Running Head: TWO UPDATING PROCESSES IN WORKING MEMORY

Two Dissociable Updating Processes in Working Memory

Yoav Kessler and Nachshon Meiran

Ben-Gurion University of the Negev, Beer-Sheva, Israel

Corresponding Address:

Yoav Kessler,

Department of Psychology,

Ben-Gurion University of the Negev,

Beer-Sheva, Israel, 84105

Email: kesslery@bgu.ac.il

Fax: +972-8-6472072

Abstract: 148 words

Main text: 7,164 words

References: 856 words (37 references)

Author's note: 57 words

Abstract

The authors show that updating 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 were either similar to the previous trial, or different in any or all of the items. Experiments 1-2 established the existence of 2 independent RT components representing the two updating processes. "Global updating cost" was sensitive to total number of items in WM (set-size), regardless of the number of items that were actually modified. "Local updating cost" was sensitive to the number of modified items, regardless of the set-size. Experiment 3 showed that participants must dismantle the representation formed by previous global updating in order to carry out new updating.

Keywords: Working Memory, Short-Term Memory, Updating, Binding, Chunking, Set-size, Reaction time

Two Dissociable Updating Processes in Working Memory

Working memory (WM) is among the core processes that enable us to deal with the ever changing environmental demands and goals. It is the mental machinery that allows us to hold and manipulate the content of our thoughts, and update them to accommodate new input. In order to accomplish this goal, WM has to keep information in a form that provides both flexibility and stability at the same time (Durstewitz, Seamans, & Sejnowski, 2000; O'Reilly, Braver, & Cohen, 1999; c.f. Goschke, 2000). On the one hand, the information must be represented in a flexible enough form to allow for rapid changes that must be implemented immediately in order to 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 crosstalk from other items stored in WM. For example, when solving a multi-stage mental computation with many interim results that need to be combined for the final outcome, it is necessary for each result to be highly stable in the face of proactive interference from previous, now irrelevant interim results, yet flexible enough to allow its modification as the solution process proceeds. This conflict between these 2 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, one should look at situations that require updating of WM contents.

The ability to rapidly and accurately update our WM 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 arithmetic 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, Miyake, Corley, Young, DeFries, & Hewitt, 2006). Put in a broader "real-life" context, WM updating is crucial for holding of a correct world-view. Keeping track of the correct information is necessary for conceiving 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), a clear distinction should be made 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 work, we will broaden this definition to *any* change in the contents of WM, being either a modification or replacement of old information. It should be noted that this phenomenal definition does not postulate any underlying mechanism or theoretical framework. In fact, the unitary phenomenal concept of WM updating may be carried out by a variety of psychological processes. Moreover, WM updating may not be carried out by the same processes in every context because the processes which accomplish it may vary between different tasks, situations, strategies, and so forth.

Morris and Jones (1990) investigated WM updating using the running memory span paradigm (Pollack, Johnson, & Knaff, 1959) that 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, such as 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, supporting the view of updating as an executive function which 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 to make inference about encoding processes is to manipulate encoding difficulty and measure the impact of this manipulation on retrieval accuracy. Since updating can be classified as a manipulation of encoding, its temporal duration could not be measured, but only its correctness. This limitation, inherent in the running span paradigm, prevented 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", making it possible to both ask and answer new questions regarding the updating process itself. Specifically, participants were presented with a series of screens, each containing 1, 2 or 3 items (memory set size) and their goal was to remember the last screen. Importantly, the participants pressed a key when they were ready to receive the next screen and the reaction time (RT) to the key press was measured. Notably, retrieval success was measured only when the series of screens ended (see Figure 1). The incorporation of RT measurement made it possible to look at updating effects when the memory set size is relatively small and accuracy is still at ceiling. Also, as will be described shortly, our paradigm allows updating to involve several items at a time rather than being limited to one item, as the running span paradigm allows. 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 at the theoretical level 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 present state of information 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, one cannot maintain the present state of information relying only on familiarity, since familiarity is insensitive to the context and may lead to treating no-longer relevant items as still relevant (Oberauer, 2001). Also, even the linking of item information to its non-temporal context is insufficient in situations when there are frequent updates. Consider an example in which an item was correctly linked to the non-temporal context (e.g., in our experiments, the digit ”3” may be linked to the leftmost frame on the screen, but then the digit inside the frame is updated to be "6", see Figure 1). Such an association could still lead one to consider a no-longer relevant item ("3") as relevant even after that item has been updated. It is therefore argued that in order to retrieve the content reliably, WM updating should be carried out by forming strong links, not only between an item to its non-temporal context, but also between the item and the exact temporal context (e.g., “6 belongs to the most recently updated WM content”) or the item to 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 overcoming proactive interference especially challenging.

