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All Updateable Objects in Working Memory Are Updated Whenever Any of Them Are Modified: Evidence From the Memory Updating Paradigm

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In a series of experiments, participants were required to keep track of 1 or 2 working memory (WM) objects, having to update their values in 80% of the trials. Updating cost, defined as the difference between update and non-update trials, was larger when 2 objects were involved compared with when there was only 1 object was involved. This finding was interpreted as evidence that the updating process encompasses both objects in WM, even though only 1 of them is actually updated. This feature of WM updating is limited to objects defined as "updateable," throughout the trial sequence. The results are explained by the need to reprogram the phonological loop when updating or the need for desynchronization followed by resynchronization of WM contents.

Keywords: working memory, updating, binding, focus of attention, processing-storage tradeoff

Working memory (WM) serves for temporary maintenance and manipulation of information. As such, it plays a crucial role in high-level cognition, including reasoning (Kyllonen & Christal, 1990), reading comprehension (Daneman & Carpenter, 1980; Just & Carpenter, 1992), mental arithmetic (Hitch, 1978), and problem solving (Engle, Tuholski, Laughlin, & Conway, 1999). Because of this, it has received considerable attention over the past 3 decades, including extensive modeling work (Miyake & Shah, 1999).

In this study, we explored the executive process of updating WM representations (e.g., Miyake et al., 2000; Morris & Jones, 1990; Yntema & Meuser, 1962). During the performance of any of the high-level tasks mentioned above, the contents of WM constantly change. These changes emerge from two sources. First, new input from the environment needs to be stored and combined with previously stored information. For example, comprehension requires constructing a representation of the scene, within WM, which is constantly expanded and updated as the message unfolds in time (Gernsbacher, 1991). Second, changes may stem from within WM by the requirement to store the products of manipulations performed on stored information. This is the case with mental computation, in which outcomes of intermediate stages of computation have to be stored and combined. In accordance with its role in these real-life cognitive tasks, updating is required in most standard psychological measures of WM capacity (for review, see Conway et al., 2005).

Despite its central role in high-level cognition, the temporal dynamics and processing constrains of updating have been examined in very few studies. The role of this study is to help fill this gap. Specifically, we examined which part of the information stored in WM is involved when updating is required. Here, at least two options are viable. The first option, which we label as *independence* and is in our mind the most intuitively plausible, is that updating is specific to the object that undergoes modification. Therefore, the time required for updating a single object should be independent of the presence of other objects in WM that do not undergo modification. The second option, *dependence*, is that updating is not specific and encompasses all objects currently activated within WM. Accordingly, the time required for updating a single object is dependent on the context and should increase if additional objects are currently maintained in WM. This study offers a metric of updating time. Accordingly, the major contribution of this work is using this "updating cost" measure, which enabled us to decide between the dependence and independence hypotheses. In addition to enhancing the understanding of an important executive function such as updating, our study has implications regarding the basic structure of WM, as will be discussed below.

Defining Updating of Working Memory Objects

To understand the function of updating in WM, we begin by defining the terms *updating* and *WM objects*. Morris and Jones (1990) defined memory updating as "the act of modifying the current status of a representation of schema in memory to accommodate new input" (p. 112). This definition requires 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. This possibility is accomplished through the "object-oriented" organization of information in memory. Accordingly, a memory object is a distinct, ad hoc integration of different pieces of information. Objects bind together pieces of information into sin-

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gular entities (cf. “object file”; Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992). Once formed, the pieces of information composing the object might be changed or modified without breaking the integrity of the whole object. For example, Kahneman et al. described watching a strange man approaching down the street: “As he reaches you and stops to greet you, he suddenly becomes recognizable as a familiar friend whom you had not expected to meet in this context. Throughout the episode, there was no doubt that a single individual was present; he preserved his unity, . . . although neither his retinal size, his shape, nor his mental label remained constant” (p. 177).

Morris and Jones (1990) investigated WM updating using the running memory paradigm (Pollack, Johnson, & Knaff, 1959). Their theoretical framework was Baddeley’s (1986) model of WM, which regards WM as composed of two domain-specific buffers: the phonological loop for maintaining verbal information and the visuospatial sketchpad for maintaining visual information. These buffers are regarded as “slave systems,” which are controlled by a central executive, responsible for scheduling the slave systems and for manipulating their information. Morris and Jones (1990) measured 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 model and does not involve the phonological loop, supporting the view of updating as an executive function that is independent of pure maintenance.

Theoretical Framework

Cowan (1988) regarded WM as consisting of the activated portions of long-term memory (LTM; for similar suggestions, see also Anderson, 1983; Cantor & Engle, 1993; Monsell, 1984; Ruchkin, Grafman, Cameron, & Berndt, 2003). According to his model, the elements in WM derive directly from LTM. Therefore, WM does not include novel or newly perceived stimuli, but rather all objects within it are familiar objects or are novel combinations of familiar objects. Most important, only a subgroup of the objects held in WM is the focus of attention. It contains the relatively more strongly activated representations, which are attended and selected for future action. The focus of attention is manipulated by processes of habituation and dishabituation to external stimuli and by biasing through a central executive that is influenced by instructions or incentives. This theory is in line with the claim that WM is a manifestation of controlled attention, serving to maintain active information and to resolve conflict and interference among memory objects (Engle & Kane, 2004; Kane & Engle, 2003).

