analysis was restricted to the first four processing phases, equating the number of trials across different list lengths. Calculating slopes separately per list length, using all processing phases, resulted in mean slopes of 37 ms ($R^2 = .98$), 34 ms ($R^2 = .98$) and 36 ms ($R^2 = .93$), for lists of 4, 5 and 6 memory items.

Although the present results support the idea that people use available time to refresh decaying memory traces by retrieving them quickly into the focus of attention, an alternative account would be to assume that the amount of representation-based interference varied across the different tasks, with more interference resulting in poorer recall. Since subjects were presented with the same material in all four tasks, differential levels of interference could not have arisen directly from the incoming information. Memory performance could not have improved in the Memory condition simply because memory items are being re-presented during the processing phase; re-presentation of memory items happens in all secondary tasks and, across participants, the same material was presented in the four different tasks. Also, an exploratory analysis suggests that recall performance of each memory item in the Memory condition is not influenced by the number of target-present probes following it, though this null result warrants further testing.

However, it is possible that the amount of interference is determined by the number of representations that are internally generated during processing. Then, to accommodate our observed pattern, one would have to assume a difference in the amount of internally generated interference between the Alphabet task and the Location task large enough to cause forgetting. It might be worth pointing out here that the comparison of the Location task and the Alphabet task served as a control comparison, aiming at replicating the findings of Barrouillet et al. (2007, 2011) of prolonged attentional capture at fixed pace resulting in poorer memory. Still, one might argue that poorer performance in the Alphabet task is caused by some kind of representation-based interference between the black letters to process and the red letters to maintain, not present in the other tasks.

One possible source of interference in the Alphabet task would occur if subjects performed a serial search through the alphabet to determine the position of the black letter. Analyzing the RTs in the Alphabet task as a function of their alphabetic position, however, did not confirm the use of this strategy. Forward serial search starting from the beginning of the alphabet should give rise to an asymmetrical pattern, with RTs increasing as the alphabetic position gets closer to the reference letter ("O"), and then flat across alphabetic positions after the reference letter. Instead, we observed a symmetrical distance effect, with faster RTs for letters that are further from the letter "O", on both sides of this reference letter (means of 663, 715 and 791 ms, for letters D-H, J-M, and N, respectively, and, means of 758, 693 and 645 ms, for letters P, Q-T, and V-Z, respectively). Together with the set-size effect observed in the Memory task indicating that participants were considering the memory items represented in WM, it seems difficult to argue that the level of internally generated interference was higher in the Alphabet task than in the Memory task. Thus, it appears difficult to account for the present pattern of findings in terms of differential levels of representation-based interference.

To conclude, our results strongly suggest that refreshing and search in WM are closely related. Because a few authors have discussed a kind of refreshing that relies on retrieval from LTM rather than WM (e.g., Loaiza & McCabe, 2012; McCabe, 2008), future research is needed towards a unified view of refreshing.

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Figure 1. Illustration of the WM task. Series of red letters to-be-remembered were presented (shown in solid boxes), each red letter being followed by a processing phase of fixed duration (6500 ms) during which four black letters (shown in broken-line boxes) were presented at a fixed pace (1 black letter per 1500 ms). The task to perform on the black letters was varied through instructions: (1) Ignore (no response required), (2) Location (is letter presented in upper or lower part of the screen?), (3) Alphabet (does the letter appear before or after the letter “O” in the alphabet?), or (4) Memory (is this letter present in or absent from the list of red letters presented so far?). The example shows the beginning of a trial (presentation of first two memory items) and examples of the decisions are shown for the black letters shown after the presentation of the first memory item, together with the attention-demanding processes assumed to be involved in each of the processing tasks (*italic*).

Figure 2. Recall performance (PCU score) as a function of the approximated Cognitive Load for the tasks performed on the processing items that followed each memory item: Ignore, Location, Alphabet or Memory task. Error bars represent standard error for both measures.