The present study provides evidence for the existence of 2 dissociable component processes of WM updating: an item-specific local process and a global process. It is argued that while local updating helps flexibility, global updating provides the necessary glue (Treisman & Gelade, 1980) required for stability. While the 2 processes have already been recognized in the literature, each one of them was treated as if it were the only WM updating process. Here we provide for the first time compelling evidence that these 2 processes co-exist.

The 2-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 only partial updating? The literature presents 2 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 do not change. The second hypothesis is that the updating process encompasses all the items in WM, regardless of their being modified or not. We turn to 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, while preserving 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 was either identical to the set presented in the previous trial, or different in 1, 2, 3, 4, or all 5 stimuli. For example, when the stimuli 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 was presented to them. Thus, upon the presentation of each stimulus set, the participants had to update their memory with the new information, and then to press a key. Reaction time (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 was presented. It was reasoned that, since 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 response slowing with an increasing number of updated stimuli. This slowing reached an asymptote, so that there was no additional slowing observed beyond 3 updated items. Vockenberg's results provide evidence supporting the local updating hypothesis, since RT was sensitive to the number of modified items *within a constant set-size*.

Global Updating Hypothesis.

In contrast to the previous hypothesis, Kessler and Meiran (2006) claimed that all the items in WM are updated together, as a whole, whenever any of them is modified. A memory updating paradigm, based on Oberauer (2002), was used. Participants had to keep track of 1 or 2 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 arithmetic operation. The participants had to apply the arithmetic 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 of 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 (arithmetic 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 2 counters as it was in sequences that involved only 1 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, most notably, 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 to be updated. These findings were taken as evidence supporting the global updating hypothesis since RT was sensitive to the WM set-size, *with a constant number of modified items*.

A Synthesis

The present study shows that both the local and global updating hypotheses are inaccurate in the sense of being special cases, and that the accurate and more general hypothesis concerns the co-existence of 2 dissociable updating processes, local and global. In order to demonstrate the co-existence of these 2 processes within the same paradigm, we varied both the set-size and the number of modified items. Participants had to keep track of series of 1, 2 or 3 items, presented in a self-paced manner. Following Vockenberg (2006), the stimuli presented in each trial were either identical to those presented in the previous trial, or different in some or all of the items. For example, with a set-size of 2 items, either 0, 1, or 2 items could be modified as compared the previous trial. RT was measured between the presentation of the stimulus set and the key press 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 2 aforementioned WM updating processes, with different stimuli (digits and meaningless visual stimuli, for Experiments 1 and 2, respectively). Experiment 3 provided further support for the role of the global updating process and ruled out some alternative explanations.

The present work extends Kessler & Meiran's (2006) study in 3 directions. First, and most importantly, while Kessler and Meiran (2006) supported the global updating hypothesis, the present results show global updating to be only one of two processes involved in WM updating. Second, the present study extends the evidence for global updating because Kessler and Meiran (2006) dealt with item modification and the present work shows 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 (2006) paradigm. Specifically, in their paradigm, different stimuli served for the update and non-update conditions. While the stimuli "+0" and "-0" indicated non-update, all other arithmetic operations indicated an update. Since 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 updating *per se*. Although we regard this claim as highly implausible given the large effects of several hundreds of milliseconds, it cannot be easily 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 to those that appeared in Trial n-1 (see Figure 1).

Experiment 1

Method

Participants

18 students from Ben-Gurion University of the Negev and the affiliated Achva and Sapir Colleges participated in the present experiment for a 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" monitors. The software was programmed in E-Prime (Schneider, Eschman, & Zuccolotto, 2002).

