Journal of Experimental Psychology:
Learning, Memory, and Cognition
2008, Vol. 34, No. 6, 1339–1348

0278-7393/08/$12.00 DOI: 10.1037/a0013078

Two Dissociable Updating Processes in Working Memory

Yoav Kessler and Nachshon Meiran
Ben-Gurion University of the Negev

The authors show that the updating of working memory (WM) representations is carried out by the cooperative act of 2 dissociable reaction time (RT) components: a global updating process that provides stability by shielding WM contents against interference and a local process that provides flexibility. Participants kept track of 1–3 items (digits or Gibson figures). In each trial, the items either were similar to those in the previous trial or were different in any or all of the items. Experiments 1 and 2 established the existence of 2 independent RT components representing the 2 updating processes. Global updating cost was sensitive to total number of items in WM (set size), regardless of the number of items that actually were modified. Local updating cost was sensitive to the number of modified items, regardless of the set size. Experiment 3 showed that participants had to dismantle the representation formed by previous global updating in order to carry out new updating.

Keywords: working memory, short-term memory, updating, binding, set size

Working memory (WM) is among the core processes that enable us to deal with our goals and the ever-changing demands of the environment. It is the mental machinery that allows us to hold and manipulate the content of our thoughts and to update our thoughts to accommodate new input. To accomplish this, WM has to keep information in a form that provides flexibility and stability at the same time (Durstewitz, Seamans, & Sejnowski, 2000; O'Reilly, Braver, & Cohen, 1999; cf. Goschke, 2000). On the one hand, the information must be represented in a form flexible enough to allow for rapid changes that must be implemented immediately, so we can proceed toward the behavioral goal. On the other hand, the rapid changes of information require WM to protect the information in its present representation from interference from its previous states or from cross-talk from other items stored in WM. For example, when WM is solving a multistage mental computation, with many interim results that will need to be combined for the final outcome, each result must be highly stable in the face of proactive interference from previous, now irrelevant, interim results, yet be flexible enough to allow its own modification as the solution process proceeds. This conflict between these two attributes of the WM system is mostly relevant when content of WM is changed. Accordingly, in order to study the differential processes that support either flexibility or stability, researchers should look at situations that require updating of WM contents.

The ability to update WM rapidly and accurately is crucial for many high-level cognitive tasks, such as reading comprehension (Carretti, Cornoldi, De Beni, & Romanò, 2005; Palladino, Cornoldi, De Beni, & Pazzaglia, 2001), reasoning (Carpenter, Just, & Shell, 1990), arithmetic calculations (Deschuyteneer, Vandierendonck, & Muyllaert, 2006), and word problem solving (Passolunghi & Pazzaglia, 2005). These tasks require us to deal with an ongoing, rapidly changing stream of information in order to accomplish our goals. Importantly, WM updating (as opposed to other executive functions of switching and inhibition) is highly correlated with both fluid and crystallized intelligence (Friedman et al., 2006). Put in a broader, "real-life" context, WM updating is crucial for holding of a correct worldview. Keeping track of the correct information is necessary so we can conceive of the world accurately without being distracted by now-irrelevant information, such as in the case of overcoming the effects of misinformation and misconceptions (Lewandowsky & Heit, 2006).

Before describing our present study, we begin with a definition of WM updating. Following Buzsáki (2006), we distinguish between the phenomenal concept of WM updating and its underlying mechanisms. The phenomenal concept of WM updating was defined by Morris and Jones (1990) as "modifying the current status of a representation of schema in memory to accommodate new input" (p. 112). This definition necessitates not only the replacement of current memory content by new material but also the modification of old information according to new input. In other words, the definition of updating makes it possible that some parts of the old material will stay intact while other parts change. In this article, we broaden this definition to any change in the contents of WM (i.e., either a modification or a replacement of old information). It should be noted that this phenomenal definition does not postulate any underlying mechanism or theoretical framework. In fact, WM updating may be carried out by a variety of psychological processes. Moreover, it may not be carried out by the same processes in every context, because the processes that accomplish WM updating may vary between tasks, situations, and strategies.

Yoav Kessler and Nachshon Meiran, Department of Psychology and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel.

The research was supported by a grant to Nachshon Meiran from the Israel Science Foundation. We thank Rotem Eren-Rabinovich for English proofreading.

Correspondence concerning this article should be sent to Yoav Kessler, Department of Psychology and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel. E-mail: kesslery@bgu.ac.il

Morris and Jones (1990) investigated WM updating using the running memory span paradigm (Pollack, Johnson, & Knaff, 1959), which measures the accuracy of recall after a series of updating operations. They found that the number of updates did not interact with manipulations affecting the phonological loop (e.g., articulatory suppression). This finding was interpreted as evidence that updating is performed in the central executive part of Baddeley's (1986) model and does not involve the phonological loop. Thus, it supports the view of updating as an executive function that is independent of pure maintenance.

The running span paradigm is a variant of the encoding–retrieval paradigm that prevails in the study of short- and long-term memory. The idea behind the encoding–retrieval paradigm is that encoding processes are covert and do not have immediate measurable output. Consequently, the only behavioral way for researchers to make inference about encoding processes is to manipulate encoding difficulty and to measure the impact of this manipulation on retrieval accuracy. Because updating can be classified as a manipulation of encoding, its correctness but not its temporal duration can be measured. This limitation, inherent in the running span paradigm, prevents a direct study of the updating process in isolation.

Our approach in the present study (see also Kessler & Meiran, 2006) diverged from the encoding–retrieval tradition and enabled direct manipulation and measurement of the updating process. Updating duration was measured directly in real time, which made it possible for us to both ask and answer new questions regarding the updating process itself. Specifically, participants were presented with a series of screens, each containing one, two, or three items (memory set size), and their goal was to remember the last screen. The participants pressed a key when they were ready to receive the next screen and the reaction time (RT) to the keypress was measured. Retrieval success was measured only when the series of screens ended (see Figure 1). The incorporation of RT measurement made it possible for us to look at updating effects when the memory set size was relatively small and accuracy was still at ceiling. Also, as we describe below, our paradigm allows updating to involve several items at a time (unlike the running span paradigm, which limits updating to one item at a time). In the present study, we capitalized on this capability and examined the joint influence of set size and the number of updated items on updating duration.