Cowan’s (1988) model was modified by Oberauer (2002), who suggested a third level of activation, forming a tripartite concentric model of WM. Accordingly, there is a distinction between holding objects for direct access and selecting an object for further action. Although several objects can be held in the region of direct access, only one among them is actively selected for action. In addition, other objects can be activated within LTM, but still not be focused on. Oberauer’s model is supported by evidence from the memory updating paradigm, described in the following section.

Memory Updating Paradigm

In this study, we used a modified version of the memory updating paradigm (Garavan, 1998; Gehring, Bryck, Jonides, Albin, & Badre, 2003; Oberauer, 2002, 2003; Salthouse, Babcock, & Shaw, 1991). Garavan, who was the first to study reaction times in this paradigm, required participants to monitor a randomly ordered sequence of triangles and squares that appeared on the screen, one at a time, in a self-paced manner. The task was to keep a separate running count for the triangles and squares and to indicate these numbers at the end of the sequence. Garavan capitalized on the self-pace and measured how long it took participants to indicate that they were ready for the next item, measuring this time as the reaction time (RT). He found that the RTs after an object switch (e.g., a triangle presented after a square) were about 300–500 ms slower than those following an object repetition (e.g., a triangle presented after a triangle). This *object switching cost* was interpreted as a capacity limitation of the focus of attention: the ability of the focus of attention to hold only one object at a time. Therefore, to update an object that is not currently attended, one has to replace the object in focus. These operations of removing the currently attended object from the focus of attention and replacing it with the other objects presumably give rise to the object switching cost. Later experiments (Oberauer, 2002, Experiment 2, 2003, Experiment 2) expanded the paradigm to include a more rigorous measurement of response times, one not relying on introspection and self-report and amenable to error estimation. In those experiments, the participants had to indicate the current value of the object in each trial instead of reporting when they were ready, demanding a response selection in every trial. An object switching cost was found even in this more rigorous test, indicating the validity of Garavan’s self-reported measurements. Further support for a single-object focus of attention stems from the work of McElree (1998, 2001), who showed this special immediate access status of the recent relevant object using the *n*-back paradigm.

Present Research Question

Which aspect of the information in WM undergoes updating? Suppose few objects are maintained in WM, but only one of them has to be modified. Does only the modified object undergo the updating process; or rather do all of the contents of WM have to be updated as a unit? This question has important consequences regarding the structure of WM and specifically the question of dependence versus independence of WM objects. There are two different notions of independence. The first, *informational independence*, means that if several objects are maintained in WM, the contents of one object (or part of its contents) can be modified without affecting the contents of any of the other objects. The second, *functional independence*, means that cognitive functions such as selection, inhibition, and updating can be directed to one object without being influenced by the presence of other objects. Whereas informational independence refers to the WM contents, functional independence refers to the duration of WM-related processes.

The multiobject approach to WM represented by the models of Cowan (1988) and Oberauer (2002) supports the view that several objects can be separately maintained within WM. However, “separately" does not mean "completely independently." From the informational perspective, it has been shown that, although different objects can hold different contents, this difference may lead to crosstalk, evident in effects such as the intrusion of information from objects that are currently irrelevant (e.g., Oberauer, 2001). Also, from the functional perspective, it has been shown that, although selection for action is specific to the relevant object, the duration of this selection process increases with the total number of objects currently maintained in WM (e.g., Oberauer, 2003).

The specificity of updating falls into the category of functional independence. The participants' success in performing the memory updating task is evidence for their ability to direct the updating process to the relevant object only. The question asked in this study is how updating duration is influenced by the presence of additional objects in WM that are not updated.

In these experiments, we tackled the question above by looking into object mixing costs. The term *mixing cost* is borrowed from the task switching literature (Fagot, 1994; Meiran, 2000; cf. Kray & Lindenberger, 2000; Los, 1996; Rubin & Meiran, 2005). The task mixing cost is the performance decrement observed in conditions involving more than one task compared with single-task conditions. Like the task mixing cost, which results from the presence of an additional, potentially relevant task, the object mixing cost indicates the costs associated with having more than one potentially action-relevant (updateable) object. Moreover, the task mixing cost is not a result of the current switching because it is observed also in trials involving task repetition, but in a context in which a task switch is possible. Similarly, the object mixing cost is observed in conditions in which the currently focused object is the same as in the preceding trial, but an object switch is possible. Therefore, the critical comparison is between object repetition trials and trials from experimental blocks involving a single object. Having introduced the term *object mixing cost*, we can now reframe our question as to whether the updating duration interacts with object mixing cost, namely whether it is larger in the mixed-object condition than in the single-object condition. In the following section, we describe a specific study that indirectly hints at a functional dependence regarding updating.