The digits 1-9 served as WM items and the letters A-Z (in upper case) served for visual masking. Question marks ("?") were used at the test phase of each trial sequence. Each stimulus subtended a visual angle of .86º (height) x .57º (width), approximately, 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 2.20º x 2.20º white frame. With set-size of 1 item, the frame appeared in the center of the screen. With set-sizes 2 and 3, the frames were arranged horizontally, with distances of .57º among them, and were aligned to the center of the screen.

Procedure

The experiment began with a practice stage composed of 3 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, separated by short breaks.

Each trial sequence began with the presentation of digits inside frames on the screen, serving as initial values (see Figure 1 for an example with a set-size of 3 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 served to increase the perceptual discriminability between the stimuli, in order to encourage the participant to treat them separately and to discourage them from treating 2 or 3 digits as composing a single 2-digit or 3-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 then to press the spacebar. After the keypress, a letter replaced the digits in each of the frames for 1,000 ms. This aspect was introduced in order to avoid 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.

****** Figure 1 about here ******

In each of the subsequent trials within the trial sequence, the condition was chosen randomly according to the following probabilities: a non-update condition (where all digits were identical to those presented in the previous trial) was administered with a 50% probability. The other conditions (i.e., of modifying any subset of the digits) 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 that the participant is 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 based on probabilities. Such prediction might have resulted in updating taking place only towards the anticipated sequence end, where they were asked to report the last stimulus-set. Consequently, we kept the probability that the sequence would end in each trial at 10%, which 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, since 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, having 9 levels corresponding to the 9 possible combinations of Set-Size and Modified-Items. These conditions were (number of modified items / set size): 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, local updating costs were compared between set-sizes in order to probe the local updating process. A second ANOVA compared the cost of modifying only 1 item, between set-sizes. This was conducted 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 proportion of correct trial sequences was 99%, 99%, and 97%, for set-sizes 1-3, respectively. 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 faster than 100 ms or slower than 4,000 ms were considered as outliers and hence 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 1-way ANOVA showed that the mean RTs in the 9 conditions were significantly different from one another, $F(8,136)=27.32$, $MSe=68,863.88$, $\eta_p^2 =.62$.

.

******** Figure 2 about here ********

<u>Local updating</u>. In order 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 non-linear contribution to the conditions' variance was both numerically negligible and non-significant, $F(1,17)=.78$, $MSe=13,700.45$, $\eta_p^2 =.04$, 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 was conducted, comparing the local updating costs between set-size=2 and set-size=3. This 2-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 2-way interaction was negligible in size and clearly non-significant, $F(1,17)=.95$, $MSe=8,484.96$, $\eta_p^2 =.05$, $p=.34$.. These results support the notion that local updating cost is similar in size for set-sizes 2 and 3, meaning that local updating is independent of set size at least within the studied range.

Global updating. In order to examine global updating, we conducted a 2-way ANOVA according to Set-Size (1 to 3) and Updating (no updating vs. 1 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, $F(2,34)=10.35$, $MSe=13{,}830.35$, $\eta_p^2=.38$, indicating an increase in the time required to modify 1 item, with set-size. 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 therefore the duration of this process prolongs 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 slower with increased WM load. The WM-load account is based in the idea of processing storage tradeoff (Just & Carpenter, 1992) according to which greater loads on storage are reflected in a reduced amount of resources needed for processing and in consequent processing slowness. We argue that this account cannot explain our results, because we show that the speed in which local updating is performed is unaffected by set size. If the observed results were attributed to storage-processing tradeoff, one would expect both processes, the global *and* the local, to be affected by set size and this prediction was not supported.

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

Experiment 2

Before discussing the theoretical implications of the findings, we replicated the results with a similar paradigm, using 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, that can lead to a global updating process, seems highly unlikely with Gibson figures.

Method

Participants

12 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 a partial course credit. All the participants reported having normal or corrected to normal vision, not having been diagnosed as suffering from learning disabilities.

Apparatus and Stimuli.

9 Gibson figures, similar in size to the digits used in Experiment 1, served as stimuli. The Apparatus and Stimuli were similar of those of Experiment 1 in all other aspects.