Despite the clear importance of WM updating, both as a theory and as a major component of many high-level cognitive functions, we lack a good understanding of its underlying processes (see Carretti, Cornoldi, & Pelegrina, 2007, for a similar argument). One of the reasons for this situation is the lack of theoretical concepts that can explain WM updating. We suggest that keeping track of the current state of information in WM requires a correct attribution of content (item) to a schema (context). Accordingly, the context can be used to retrieve its content. However, present theories of recollection cannot explain how this can be done. When the information in WM is updated rapidly, the individual cannot maintain the present state of information by relying on familiarity alone, because familiarity is insensitive to the context and may lead the individual to treat no-longer-relevant items as still relevant (Oberauer, 2001). Also, even the linking of item information to its nontemporal context is insufficient in situations in which there are frequent updates. Consider an example in which an item is correctly linked to the nontemporal context: As shown in Figure 1, the digit *3* is linked to the leftmost frame on the screen, but then the digit inside the frame is updated to be *6*. Such an association could lead the individual to consider a no-longer-relevant item (*3*) as relevant even after that item has been updated. It is therefore argued that, if we are to retrieve WM content reliably, updating should be carried out by formation of strong links, not only between an item and its nontemporal context but between the item and the exact temporal context (e.g., "*6* belongs to the most recently updated WM content") or the item and the other items currently held in WM (e.g., "*6* was the leftmost item when *2* was the middle item and *4* was the rightmost item"). In other words, frequent WM updates make it especially challenging for us to overcome proactive interference.

The present study provides evidence for the existence of two dissociable component processes of WM updating: an item-specific local process and a global process. We argue that though local updating helps flexibility, global updating provides the glue (Treisman & Gelade, 1980) required for stability. Although the two processes have been recognized in the literature, each of them was treated as if it were the only WM updating process. Here, we provide for the first time compelling evidence that these two processes coexist.

The two-process issue refers to the specificity of the updating process. For example, consider a situation in which several items are maintained in WM, but only a subset of them has to be modified due to new input from the environment. How is this situation handled? Which processes are involved in this multi-item but partial updating? The literature presents two contrasting views regarding this and similar scenarios. The first hypothesis is that updating is specific to the items that underwent a modification and does not involve the items that have not changed. The second hypothesis is that the updating process encompasses all the items in WM, whether or not they have been modified. We discuss each of these hypotheses in detail.

Local Updating Hypothesis

The ability to hold separate items in WM, each carrying a different piece of information, dictates the need for selective access, retrieval, and updating for each of them separately. Informational independence among items stored in WM requires a specific updating process that modifies a subset of the items in WM and preserves the content of the other items (Hazy, Frank, & O'Reilly, 2006).

Vockenberg (2006) provided evidence that supports the existence of such a local updating process. Participants in her experiments were presented with sets of 5 stimuli (letters or words, in different experiments). At the beginning of the trial sequence, initial stimuli sets were presented on the screen and had to be memorized. In each of the following trials, a new 5-item set appeared, which either was identical to the set presented in the previous trial or was different in 1, 2, 3, 4, or all 5 stimuli. For example, when the stimulus set in the preceding trial was *WAKOG,* the stimulus set in the present trial could be *WAKOG* (no updating), *WABOG* (updating of 1 letter), *LABOG* (updating of 2 letters), and so forth. Accordingly, the number of local updating processes varied between trials, between 0 and 5. The participants were instructed to remember only the last set that had been