Related Findings

Oberauer (2003) examined the effect of object switching under update and non-update conditions. Although these conditions were not directly compared within one experiment, the results indirectly support the dependence hypothesis that the consolidation process acts upon all WM objects whenever an update is required.

Specifically, in Experiments 1a and 1b in Oberauer (2003) study, the object switching paradigm was used, with the exception that the object values were not updated during the miniblock (for a similar manipulation, see also Oberauer, 2002, Experiment 2). Rather, the arithmetic operations were applied to the initial object values and not to an ongoing counter. For example, suppose that the initial value of one object was *5*, followed by the operation *+2*. The participant had to mentally perform the calculation *5 + 2* and to indicate the result *7* using the keypad, but not to update the object's value in mind. In the following trial, for example, the operation could be *−3*, and the participant had to mentally perform the calculation *5 – 3* and to indicate the result *2*. Therefore, this task involved a selection of objects for action, but these objects were not updated. It was found that object repetition RTs increased mainly from a set size of one to two objects, but increased only moderately (Experiment 1a) or did not change (Experiment 1b) between set sizes of two and four objects. This result suggests that the retrieval duration of object values does not depend on memory load beyond two objects. Thus, in Oberauer's (2003) experiments, object mixing cost (the difference in object repetition RTs between the single-object and mixed-object conditions) did not interact with a set size beyond two objects when updating was not required.

In contrast, in Experiment 2 in Oberauer's (2003) study, updating was required. Specifically, arithmetic expressions (e.g., *2 + 5*) appeared randomly inside fixed frames on the screen. The participants were asked to remember the last outcome associated with each frame, but did not have to retrieve the previous value to perform the task. In this experiment, nonswitch RTs increased as a function of working memory set size from two to four objects. Comparing Experiments 1a and 1b on the one hand with Experiment 2 on the other hand indicates that object mixing cost interacts with set size even beyond a load of two objects because updating takes longer the more objects are held in WM. Our interpretation of this result is in favor of the dependence hypothesis claiming that the updating of information applies to all objects in WM whenever any of them are modified.

Present Experiments

Although offering some relevant data regarding updating, Oberauer's (2003) experiments were not designed to investigate updating per se, but to examine factors affecting the object switching cost. Thus, the results were not discussed with regard to the process of updating. In the present study, we aimed to manipulate updating to investigate its nature. Operationally, whereas the critical updating manipulation was done between experiments in Oberauer's study, so updating cost, properly defined, was not measurable, we manipulated updating within participants in the present experiments. This change enabled us to compare update and non-update conditions as a within-participants independent variable and consequently to measure updating cost. Measuring updating cost enabled us to decide between different hypotheses concerning updating of WM contents. To do so, we added a non-update condition using the arithmetic operation *+0* or *−0*. In these trials, the arithmetic operation did not lead to any change in the object's value and thus did not require an update. This enabled us to calculate updating cost as the difference between the update and non-update conditions. If updating is functionally independent of other objects, we would expect the updating cost to be similar in the single-object and mixed-object conditions. However, if updating functionally depends on other objects, we would expect it to be substantially larger in the mixed-object condition.

Experiment 1

The goal of Experiment 1 was to replicate previous findings in the memory updating paradigm before turning to manipulation of updating. This experiment therefore did not involve our critical updating manipulation. In this experiment and throughout all experiments reported, we used two perceptual cues for each WM object (see Figure 1). Specifically, our objects were "triangles," perceptually cued by each of two different triangles, and "rectan-