Procedure

The procedure was identical to this of Experiment 1, except for the memory test at the end of the trial sequence. Since 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 forming a stable association between these figures and the digits.

Results

Although Gibson figures are visually meaningless stimuli, all the participants reported that they generated verbal labels for these figures throughout the task. These labels were individual self-generated words, such as "bulb", "tent", "umbrella", and so forth. This fact does not undermine the main motivation to prevent chunking into meaningful units (2-4-5 into 245), which is something that none of the participants has reported.

Accuracy

The proportion of sequences in which the report of the final display was correct was 97%, 95%, and 88%, for set-sizes 1-3, respectively, $F(2,22)=6.77$, $MSe=.0047$, $\eta_p^2 =.38$. Accuracy with set-size of 3 items was significantly worse than with 1 and 2 items, $F(1,11)=12.34$, $MSe=.0047$, $\eta_p^2 =.53$. The latter 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, that included all the 9 conditions, indicated a significant difference, $F(8,88)=117.48$, $MSe=34{,}316.64$, $\eta_p^2=.91$.

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, $F(1,11)=48.68$, $MSe=14{,}076.83$, $\eta_p^2=.82$, which explained 93% of the inter-condition variance, but not the quadratic trend contrast, $F(1,11)=2.00$, $MSe=23{,}805.26$, $\eta_p^2=.15$, $p=.18$. These results show that the increase was linear and as such establish the existence of a local updating cost. In order to show that this cost is independent of set-size, we conducted an ANOVA comparing the local updating cost (measured as the RT increase from modifying 1 item to modifying 2 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 well as the main effect for Set-Size, $F(1,11)=65.18$, $MSe=83{,}302.11$, $\eta_p^2=.86$. As in Experiment 1, the 2-way interaction was negligible in size and clearly non-significant, $F(1,11)=1.06$, $MSe=15{,}793.01$, $\eta_p^2=.09$, $p=.33$, showing that the local updating cost is independent of set size.

Global updating. In order to probe the global updating cost, we conducted an ANOVA comparing the cost of modifying 1 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, $F(2,22)=41.01$, $MSe=8{,}399.16$, $\eta_p^2=.79$, indicating an increase in the time required to modify 1 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 well as 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 1-2

The results demonstrate the co-existence of both 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 in order to jointly retain 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 has been updated. The role of the global updating process is to stabilize the WM contents, thereby protecting them against potential interference. The fact that such a process exists indicates a functional dependence between WM representations. Importantly, it 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 an additional behavioral marker for high-order integration between all the items in WM aside from global updating cost. 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 passive storage of information, WM is responsible for binding information together and accordingly to the creation of new representations. Binding was previously discussed in reference to several levels of generalization. First, features of the same object are arguably bound together in visual WM, creating the phenomenal experience of a singular, integrated object (Kahneman, Treisman & Gibbs, 1992; Raffone & Wolters, 2001; Treisman & Zhang, 2006). Second, it was shown that binding object's attributes is not limited to its perception, but also includes 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 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 of 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 a 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 faster when the entire WM content is replaced as compared to when only part of the content is replaced.

Experiment 3 had a secondary goal. 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 need to update WM contents and the time needed to detect the changes could have possibly accounted for some of our findings as elaborated already. Therefore, detecting new information in the preceding experiments required both perceptual scanning (to detect the new information) and memory scanning (to determine if the information is new). Moreover, memory scanning is known to increase with memory set-size (Sternberg, 1969). The need for both of these scanning operations was removed in Experiment 3 in which the display contained only the new information while the positions holding old information were marked by asterisks. Consequently, there was no need to scan the display digits to detect the new ones because only new digits were presented. Similarly, there was no need to consult memory to determine if the digits are new because the digits that were presented were always new.

Method

Participants

12 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 a 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 this of Experiment 1, with one exception. Instead of presenting all item values in each trial, only the modified values were presented. An asterisk that appeared inside a frame indicated that its corresponding value was not modified (see Figure 1).