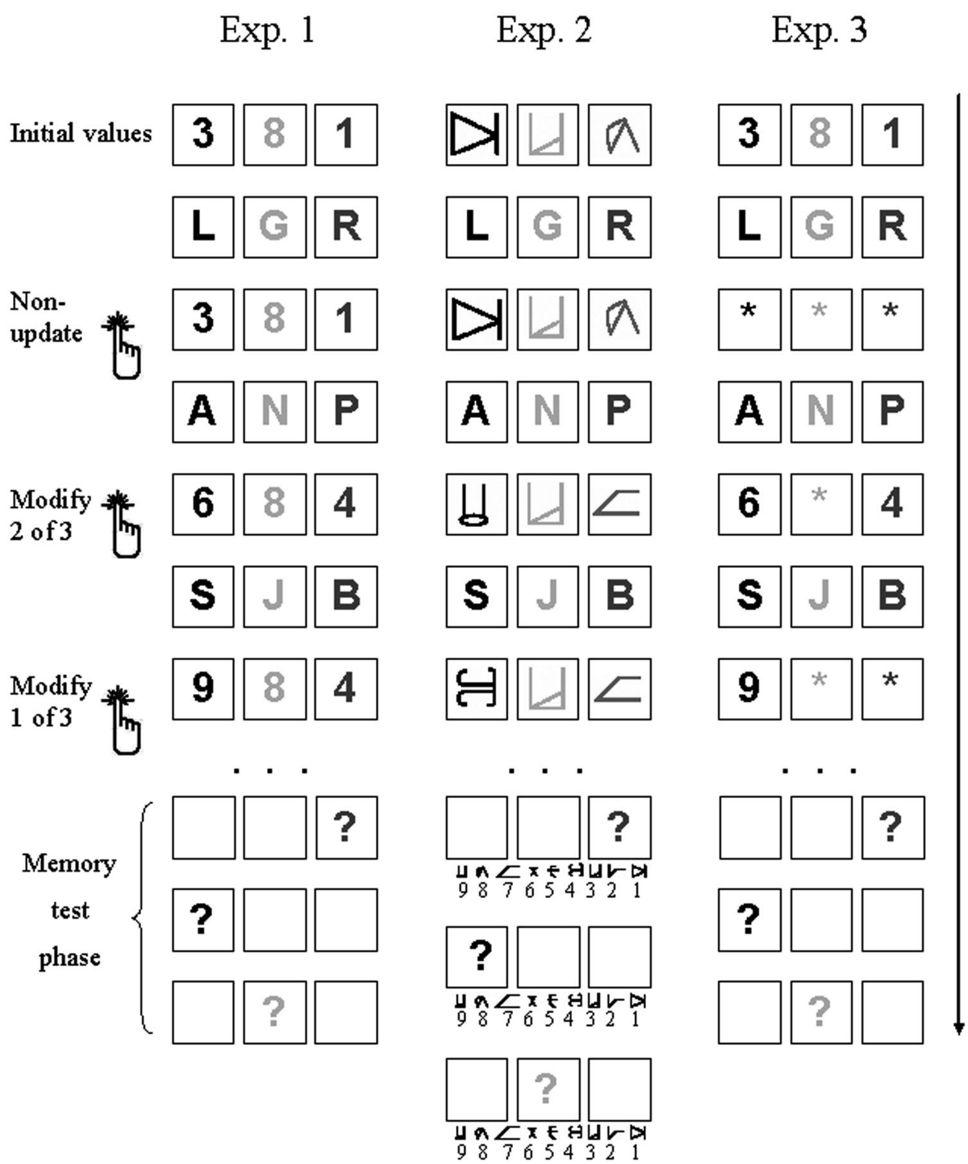

Figure 1. A schematic description of a trial sequence with set size of 3 items, in Experiments 1–3. The finger symbol represents reaction time measurement. The number of trials within the trial sequence was varied randomly.

presented to them. Thus, upon the presentation of each stimulus set, the participants had to update their memory with the new information and then press a key. RT was measured in each trial. After a varying number of trials, a memory test was administered, in which the participants were required to recall the last stimulus set that had been presented. Vockenberg reasoned that, because the termination of the trial sequence was unexpected, the participants had to update their WM with the new information in every trial. The results indicated a response slowing with an increasing number of updated stimuli. This slowing reached an asymptote, so that no additional slowing was observed beyond three updated items. Vockenberg's results provide evidence supporting the local updating hypothesis, because RT was sensitive to the number of modified items within a constant set size.

Global Updating Hypothesis

In contrast to Vockenberg, Kessler and Meiran (2006) claimed that all the items in WM are updated together, as a whole, whenever any of them is modified. They used a memory updating paradigm that was based on Oberauer (2002). Participants had to keep track of one or two running counters related to shape categories. Each trial series began with the presentation of an initial value (a digit) for each shape category (e.g., the digit *2* was associated with rectangles). Then, in each trial, a shape was presented with an arithmetical operation. The participants had to apply the arithmetical operation to the value that corresponded to the relevant shape's category, to remember the new outcome, and to press a key in order to move to the next trial. After nine trials, the participants had to report the final value that corresponded to each shape category. Importantly, while the arithmetic operation involved adding or subtracting small digits in 80% of the trials (update trials), it was +0 or −0 in 20% of the trials. The later operations did not require a modification of the relevant counter and hence were considered non-update trials. Updating cost was defined as the difference between trials that required an update of the relevant counter (arithmetical operations other than *+0* or *−0*) and non-update trials. The major finding was that updating cost was at least twice as large in trial sequences that required keeping track of two counters as it was in sequences that involved one counter. Although only one counter was modified at a time, updating cost was sensitive to the total number of WM items. In their work, Kessler and Meiran ruled out a number of alternative explanations, the most notable of which was an explanation in terms of slowing due to WM load. Specifically, they showed that updating cost was insensitive to the presence of newly encoded load information if that load was never updated. These findings were taken as evidence supporting the global updating hypothesis, because RT was sensitive to the WM set size when the number of modified items was constant.

A Synthesis

The present study shows that the local and global updating hypotheses are both inaccurate in the sense of being special cases and that the accurate and more general hypothesis concerns the coexistence of two dissociable updating processes (i.e., local and global). To demonstrate the coexistence of these two processes within the same paradigm, we varied both the set size and the number of modified items. Participants had to keep track of a series of one, two, or three items that was presented in a self-paced manner. Following Vockenberg (2006), we presented stimuli in each trial that either were identical to those presented in the previous trial or were different in some or all of the items. For example, with a set size of two items, zero, one, or two items could be modified as compared with the previous trial. RT was measured between the presentation of the stimulus set and the keypress that was made to advance to the next display. To verify that participants kept the updated contents in WM, we asked them to report the final value of each of the items when the series ended. Note, however, that retrieval was not required when RT was measured. Experiments 1 and 2 were designed to demonstrate the co-occurrence of the two aforementioned WM updating processes and used different stimuli (digits and meaningless visual stimuli, respectively). Experiment 3 provided further support for the role of the global updating process and ruled out some alternative explanations.

The present study extends Kessler & Meiran's (2006) work in three directions. First and most important, although Kessler and Meiran supported the global updating hypothesis, our results showed global updating to be one of two processes involved in WM updating. Second, the present study extends the evidence for global updating, because Kessler and Meiran dealt with item modification and our work showed that global updating takes place when the task involved item replacement. Finally, the paradigm used in the present study removes a confound between updating and stimulus that was present in Kessler and Meiran's paradigm. Specifically, in their paradigm, different stimuli served for the update and non-update conditions. Although the stimuli *+0* and *−0* indicated no update, all other arithmetic operations indicated an update. As the condition and the stimuli were confounded, one could argue that the effects stemmed (at least in part) from the specific stimuli that were used, rather than from the updating per se. Although we regard this claim as highly implausible, given the large effects of several hundreds of milliseconds, it cannot easily be dismissed. Therefore, in the experiments reported here, the same stimuli served in all the conditions. The condition (update vs. non-update) was defined by the relation between the stimuli that were presented in Trial n and those that appeared in Trial $n - 1$ (see Figure 1).

Experiment 1

Method

Participants

Eighteen students from Ben-Gurion University of the Negev and the affiliated Achva and Sapir Colleges participated in the present experiment for partial course credit. All the participants reported having normal or corrected-to-normal vision and not having been diagnosed as suffering from learning disabilities.

Apparatus and Stimuli

The experiment was run on Pentium 4 computers with 17-in. monitors. The software was programmed in E-Prime (Schneider, Eschman, & Zuccolotto, 2002). The digits 1–9 served as WM items, and the letters *A* through *Z* (in uppercase) served as visual masking. Question marks were used at the test phase of each trial sequence. Each stimulus subtended a visual angle of approximately .86° (height) × .57° (width), assuming a 60-cm viewing distance. The digits and letters were presented in red, cyan, or yellow on a black background. Each stimulus was presented inside a 2.20° × 2.20° white frame. With a set size of one item, the frame appeared in the center of the screen. With set sizes 2 and 3, the frames were arranged horizontally, with distances of .57° among them, and were aligned to the center of the screen.