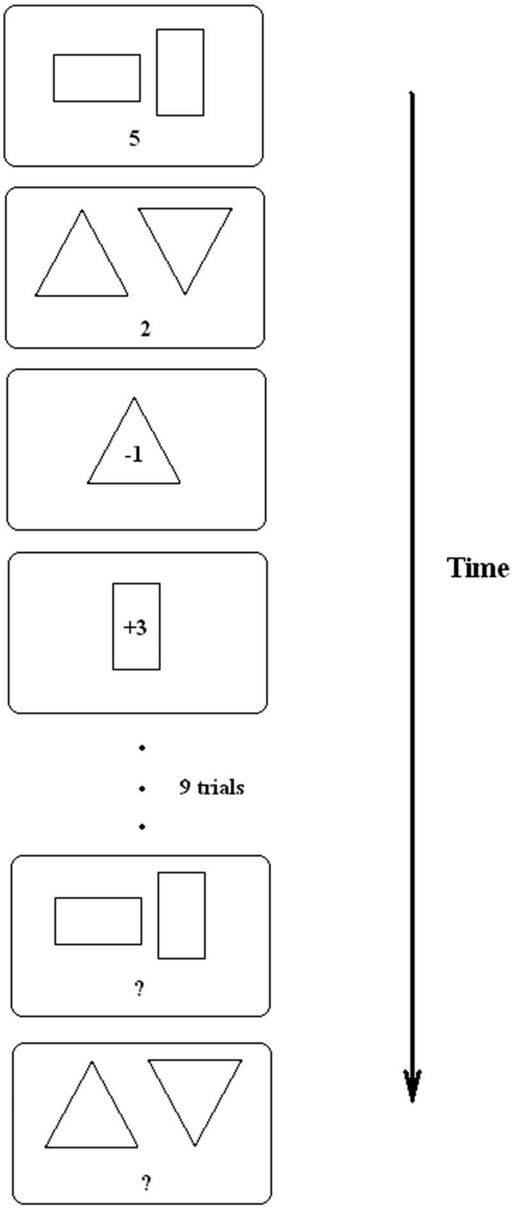

Figure 1. Schematic representation of a miniblock in the mixed-object condition in Experiments 1 and 2. The miniblock began with the presentation of initial values for both objects, followed by a sequence of nine trials, each composed of an arithmetic operation applied to one of the objects. The participants indicated the completion of the mental computation by pressing the *space bar* key. At the end, they were asked to type in the final value related to each object. Each trial, excluding the first, was mapped to the relevant level of the object switching variable (switch, nonswitch-same, and nonswitch-different).

gles," perceptually cued by each of two different rectangles. By doing so, the objects were defined as abstract semantic categories ("triangles" and "rectangles") rather than as specific perceptual figures. This manipulation was in line with the aforementioned example of Kahneman et al. (1992) showing that objects are internal representations, which do not necessarily depend on consistent external percepts. Applying two perceptual cues for each object could disentangle object repetition and cue repetition (e.g., Gehring et al., 2003; for similar ideas regarding the task switching paradigm, see also Logan & Bundesen, 2003, 2004; Mayr & Kliegl, 2003). At this point, a comment on terminology is pertinent. All but one of the previous studies using the object switching paradigm defined object switching cost as the difference between object switching and object repetition, which also involved cue repetition (the exception is Gehring et al.). In other words, these studies did not separate cue repetition from object repetition. For the sake of clarity and in keeping with previous definitions, we also defined object switching cost as the difference between the switch and nonswitch with the same cue conditions. However, to address the possible contribution of cue repetition, we included a manipulation of cue switching without object switching. Accordingly, we defined two contrasts that will be reported as well, despite involving multiple dependent comparisons: "Cue repetition gain" was defined as the difference between the nonswitch-same and nonswitch-different conditions, and "pure counter switching cost" was defined as the difference between the switch- and nonswitch-different conditions (see Table 1).

Method

Participants

Twelve undergraduate students from Ben-Gurion University and the affiliated Sapir and Achva Colleges participated in the experiment for partial course credit. One participant was replaced due to a total failure to perform in the mixed-object condition (none of the mixed miniblocks was performed correctly). The participants reported normal or corrected-to-normal vision.

Apparatus and Stimuli

The experiment was run on IBM clone Pentium III computers with 17-in. monitors. The software for the experiment was programmed in E-Prime (Schneider, Eschman, & Zuccolotto, 2002a, 2002b). The object cues were rectangles and triangles. Two types of rectangles were used, horizontal and vertical. The rectangles subtended visual angles of 4.80° × 1.74°, assuming a 60-cm viewing distance. Also, two types of triangles were used, upward and downward pointing. The triangles subtended visual angles of 4.80° × 4.98°. The area inside the rectangles and triangles was equal. The shapes were drawn in white on a black screen. Before each miniblock, a digit between 1 and 9 appeared under each pair of cues. The digits subtended a visual angle of .48° × .76°. In each trial of the miniblock, a digit between 1 and 9, not including 5, appeared in the center

Table 1
Summary of the Effects for Object Switching and Updating

Variable and effect	Definition
Object switching	
Switching cost	Switch − NS-same
Mixing cost	1/2·[(NS-same + NS-different) − (single-same + single-different)]
Cue repetition gain	NS-different − NS-same
Pure counter switching cost	Switch − NS-different
Updating	
Updating cost	Update − nonupdate

of the object cue. Also, a + or − sign appeared to left of the digit and subtended a visual angle of .48° × .48°.

Procedure

The experiment was composed of three blocks organized into what we call a *block-sandwich design* (see Rubin & Meiran, 2005). The first and last blocks included 10 single-object miniblocks each. The second block included 50 mixed-object miniblocks. In this manner, the average serial position of these two critical conditions is equated. The identity of the objects for the single blocks was counterbalanced so that half of the participants used rectangles as object cues for the first block and triangles for the second block and vice versa for the other half.

Single-object miniblocks. Each single-object miniblock began with the presentation of an initial value. The two object cues were presented in the center of the screen with a number below them. The participants had to memorize the number and to press the *space bar* key. Then, nine trials containing arithmetic operations appeared. In each trial, one of the object cues appeared in the center of the screen with an arithmetic expression inside of it. The participants had to apply the operation to the number they remembered and to memorize the outcome. Then, they had to press the *space bar* key. After nine trials, the two object cues appeared with a question mark underneath. In this screen, the participants had to enter the current value of the object and to press the *enter* key. The Hebrew words for *counting error* appeared for 1,000 ms if the response was incorrect.