Results

Accuracy

The proportion of trial sequences whose final display was reported correctly was 98%, 96%, and 92%, for set-sizes 1-3, respectively, $F(2,22)=4.29$, $MSe=.0028$, $\eta_p^2=.28$. Accuracy with set-size of 3 items was significantly worse than with 1 and 2 items, $F(1,11)=5.46$, $MSe=.0040$ $\eta_p^2=.33$. The latter 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 these of Experiments 1 and 2 (exclusion rate was 0.9%).

The results clearly support our prediction. The omnibus ANOVA, that included all the 9 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 conditions involving partial updating (see Figure 3). Condition 2/2 was quicker than 1/2, $F(1,11)=13.15$, $MSe=39{,}254.87$, $\eta_p^2=.54$, and Condition 3/3 was quicker than both 1/3 and 2/3, $F(1,11)=26.17$, $MSe=86{,}836.18$, $\eta_p^2=.70$.

******** Figure 3 about here ********

Local updating. As in the previous experiments, a local updating cost was found, and it was probed by 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 also evident. An ANOVA compared the cost of modifying 1 item between set-sizes, with Updating and Set-Size as independent variables yielded two significant main effects, $F(1,11)=67.13$, $MSe=71{,}766.41$, η_p^2=86, and $F(2,22)=43.30$, $MSe=60{,}607.31$, $\eta_p^2=.80$, respectively. Importantly, the 2-way interaction was also significant, $F(2,22)=49.44$,

$MSe=30{,}170.58$, $\eta_p^2=.82$. The global updating cost was 41 ms, 477 ms, and 1,036 ms for Set-Sizes 1-3, respectively. 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.

Discussion

In the present experiment we presented only the updated information while non-updated information was marked by asterisks and was not presented. The most important fining of the present experiment is that when all the items were updated, RT was quicker than when a sub-set was updated. This finding shows that participants had to dismantle the high-order representation when only a 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 and not the quickest responses as we have found. We were also able to replicate the main findings of Experiments 1 and 2. Importantly, Experiment 3 used the same stimuli as Experiment 1. When there was no need to dismantle the high-order representation (0/1, 0/2, 0/3 as well as 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, that is 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 predicts that RT would be longer when more retrieval was required (Condition 1/3, that required retrieval of 2 items) than when less retrievals were required (Condition 2/3, that required retrieval of 1 item).

General Discussion

In the present work we asked participants to remember the last display in a series of displays with an unpredicted length. The key press to advance to the next display enabled us to measure RT. We also verified that they 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. Since 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 took place. It is argued that this stabilization is carried out by binding, or chunking, all the items in WM into one complex representation. Accordingly, 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, where all the information was presented to the participants, since a simpler way to handle this situation was to create the new complex representation from scratch.

In this work, we decomposed WM updating to 2 subordinate processes, and presented new data supporting the global process. In the next paragraphs, we will try to sketch an outline for a broader theory, in which these processes can be implemented. According to this theory, the necessary condition for WM updating to occur is that a change in the environment would be recognized, or an internal process that would eventually change the content of WM will be launched. Local and global updating processes follow this initial detection.

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

Once a change was detected, updating takes place, beginning with local updating. It was shown by Vockenberg (2006), as well as in 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. Since encoding is faster as the input is more similar to the content of WM, the time taken for updating is shorter as 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 is in re-stabilization achieved by forming 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 the global updating reflects the formation of an attended global representation.

The theoretical implications of the present study extend beyond the updating process *per se*. Rather, they also 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 & Philips, 1998, for review). The co-existence of both 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: 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 3x8 rely on the process of "Memory updating"? 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.

Jiménez, L., & Méndez, C. (1999). Which attention is needed for implicit sequence learning? Journal of Experimental Psychology: Learning, Memory and Cognition, 25, 236-259.

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.

Kahnemann, 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.

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psychological Review, 63, 81-97.

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.

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.

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.

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., Zaho, 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. (2002a). E-Prime User's Guide. Pittsburgh:Psychology Software Tools Inc.

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.