Procedure

The experiment began with a practice stage composed of three trial sequences, one for each set size, followed by three experimental blocks, one for each set size. The presentation order of these blocks was counterbalanced across participants. Each block comprised 20 trial sequences, which were separated by short breaks.

Each trial sequence began with the presentation of digits inside frames on the screen; these served as initial values (see Figure 1 for an example with a set size of three digits). The number of frames and digits corresponded to the WM set size. The stimuli inside each frame were presented in different colors. The assignment of colors to frames was randomly determined at the beginning of each trial sequence and remained constant until the end of the sequence. The color manipulation increased the perceptual discriminability between the stimuli. This encouraged the participants to treat the stimuli separately and discouraged them from treating two or three digits as if they composed a single two- or three-digit number. Upon the presentation of digits inside the frames, the participants were required to remember the digits associated with each color and position and to press the space bar. After the keypress, a letter replaced the digits in each of the frames for 1,000 ms. We introduced this aspect to deter participants from performing the task on the basis of visual similarity between adjacent trials. The letters were chosen randomly, and the participants were instructed to ignore them.

In each of the subsequent trials within the trial sequence, the condition was chosen randomly according to the following probabilities: A non-update condition (in which all digits were identical to those presented in the previous trial) was administered with a 50% probability. The other conditions (i.e, those in which any subset of the digits had been modified) were administered with equal probabilities. In each trial, RT was measured as the time passing from the presentation of the digit stimuli to the keypress that indicated the participant was ready to move to the next trial.

Following Vockenberg (2006), we wanted to avoid a situation in which participants could predict when the sequence of trials would end on the basis of probabilities. Such prediction might have resulted in updating taking place only toward the anticipated sequence end, when participants were asked to report the last stimulus set. Consequently, we kept the probability that the sequence would end in each trial at 10%; this percentage implied that the trial sequence length was distributed geometrically, with an expected value of 10. Given the geometric distribution, the actual range was between 1 and 70. At the end of each trial sequence, a question mark appeared inside each of the frames, one at a time, and the participant had to key in the last digit associated with this frame. The order in which the question marks appeared in the frames was random.

Design and Analysis

The two independent within-subject variables were set size and modified items. However, these variables do not create a fully factorial design, because the number of levels of modified items increases with set size. Accordingly, an omnibus analysis of variance (ANOVA) was conducted with condition as a within-subject independent variable that had nine levels corresponding to the nine possible combinations of set size and modified items. These conditions (number of modified items/set size) were as follows: 0/1 (i.e., zero updating/set size = 1), 1/1, 0/2, 1/2, 2/2, 0/3, 1/3, 2/3, and 3/3. Then, the analysis was conducted in two stages. First, we compared local updating costs between set sizes in order to probe the local updating process. A second ANOVA compared the cost of modifying only one item, between set sizes. We conducted this analysis in order to probe the global updating process. Alpha was .05 in all the analyses.

Results and Discussion

Accuracy

Trial sequences were considered correct only if all values were reported correctly at the end of the sequence. The percentages of correct trial sequences were 99%, 99%, and 97%, respectively, for set sizes 1, 2, and 3. The set size effect was marginally significant, $F(2, 34) = 3.12$, $MSE = .0010$, $\eta_p^2 = .16$, $p = .06$.

RT

Only trials within sequences in which the final values were reported correctly were analyzed for RT. RTs shorter than 100 ms or longer than 4,000 ms were considered as outliers and hence were removed from the analysis (2.3%). RTs for the initial values in each trial sequence were not included in the analysis.

The RT results are presented in Figure 2. A one-way ANOVA showed that the mean RTs in the nine conditions were significantly different from one another, $F(8, 136) = 27.32$, $MSE = 68{,}863.88$, $\eta_p^2 = .62$.

Local updating. To probe the local updating cost, we examined the difference between Conditions 1/3, 2/3, and 3/3. The RT varied significantly among these conditions, $F(2, 34) = 13.03$, $MSE = 14{,}012.94$, $\eta_p^2 = .43$. The contrast examining the linear trend between these conditions was significant, $F(1, 17) = 24.75$, $MSE = 14{,}325.43$, $\eta_p^2 = .59$, and explained 97% of the variance among the three conditions. The fact that the quadratic trend, which represents the nonlinear contribution to the conditions' variance, was both numerically negligible and nonsignificant, $F(1, 17) = .78$, $MSE = 13{,}700.45$, $\eta_p^2 = .04$, indicates that RT increases linearly with the number of modified items within a given set size. Note that the test of linearity could be conducted only for set size 3. A second ANOVA compared the local updating costs between set size 2 and set size 3. This two-way ANOVA included set size (2 vs. 3) as one independent variable and updated items (1 vs. 2) as the second independent variable. The main effect of updated items was significant, $F(1, 17) = 9.54$, $MSE = 21{,}959.82$, $\eta_p^2 = .36$, as well as the main effect for set size, $F(1, 17) = 11.51$, $MSE = 217{,}369.59$, $\eta_p^2 = .40$. Importantly, the two-way interaction was negligible in size and was clearly nonsignificant, $F(1, 17) = .95$, $MSE = 8{,}484.96$, $\eta_p^2 = .05$, $p = .34$. These results support the notion that local updating cost is similar in size for set sizes 2 and 3. This means that local updating is independent of set size, at least within the studied range.