Mixed miniblocks. The procedure for the mixed miniblocks was similar to that for the single miniblocks except that two objects had to be remembered and manipulated. Each mixed-object miniblock started with two initial-value screens, one for each object (see Figure 1). The rectangles' initial values always appeared first. In each trial, one of the object cues was presented, and the relevant object had to be manipulated. At the end of the miniblock, each of the two pairs of object cues appeared with a question mark underneath. Again, the rectangles appeared before the triangles.

The participants were informed that the initial value of each object, as well as the intermediate and final values, was a number between 1 and 9, excluding 5. They were encouraged to emphasize accuracy over speed.

Analytic Procedure and Design

Only trials from miniblocks in which the final object values were correct were analyzed. RTs from trials shorter then 100 ms or longer then 10,000 ms were discarded as outliers. Also, the first trial of each miniblock was omitted from the analysis. The independent variable was object switching, which had five levels: switch, nonswitch with same cue (nonswitch-same), nonswitch with different cue (nonswitch-different), single same cue (single-same), and single different cue (single-different). We adopted $\alpha = .05$ in all analyses. Also, 95% confidence intervals (CIs) are reported separately for each contrast (Masson & Loftus, 2003).

Results

The participants performed correctly in 54% of the mixed-object miniblocks and in 84% of the single-object blocks, $t(11) = 4.28$, $p < .001$.

RT

A one-way within-participants analysis of variance (ANOVA) was conducted. The main effect for object switching was significant, $F(4, 44) = 23.95$ ($MSE = 213{,}742.11$; see Figure 2).

All subsequent planned contrasts performed to examine specific hypotheses were also significant. The object switching cost was 675 ms, $F(1, 11) = 19.24$ ($MSE = 142{,}088.26$, 95% CI = 393, 957). The pure counter switching cost was 470 ms, $F(1, 11) = 10.81$ ($MSE = 122{,}619.63$, 95% CI = 208, 732). Also, a cue repetition gain of 205 ms was observed, $F(1, 11) = 13.72$ ($MSE = 18{,}385.95$, 95% CI = 103, 307). This cue repetition gain was absent in the single blocks, $F(1, 11) = .11$ ($MSE = 19{,}068.15$). Finally, a large object mixing cost of 915 ms was observed, $F(1, 11) = 24.10$ ($MSE = 416{,}468.44$, 95% CI = 432, 1,398). The mixing cost was calculated by averaging the two mixed-object nonswitch conditions as compared with the average of the two single conditions. This set of results fully replicates previous findings in this paradigm and sets the stage for our core explorations.

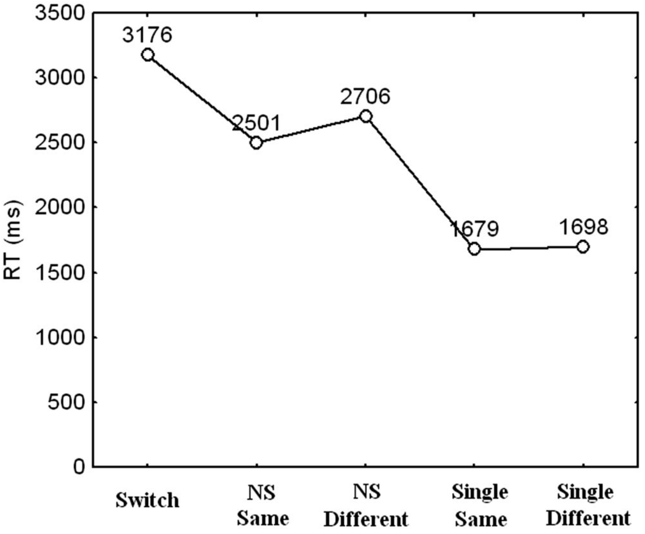

Figure 2. Experiment 1: mean reaction times (RT) as a function of object switching. The findings of object switching cost, object mixing cost, and cue repetition gain were replicated. NS = nonswitch.

Experiment 2

In Experiment 2, we manipulated updating directly to address the main question of interest. To this end, we introduced an additional manipulation of object updating, which was combined factorially with object switching. This was done by adding a non-update condition, in which the operation was either *+0* or *−0*, in 20% of the trials. This experiment was similar to Experiment 1 in every other aspect.

Method

Participants

Twelve students from the same participant pool as in Experiment 1 participated in the experiment.

Procedure

The general procedure was the same as used in Experiment 1. A non-update condition was randomly applied with a probability of 20% in both the mixed and single blocks. The participants were not informed about this manipulation in the instruction phase of the experiment.

Results

The participants performed correctly in 77% of the mixed-object miniblocks and in 87% of the single-object blocks, *t*(11) = 1.56, *p* = .07.

RT

A two-way ANOVA was conducted with object switching and updating as within-participants variables. Significant main effects were found for both object switching, *F*(4, 44) = 37.45 (*MSE* = 73,944.75), and updating, *F*(1, 11) = 53.20 (*MSE* = 455,517.35). In addition, the two-way interaction was also significant, *F*(4, 44) = 29.62 (*MSE* = 28.995.56; see Figure 3).