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

Authors Note:

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

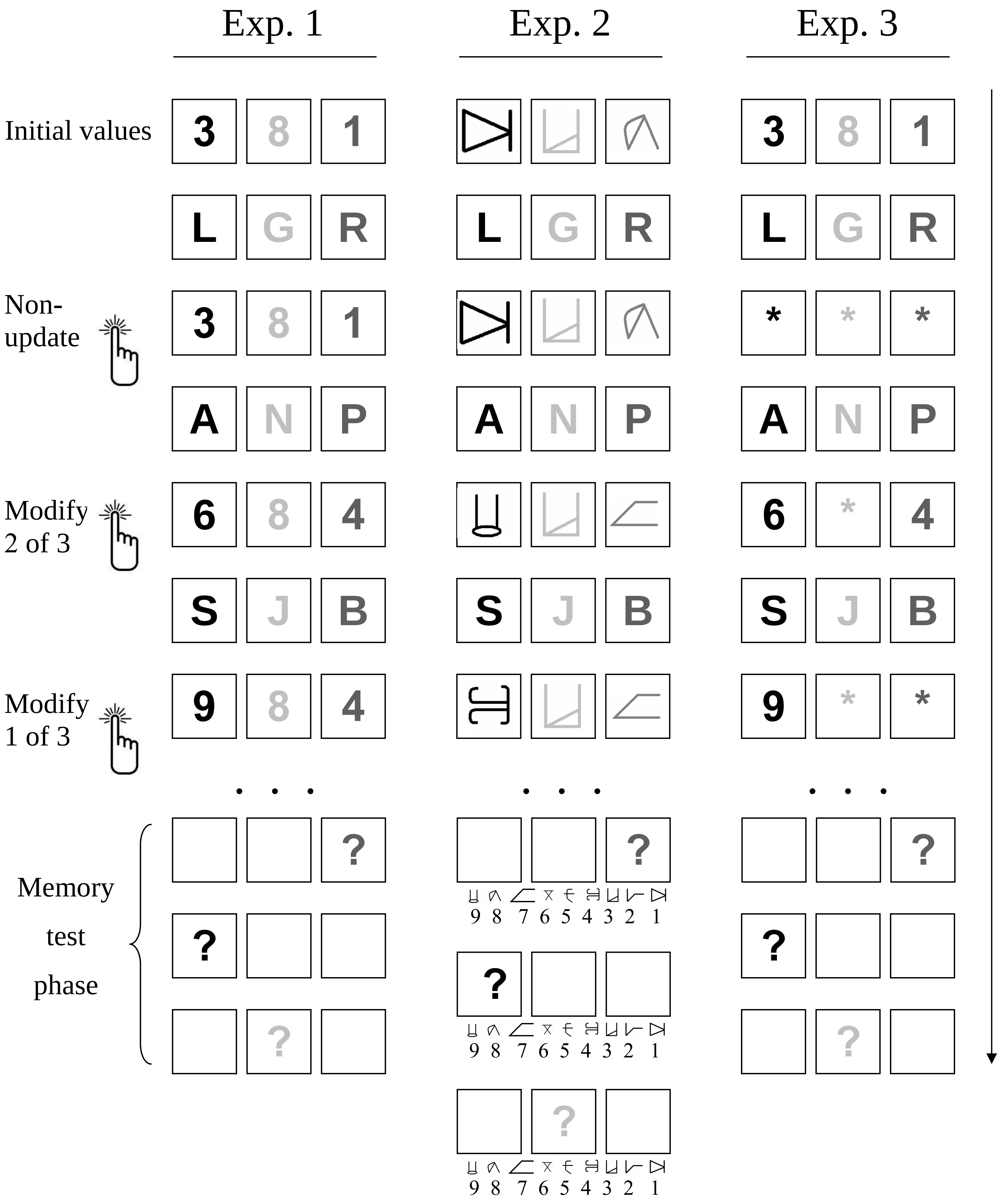
The research was supported by a grant to the second author from the Israel Science Foundation. We wish to thank Rotem Eren-Rabinovich for English proofreading.