Global updating. To examine global updating, we conducted a two-way ANOVA according to set size (1, 2, or 3) and updating

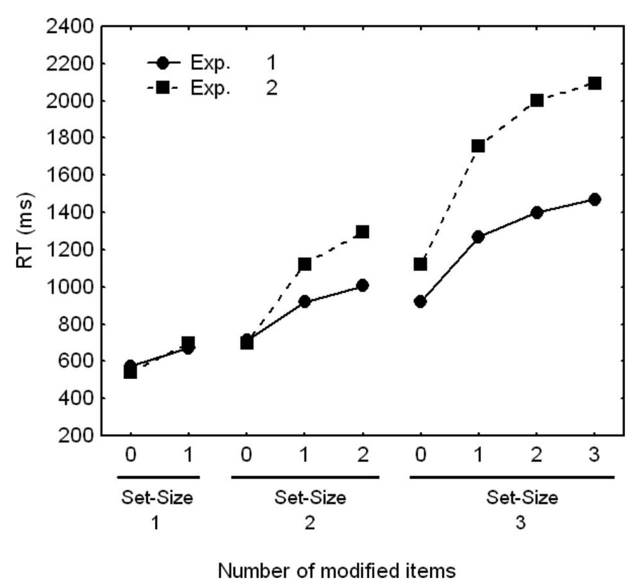

Figure 2. Mean reaction time (RT) by condition for Experiments 1 and 2.

(no updating vs. one modified item) on Conditions 0/1, 1/1, 0/2, 1/2, 0/3, and 1/3. Both main effects were significant, $F(1, 17) = 27.77$, $MSE = 46{,}081.14$, $\eta_p^2 = .62$, and $F(2, 34) = 28.34$, $MSE = 71{,}688.93$, $\eta_p^2 = .63$, for updating and set size, respectively. Most importantly, the interaction was significant, $F(2, 34) = 10.35$, $MSE = 13{,}830.35$, $\eta_p^2 = .38$, which indicates an increase with set size in the time required to modify one item. The difference in global updating cost between set sizes 1 and 2 was significant, $F(1, 17) = 5.02$, $MSE = 10{,}514.23$, $\eta_p^2 = .23$, and the difference between set sizes 2 and 3 was just significant, $F(1, 17) = 4.31$, $MSE = 21{,}395.41$, $\eta_p^2 = .20$, $p = .05$. These results support the existence of a global updating process.

We claim that the global updating cost encompasses all the items in WM and that, therefore, the duration of this process lengthens with increasing set size. However, one could argue that the global updating cost represents the effects of increased WM load. According to this account, only the modified items are updated, but this local updating process becomes lengthier with increased WM load. The WM load account is based in the idea of processing storage trade-off (Just & Carpenter, 1992), according to which greater loads on storage are reflected in a reduced amount of resources available for processing and in consequent processing slowness. We argue that this account cannot explain our results, which showed that the speed at which local updating is performed is unaffected by set size. If the observed results were attributed to storage–processing trade-off, one would expect both processes, the global and the local, to be affected by set size. This prediction was not supported.

An alternative account for our results is that participants needed to scan the display first in order to identify which items, if any, had been modified. This account predicts an lengthening in RT with increasing set size, due to serial scanning (Sternberg, 1966). Experiment 3 provides direct evidence against the memory search account. Before we show this, we further establish the generality of the findings reported above, using different stimuli. This was our goal in Experiment 2.

Experiment 2

We replicated the results of Experiment 1 using a similar paradigm and different memory items. To this end, we used Gibson figures (Gibson, Gibson, Pick, & Osser, 1962; see Figure 1). Except for generalizing the previous findings, the use of Gibson figures discourages using strategic binding of the memory items, of rehearsing the set as a single number (e.g., remembering 2-4-5 as 245). This strategy, which can lead to a global updating process, seemed highly unlikely to occur with Gibson figures.

Method

Participants

Twelve students from Ben-Gurion University of the Negev and the affiliated Achva and Sapir Colleges, who did not participate in Experiment 1, participated in the present experiment for partial course credit. All the participants reported having normal or corrected-to-normal vision and not having been diagnosed as suffering from learning disabilities.

Apparatus and Stimuli

Nine Gibson figures, similar in size to the digits we used in Experiment 1, served as stimuli. The apparatus and stimuli were similar to those we used in Experiment 1 in all other aspects.

Procedure

The procedure was identical to that of Experiment 1, except for the memory test at the end of the trial sequence. Because Gibson figures are meaningless, a recognition test (rather than recall, as in Experiment 1) was administered. A question mark appeared inside each of the frames, in a random order. All the Gibson figures appeared in a row at the bottom of the screen, with digits below them. The participant had to press the digit keys that corresponded to the relevant Gibson figure (see Figure 1). The mapping of Gibson figures to digits changed randomly in each trial sequence to prevent the participants from forming a stable association between these figures and the digits.

Results

Although Gibson figures are visually meaningless stimuli, all the participants reported that they had generated verbal labels for these figures throughout the task. These labels were individual, self-generated words, such as *bulb, tent,* and *umbrella.* This fact did not undermine our intent of preventing the chunking of stimuli into meaningful units (2-4-5 into 245), as none of the participants reported such chunking.

Accuracy

The percentages of sequences in which the report of the final display was correct were 97%, 95%, and 88%, respectively, for set sizes 1, 2, and 3, $F(2, 22) = 6.77$, $MSE = .0047$, $\eta_p^2 = .38$. Accuracy with set size 3 was significantly worse than with set sizes 1 and 2, $F(1, 11) = 12.34$, $MSE = .0047$, $\eta_p^2 = .53$. The latter set sizes did not differ significantly, $F(1, 11) = 1.10$, $MSE = .0047$, $\eta_p^2 = .09$.

RT

The criteria for RT exclusion (2.0%) were similar to these of Experiment 1. The RT results are presented in Figure 2. The first ANOVA, which included all nine conditions, indicated a significant difference among them, $F(8, 88) = 117.48$, $MSE = 34{,}316.64$, $\eta_p^2 = .91$.

Local updating. As in Experiment 1, we probed the local updating cost by looking at the RT difference among Conditions 1/3, 2/3, and 3/3. The main effect among these conditions was significant, $F(2, 22) = 19.35$, $MSE = 18{,}941.05$, $\eta_p^2 = .64$. The contrast examining the linear trend between these conditions was significant, $F(1, 11) = 48.68$, $MSE = 14{,}076.83$, $\eta_p^2 = .82$, and explained 93% of the intercondition variance but not the quadratic trend contrast, $F(1, 11) = 2.00$, $MSE = 23{,}805.26$, $\eta_p^2 = .15$, $p = .18$. These results showed that the increase was linear and established the existence of a local updating cost. To show that this cost was independent of set size, we conducted an ANOVA comparing the local updating cost (measured as the RT increase from modifying one item to modifying two items) in set sizes 2 and 3. The main effect for local updating was significant, $F(1, 11) = 32.92$, $MSE = 15{,}892.26$, $\eta_p^2 = .75$, as was the main effect for set size, $F(1, 11) = 65.18$, $MSE = 83{,}302.11$, $\eta_p^2 = .86$. As in Experiment 1, the two-way interaction was negligible in size and was clearly nonsignificant, $F(1, 11) = 1.06$, $MSE = 15{,}793.01$, $\eta_p^2 = .09$, $p = .33$. This result showed that the local updating cost was independent of set size.