Object switching cost was smaller than in Experiment 1 in both the update and non-update conditions. There were significant switching costs of 230 ms in the update condition, *F*(1, 11) = 8.96 (*MSE* = 35,308.58, 95% CI = 89, 371), and 151 ms in the non-update condition, *F*(1, 11) = 13.14 (*MSE* = 10,474.74, 95% CI = 74, 228). The interaction between object switching cost contrast and updating was nonsignificant, *F*(1, 11) = .81 (*MSE* = 22,386.75). In the update condition, the pure counter switching cost was marginally significant, 148 ms, *F*(1, 11) = 4.08 (*MSE* = 32,254.90, 95% CI = 14, 282). In the non-update condition, the pure counter switching cost was also marginally significant, 121 ms, *F*(1, 11) = 3.08 (*MSE* = 28,550.64, 95% CI = −5, 247). The cue repetition gain was small and nonsignificant in the update condition, 82 ms, *F*(1, 11) = 1.76 (*MSE* = 22,751.14, 95% CI = −31, 195), and nonsignificant in the non-update condition, 30 ms, *F*(1, 11) = .17 (*MSE* = 33,300.40, 95% CI = −107, 167). No cue repetition gain was observed in the single-object condition ($F < 1$ for both conditions).

A large object mixing cost of 889 ms was found in the update condition, *F*(1, 11) = 76.12 (*MSE* = 124,473.25, 95% CI = 625, 1,153). This mixing cost was smaller in the non-update condition, 217 ms, *F*(1, 11) = 5.28 (*MSE* = 107,297.87, 95% CI = −28, 462). The overadditive interaction between the mixing cost contrast and updating was also significant, *F*(1, 11) = 77.72 (*MSE* = 34,786.61).

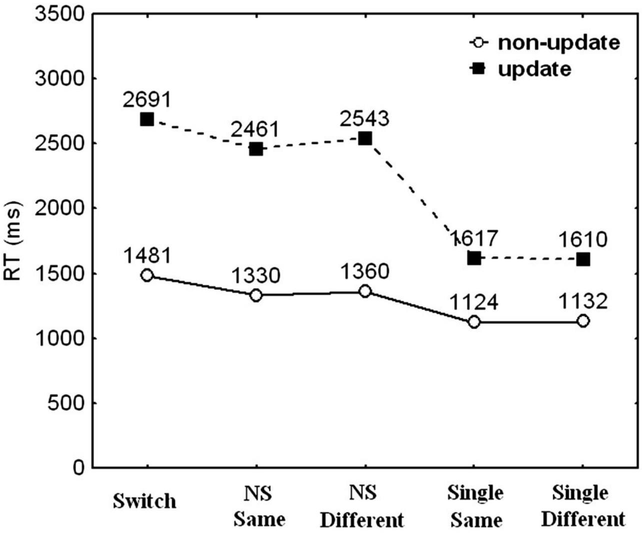

Figure 3. Experiment 2: mean reaction times (RT) as a function of object switching and updating. Updating cost, defined as the difference between update and non-update trials, was larger in the mixed-object condition than in the single-object condition. NS = nonswitch.

Discussion

The results are straightforward: The overadditive interaction between object mixing cost and updating showed that updating cost was more than twice as large in the mixed-object condition than in the single-object condition. This result is consistent with the hypothesis that, when updating is required, the entire WM content is updated rather than the relevant object only. In other words, updating is longer with larger WM load. As will be shown below (see Experiment 4), this is not due to informational load per se, but rather is specific to updateable objects.

It is interesting that object switching cost was present even when no updating was required. In non-update trials, the current values of both objects needed only to be maintained, but not modified. Therefore, there appears to have been no reason to switch to the relevant object, especially when there was not even a need to retrieve its current value. This can be explained by the fact that object switching cost relies, at least partly, on bottom-up automatic processes that do not depend on the overt process performed in that trial. The cue repetition effect is related to this hypothesized automatic bottom-up process. In fact, object switching costs in this experiment relied mainly on this component. Another possibility is that the processes of access and updating are performed serially, so the object is accessed first and only then is its value updated. Assuming such a serial process is reasonable given the high control demands of the situation, which have been shown to increase serial processing (Luria & Meiran, 2005). According to this explanation, we suggest that this object access operation was interrupted once the participant realized that no updating would be required. This conjecture is supported by a subsequent analysis including only trials that appeared *after* a non-update trial. If object retrieval was aborted in the previous trial, which did not involve an update, then no switching cost should have been observed. The reason is because the access to the object was interrupted, and the focus of attention was not on the previously relevant object. The result of the new analysis supported this explanation, showing a small and nonsignificant switching *gain* of 67 ms, *F*(1, 11) = .36 (*MSE* = 77,175.74, 95% CI = −110, 244).