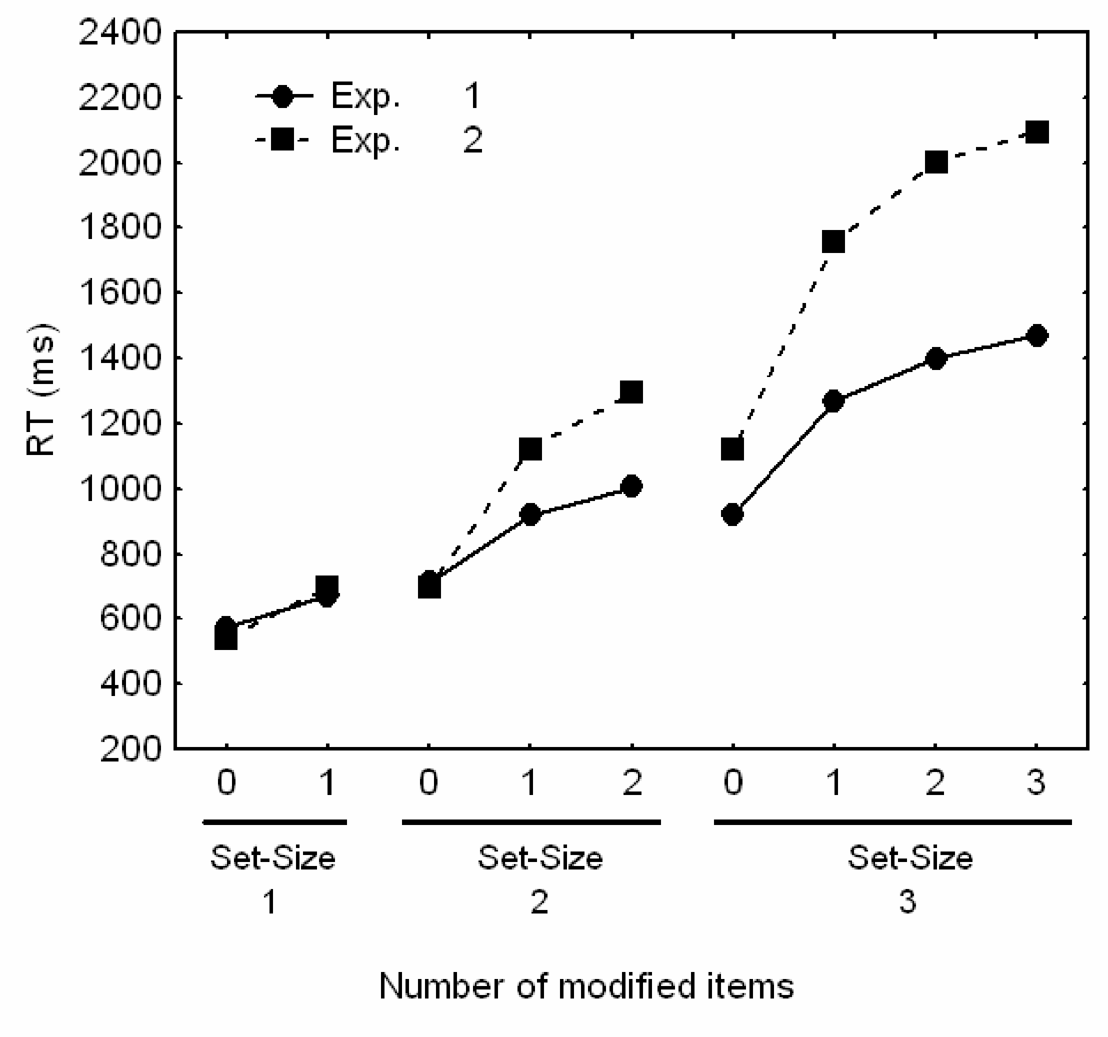
Figure Captions

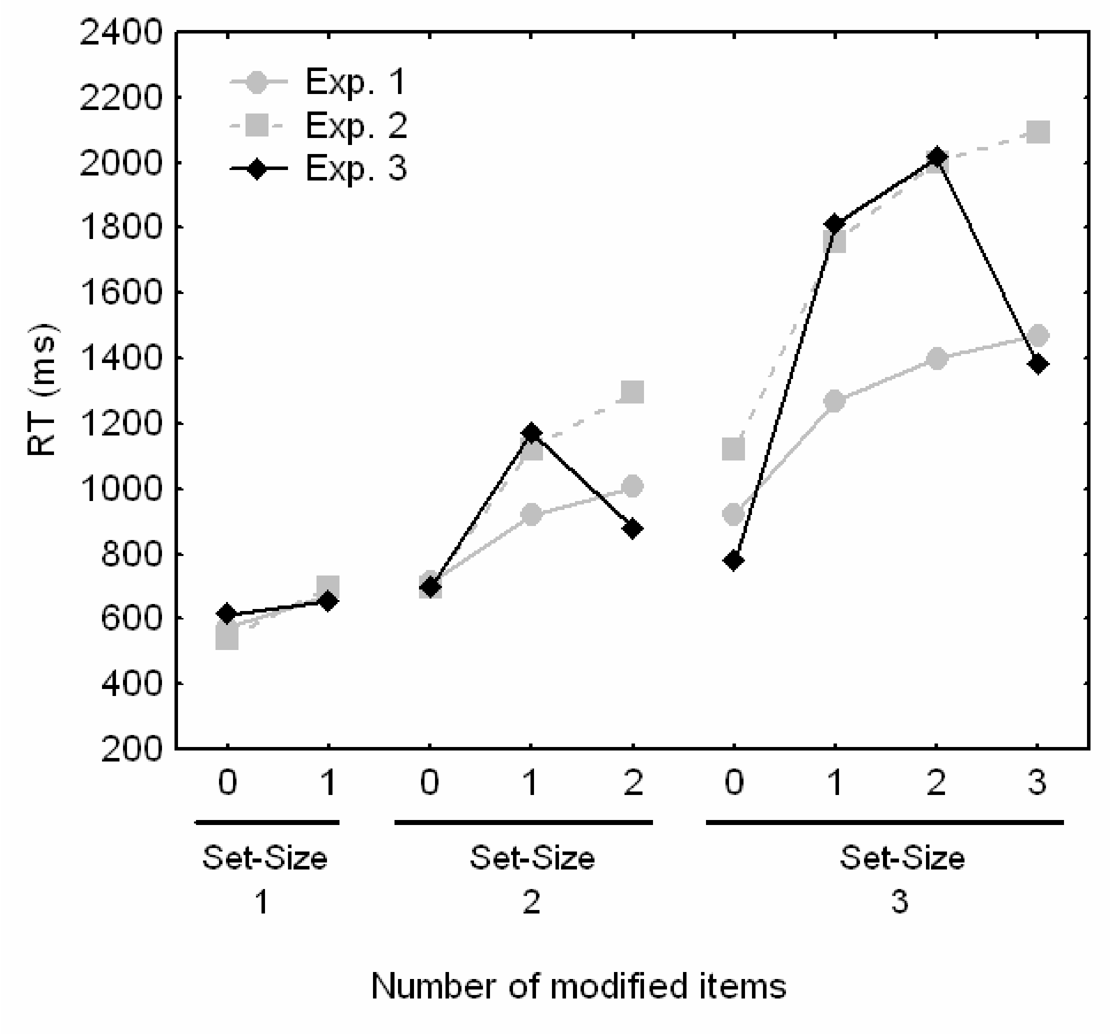
Figure 1. A schematic description of a trial sequence with set-size of 3 items, in Experiments 1-3. The finger symbol represents RT measurement. The number of trials within the trial sequence was varied randomly, see text for details.

Figure 2. Mean RT by Condition, Experiments 1-2.

Figure 3. Mean RT by Condition, Experiment 3. The results of Experiments 1-2 are presented in gray for comparison.


Exp. 1
Exp. 2
Exp. 3
Initial values
3 8 1
L G R
Non-update
3 8 1
A N P
Modify 2 of 3
6 8 4
S J B
Modify 1 of 3
9 8 4
Memory test phase
?
?
?
9 8 7 6 5 4 3 2 1
L G R
A N P
S J B
* * *
6 * 4
9 * *


RT (ms)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
Exp. 1
Exp. 2
0
1
0
1
2
0
1
2
3
Set-Size 1
Set-Size 2
Set-Size 3
Number of modified items


Exp. 1
Exp. 2
Exp. 3
RT (ms)
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1
0
1
2
0
1
2
3
Set-Size 1
Set-Size 2
Set-Size 3
Number of modified items