Global updating. To probe the global updating cost, we conducted an ANOVA comparing the cost of modifying one item between set sizes, with updating (0, 1) and set size (1, 2, 3) as variables. As in Experiment 1, both main effects were significant, $F(1, 11) = 107.66$, $MSE = 27{,}529.27$, $\eta_p^2 = .91$, and $F(2, 22) = 99.51$, $MSE = 41{,}749.56$, $\eta_p^2 = .90$, for updating and set size, respectively. Also, the interaction was significant, $F(2, 22) = 41.01$, $MSE = 8{,}399.16$, $\eta_p^2 = .79$; this result indicated an increase in the time required to modify one item with larger set sizes. The difference in global updating cost between set sizes 1 and 2 was significant, $F(1, 11) = 18.77$, $MSE = 11{,}314.83$, $\eta_p^2 = .63$, as was the difference between set sizes 2 and 3, $F(1, 11) = 17.42$, $MSE = 7{,}745.93$, $\eta_p^2 = .61$. These results support the existence of a global updating process.

Discussion of Experiments 1 and 2

The results demonstrate the coexistence of local and global updating processes in WM. We argue that the role of the local updating processes is to modify the information of the relevant items and to leave the other items intact. As noted by Hazy et al. (2006), this specificity is crucial for the joint retention of multiple and separate WM representations. Each representation can be modified without changing the others, and the cost of this modification is proportional to the number of items that have been updated. The role of the global updating process is to stabilize the WM contents and thereby protect them against potential interference. The fact that such a process exists indicates a functional dependence between WM representations and shows that the WM contents are bound into a complex but unitary representation. Experiment 3 addresses this issue.

Experiment 3

Experiment 3 was designed to provide another behavioral marker (in addition to global updating cost) for high-order integration between all the items in WM. We used the paradigm of Experiment 1, with one variation: Only new information appeared in each trial, rather than the values of all the items. When the value related to a frame was not modified, the digit did not appear, and an asterisk was presented inside the relevant frame (see Figure 1).

The notion of a unitary, complex WM representation is discussed in the literature in regard to several levels of representation. It is now clear that, except for the passive storage of information, WM is responsible for the binding of information and, accordingly, for the creation of new representations. Binding is discussed earlier in reference to several levels of generalization. First, features of the same object are arguably bound together in visual WM and so create the phenomenal experience of a singular, integrated object (Kahneman, Treisman, & Gibbs, 1992; Raffone & Wolters, 2001; Treisman & Zhang, 2006). Second, it was shown that the attributes of the bound object are not limited to its perception but include the action codes that were used to act upon it (Hommel, 1998). Third, binding was shown to occur even between visual and verbal modalities (Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000). Baddeley's (2000) idea of an episodic buffer that is both integrative and related to long-term memory (LTM) was suggested to account for these phenomena. Here, we extend this view, which concerned the binding of features into an object, to the binding among several WM objects.

A unique marker used by researchers to demonstrate high-order integrations concerns the comparison of partial and complete content change. Without high-order integration, complete content change should be more difficult than should partial content change. With high-order integration, the relationship reverses, because partial content change requires the dismantling of the complex representation to allow the formation of a new one, whereas dismantling is not required when the content change is complete (Hommel, 1998; Kahneman et al., 1992). Accordingly, we predicted that RT would be shorter when the entire WM content was replaced than when part of the content was replaced.

There was a secondary goal in Experiment 3. Specifically, in the previous experiments, participants had to detect a change in the display relative to the preceding display in order to know if they needed to update WM contents; the time they needed to detect the changes could have accounted for some of our findings. Accordingly, in the preceding experiments, detection of new information required both perceptual scanning (to detect the new information) and memory scanning (to determine if the information was new). Moreover, memory scanning is known to increase with memory set size (Sternberg, 1966). The need for both of these scanning operations was removed in Experiment 3, in which the display contained only the new information and the positions holding old information were marked by asterisks. Consequently, there was no need to scan the display digits to detect the new ones, as only new digits were presented. Similarly, there was no need to consult memory to determine if the digits were new, because the digits that were presented were always new.

Method

Participants

Twelve students from Ben-Gurion University of the Negev and the affiliated Achva and Sapir Colleges, who did not participate in Experiments 1 and 2, participated in the present experiment for partial course credit. All the participants reported having normal or corrected-to-normal vision and not having been diagnosed as suffering from learning disabilities.

Procedure

The procedure was identical to that of Experiment 1, with one exception. Instead of presenting all item values in each trial, we presented only the modified values. An asterisk that appeared inside a frame indicated that its corresponding value had not been modified (see Figure 1).

Results

Accuracy

The percentages of trial sequences whose final display was reported correctly were 98%, 96%, and 92%, respectively, for set sizes 1, 2, and 3, $F(2, 22) = 4.29$, $MSE = .0028$, $\eta_p^2 = .28$. Accuracy with set size 3 was significantly worse than with set sizes 1 and 2, $F(1, 11) = 5.46$, $MSE = .0040$, $\eta_p^2 = .33$. Set sizes 1 and 2 did not differ significantly, $F(1, 11) = 1.54$, $MSE = .0017$, $\eta_p^2 = .12$, $p = .24$.