Finally, the switching cost in the update condition was much smaller than in Experiment 1. This switching cost, measured as the difference between object switching and object repetition (same cue) was 675 ms in Experiment 1 compared with only 230 ms in Experiment 2. At present, we will not offer an explanation for this result.

Experiment 3

Oberauer (2003, Experiments 1a and 1b) found object switching costs when only the retrieval of object content was required, but the content was not updated. This finding implies that the retrieval of object content is a sufficient condition for observing switching cost. If so, the object switching cost is expected to vanish totally when sufficient time is given for such retrieval in advance of the arithmetic operation. In this experiment, we manipulated the preparatory interval for the upcoming object. Specifically, we manipulated the cue–target interval, namely the time between the presentation of the shape and the presentation of the arithmetic operation, to be either short (100 ms) or long (1,000 ms). The long cue–target interval was longer than the switching cost we observed in Experiments 1 and 2 and those reported in the literature and therefore should have provided ample opportunity for preparation. Therefore, we hypothesized that the long cue–target interval would be sufficient to perform all operations involved in switching the object and that no switching cost would be observed in the long cue–target interval. This prediction seems trivial because it is in line with all of the literature concerning *object* switching. However, a counterexample from the task switching domain demonstrates that a full preparation is not the only possible outcome. Specifically, task switching experiments involve the application of one of two (or more) sets of rules to presented stimuli, creating task switch and nonswitch conditions. One of the most robust findings in task switching is that task switching cost persists (Rogers & Monsell, 1995) even after a very long preparatory interval (e.g., 10 s; Meiran & Chorev, 2005). This component of the task switching cost is called *residual switching cost* (cf. De Jong, 2000).

We predicted that, in contrast to switching cost, updating cost would not be affected by cue–target interval manipulation. The reason for this is that updating cannot begin before the arithmetic operation is presented. This prediction stems from the "serial processing under load" hypothesis. It contrasts with the prediction stemming from the "bottom-up" hypothesis, which we suggested beforehand. According to this explanation, the larger updating cost in the mixed-object condition stems from greater retrieval demands in the mixed condition. Moreover, retrieval is needed in update trials only, but is unnecessary in non-update trials. Alternatively, it might be that, for some reason, participants use a strategy of resetting their focus after performing a trial in the mixed condition, which may happen in every trial or in some trials only. By resetting we mean that the participants are roughly equally prepared for each object, perhaps by disengaging the attentional focus. Such a strategy would partly diminish the object switching cost, as was actually found in Experiment 2. Also, it would contribute to larger updating cost in the mixed condition because selection among the objects is needed in *every* mixed-object condition, including both switch and nonswitch trials, whereas it is not needed in the single-object blocks.

The line of reasoning above allows us to evaluate the source of the object mixing cost and, indirectly, shed light on the nature of the updating operation. If object selection is performed only (or mostly) in switch trials, this operation should be reflected in the object switching cost and not in the object mixing cost. Also, assuming that selection can be preparatory, switching cost should be eliminated given a long cue–target interval. If, however, the larger updating cost in the mixed condition stems from the tendency to reset the focus after each trial, then the difference in updating between the mixed- and single-object conditions should decrease in the long cue–target interval. This is, of course, only if the cue–target interval is used for advanced preparation (see especially De Jong, 2000).

Method

Participants

Twenty-five students from the same participant pool as in the previous experiments participated in this experiment. Two participants did not finish their experimental session due to a power outage and were therefore removed from the analysis.

Procedure

The general procedure was similar to that used in Experiment 2, except for the advance cuing of the relevant object. In each trial, the shape appeared for a short or long cue–target interval (100 or 1,000 ms, respectively), and then the arithmetic operation was presented. The cue–target intervals were chosen randomly with equal probabilities.

Results

The participants performed correctly in 78% of the mixed-object miniblocks and in 92% of the single-object blocks, $t(22) = 5.70$, $p < .0001$.

RT

A three-way ANOVA was conducted with cue–target interval, object switching, and updating as within-participants variables. All effects of this design were significant. Main effects were found for cue–target interval, $F(1, 22) = 78.51$ ($MSE = 50{,}319.26$); object switching, $F(4, 88) = 36.88$ ($MSE = 193{,}527.65$); and updating, $F(1, 22) = 156.88$ ($MSE = 715{,}705.50$). Two-way interactions were found between object switching and cue–target interval, $F(4, 88) = 3.96$ ($MSE = 39{,}559.00$); updating and cue–target interval, $F(1, 22) = 13.64$ ($MSE = 28{,}094.08$); and object switching and updating, $F(4, 88) = 66.90$ ($MSE = 49{,}940.55$). The three-way interaction was also significant, $F(4, 88) = 3.60$ ($MSE = 37{,}741.35$).