RT

The criteria for inclusion in the analysis were similar to those of Experiments 1 and 2 (exclusion rate was 0.9%). The results clearly support our prediction. The omnibus ANOVA, which included all the nine conditions, indicated a significant difference, $F(8, 88) = 52.80$, $MSE = 61{,}991.33$, $\eta_p^2 = .83$. Conditions involving a modification of all the items were associated with quicker responses than were conditions involving partial updating (see Figure 3). Condition 2/2 was quicker than Condition 1/2, $F(1, 11) = 13.15$, $MSE = 39{,}254.87$, $\eta_p^2 = .54$, and Condition 3/3 was quicker than Conditions 1/3 and 2/3, $F(1, 11) = 26.17$, $MSE = 86{,}836.18$, $\eta_p^2 = .70$.

Local updating. As in the previous experiments, a local updating cost was found. It was probed with an analysis of the difference between Conditions 2/3 and 1/3, $F(1, 11) = 4.82$, $MSE = 52{,}176.52$, $\eta_p^2 = .30$, $p = .05$.

Global updating. A global updating cost was evident. An ANOVA that compared the cost of modifying one item between set sizes, with updating and set size as independent variables, yielded two significant main effects, $F(1, 11) = 67.13$, $MSE = 71{,}766.41$, $\eta_p^2 = 86$, and $F(2, 22) = 43.30$, $MSE = 60{,}607.31$, $\eta_p^2 = .80$, respectively. Importantly, the two-way interaction was also significant, $F(2, 22) = 49.44$, $MSE = 30{,}170.58$, $\eta_p^2 = .82$. The difference in global updating cost between set sizes 1 and 2 was significant, $F(1, 11) = 25.05$, $MSE = 22{,}694.41$, $\eta_p^2 = .69$, as was the difference between set sizes 2 and 3, $F(1, 11) = 47.38$, $MSE = 19{,}807.32$, $\eta_p^2 = .81$. The existence of global updating cost in this experiment shows that this component cannot be attributed to memory search, because such a search was not required.

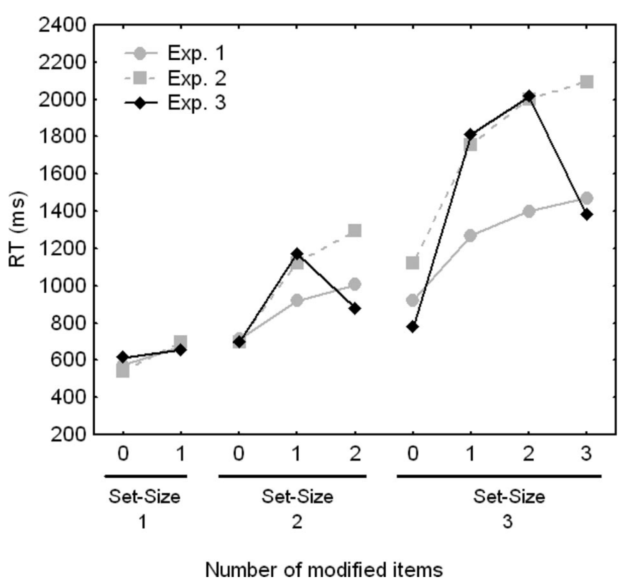

Figure 3. Mean reaction time (RT) by condition for Experiment 3. The results of Experiments 1 and 2 are presented in gray for comparison.

Discussion

In Experiment 3, we presented only the updated information; non-updated information was marked by asterisks and was not presented. The most important finding of the present experiment is that when all the items were updated, RT was shorter than when a subset of the items was updated. This finding shows that participants had to dismantle the high-order representation when only part of the information was updated in order to form a new high-order representation.

This finding provides strong support for the presence of a global updating process, because if there were only local updating, the conditions in which all the information was updated should have produced the slowest responses (rather than the quickest responses, as we found). We were also able to replicate the main findings of Experiments 1 and 2. Importantly, Experiment 3 used the same stimuli as did Experiment 1. When there was no need to dismantle the high-order representation (Conditions 0/1, 0/2, and 0/3 as well as Conditions 1/1, 2/2, and 3/3), the results of the two experiments were very similar (see Figure 3).

The present results allow us to rule out an additional alternative explanation based on the notion of retrieval. According to this explanation, when updating was partial, participants had to retrieve the missing information. The results contradicted this account, which wrongly predicted that RT would be longer when more retrieval was required (Condition 1/3, which required retrieval of two items) than when fewer retrievals were required (Condition 2/3, which required retrieval of one item).

General Discussion

In the present study, we asked participants to remember the last display in a series of displays with an unpredicted length. The keypress to advance to the next display enabled us to measure RT. We also verified that participants kept the information in WM by means of a recall test that was given when the series of displays ended. We focused on RT and examined the joint influence of two manipulations: memory set size and the number of updated items. Experiments 1 and 2 showed a dissociation between local and global updating processes. Because the local process was sensitive to the number of modified items, we suggest that this process is responsible for actually modifying the relevant values. In contrast, we suggest that the global process that was sensitive to the total set size is responsible for stabilizing the representations in WM after the relevant modification takes place. It is argued that this stabilization is carried out by binding, or chunking, all the items in WM into one complex representation. Experiment 3 shows that participants need to dismantle the high-order representation when update is partial. Presumably, the creation of a new high-order representation requires that the new items involved would be disconnected from their previous global structure. Note, however, that this dismantling process was not required in Experiments 1 and 2, in which all the information was presented to the participants, because a simpler way to handle this situation was to create the new complex representation from scratch.

In this study, we decomposed WM updating into two subordinate processes and presented new data that supported the global process. In the next paragraphs, we sketch an outline for a broader theory, in which these processes can be implemented. According to this theory, the necessary condition for the occurrence of WM updating is that a change in the environment is recognized or an internal process that will eventually change the content of WM is launched. Local and global updating processes follow this initial detection.

Note that the detection of a relevant change in the environment is not trivial, as it requires constant monitoring of the items that are currently held in WM. According to Cowan (1988), only a subset of all the activated items in LTM can be attended to at any given moment. This focus of attention holds a limited number of items and is the locus in which mental operations take place. In this sense, updating can occur only within the focus of attention. This component of detection was not tested directly in our study.

Once a change is detected, updating takes place, beginning with local updating. It was shown by Vockenberg (2006), as well as the present study, that the time required for this stage is proportional to the amount of information that is changed. The increase in RT as a function of the number of updated items (local updating) can be explained as reflecting the lingering activation of the old items in LTM (activated LTM). This approach regards the local updating cost as a product of encoding the whole sequence of items whenever an update is required. Because encoding is faster when the input is more similar to the content of WM, the time taken for updating is shorter when more items are similar.

The final stage of WM updating involves the creation of a global representation out of the new items now stored in WM. According to our view, the modification of any of the items in WM makes the entire system unstable. We argue that the role of the global updating process entails restabilization achieved by formation of a unitary complex representation that essentially binds each item with the context (the other items) in which it was presented. At the implementation level of explanation, Kessler and Meiran (2006) suggested several mechanisms that may act to compose this complex representation. These include rehearsal, reprogramming the phonological loop (Baddeley, 1986), short-term consolidation (Jolicœur & Dell'Acqua, 1998), and temporal synchronization (Lisman & Idiart, 1995). An intriguing possibility is that structure that has been created by the global updating process is later transferred to LTM as a new episodic memory.

Our theory maps nicely into Cowan's (1988) and Oberauer's (2001) view of WM. These authors argued that the focus of attention is directed to contents that are present in activated LTM. Accordingly, we argue that local updating reflects the placement of items in activated LTM and that global updating reflects the formation of an attended global representation.

The theoretical implications of the present study extend beyond the updating process and address the controversy over the nature of WM limitations. A long tradition of research has shown that WM capacity is restricted by the number of items that can be maintained simultaneously (Cowan, 2001, for review). Other authors have claimed that the restriction is on the hierarchical complexity of the relations among the representations (Halford, Wilson, & Phillips, 1998, for review). The coexistence of local and global updating processes implies that WM representations are both separate and unified at the same time, at different levels of the hierarchical structure of WM.

References

Baddeley, A. D. (1986). *Working memory.* Oxford, England: Clarendon Press.

Baddeley, A. D. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences, 4,* 417–423.

Buzsáki, G. (2006). *Rhythms of the brain.* New York: Oxford University Press.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven progressive matrices test. *Psychological Review, 97,* 404–431.

Carretti, B., Cornoldi, C., De Beni, R., & Romanò, M. (2005). Updating in working memory: A comparison of good and poor comprehenders. *Journal of Experimental Child Psychology, 91,* 45–66.

Carretti, B., Cornoldi, C., & Pelegrina, S. L. (2007). Which factors influence number updating in working memory? The effects of size distance and suppression. *British Journal of Psychology, 98,* 45–60.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104,* 163–191.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24,* 87–185.

Deschuyteneer, M., Vandierendonck, A., & Muyllaert, I. (2006). Does solution of metal arithmetic problems such as $2 + 6$ and 3×8 rely on the process of "memory updating"? *Journal of Experimental Psychology, 53,* 198–208.

Durstewitz, D., Seamans, J. K., & Sejnowski, T. J. (2000). Neurocomputational models of working memory. *Nature Neuroscience, 3,* 1184–1191.

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science, 17,* 172–179.

Gibson, E. J., Gibson, J. J., Pick, A. D., & Osser, H. (1962). A developmental study of the discrimination of letter-like forms. *Journal of Comparative and Physiological Psychology, 55,* 897–906.

Goschke, T. (2000). Intentional reconfiguration and involuntary persistence in task-set switching. In S. Monsell and J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 331–355). Cambridge, MA: MIT Press.

Halford, G., Wilson, W. H., & Phillips, S. (1998). Processing capacity defined by relational complexity: Implications for comparative, developmental, and cognitive psychology. *Behavioral and Brain Sciences, 21,* 803–864.

Hazy, T. E., Frank, M. J., & O'Reilly, R. C. (2006). Banishing the homunculus: Making working memory work. *Neuroscience, 139,* 105–118.

Hommel, B. (1998). Event files: Evidence for automatic integration of stimulus-response episodes. *Visual Cognition, 5,* 183–216.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology, 36,* 138–202.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99,* 122–149.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object- specific integration of information. *Cognitive Psychology, 24,* 175–219.

Kessler, Y., & Meiran, N. (2006). All updateable objects in working memory are updated whenever any of them is modified: Evidence from the memory updating paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32,* 570–585.

Lewandowsky, S., & Heit, E. (2006). Some targets for memory models. *Journal of Memory and Language, 55,* 441–446.

Lisman, J. E., & Idiart, M. A. P. (1995). Storage of 7 ± 2 short-term memories in oscillatory subcycles. *Science, 267,* 1512–1515.

Morris, N., & Jones, D. M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology, 81,* 111–121.

Oberauer, K. (2001). Removing irrelevant information from working memory: A cognitive aging study with the modified Sternberg task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 948–957.

O'Reilly, R. C., Braver, T. S., & Cohen, J. D. (1999). A biologically based computational model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 375–411). New York: Cambridge University Press.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28,* 411–421.

Palladino, P., Cornoldi, C., De Beni, R., & Pazzaglia, F. (2001). Working memory and updating processes in reading comprehension. *Memory & Cognition, 29,* 344–354.

Passolunghi, M. C., & Pazzaglia, F. (2005). A comparison of updating processes in children good or poor in arithmetic word problem solving. *Learning and Individual Differences, 15,* 257–269.

Pollack, I., Johnson, I. B., & Knaff, P. R. (1959). Running memory span. *Journal of Experimental Psychology, 57,* 137–146.

Prabhakaran, V., Narayanan, K., Zhao, Z., & Gabrieli, J. D. E. (2000). Integration of diverse information in working memory within the frontal lobe. *Nature Neuroscience, 3,* 85–90.

Raffone, A., & Wolters, G. (2001). A cortical mechanism for binding in visual working memory. *Journal of Cognitive Neuroscience, 13,* 766–785.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime user's guide.* Pittsburgh, PA: Psychology Software Tools.

Sternberg, S. (1966). High-speed scanning in human memory. *Science, 153,* 652–654.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97–136.

Treisman, A., & Zhang, W. (2006). Location and binding in visual working memory. *Memory & Cognition, 34,* 1704–1719.

Vockenberg, K. (2006). *Updating of representations in working memory.* Unpublished doctoral dissertation, University of Potsdam.

Received June 18, 2007
Revision received May 13, 2008
Accepted May 16, 2008 ■