Object switching cost in the update condition was 329 ms in the short cue–target interval, $F(1, 22) = 10.46$ ($MSE = 118{,}873.59$, 95% CI = 156, 502), and 142 ms in the long cue–target interval, $F(1, 22) = 1.04$ ($MSE = 223{,}016.68$, 95% CI = −95, 379), which was nonsignificant, however. This reduction in switching cost by preparation was nearly significant, $F(1, 22) = 3.43$ ($MSE = 58{,}413.61$), $p = .08$. The residual switching cost is the cost observed given a long preparation interval. As indicated above, the residual switching cost was nonsignificant in the update condition. One of the participants in this experiment produced a remarkably high residual switching cost in the update condition, 2,588 ms, compared with the other participants, whose average residual cost was 31 ms. When this participant was removed from the analysis, the residual switching cost was very small, 31 ms, and nonsignificant, $F(1, 21) = .12$ ($MSE = 84{,}792.05$, 95% CI = −119, 181; see Figure 4). To avoid the risk of contaminating the other results, the outlier participant was excluded from all subsequent analyses. With the outlier removed, switching cost in the short cue–target interval was 254 ms for the update condition, $F(1, 21) = 12.41$ ($MSE = 57{,}214.96$, 95% CI = 131, 377). In the non-update condition, switching cost was 17 ms and nonsignificant in the short cue–target interval, $F(1, 21) = .16$ ($MSE = 20{,}567.52$, 95% CI = −57, 91), and 65 ms and nonsignificant

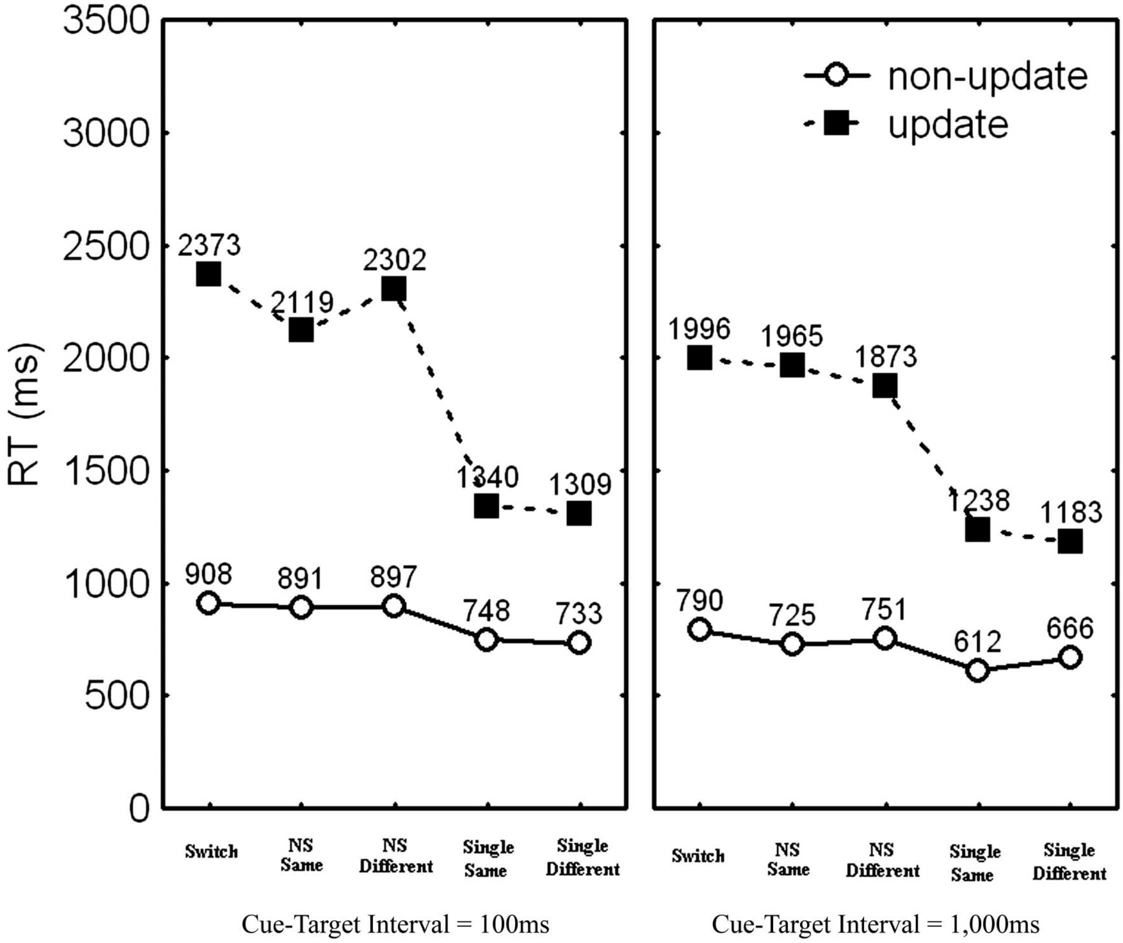

Figure 4. Experiment 3: mean reaction times (RT) as a function of object switching, updating, and cue–target interval. Object switching cost was eliminated by sufficient advance preparation. The interaction between object mixing cost and updating was only slightly reduced. NS = nonswitch.

in the long cue–target interval, *F*(1, 21) = 1.54 (*MSE* = 30,100.73, 95% CI = −72, 106).

Regarding the two components of object switching cost, pure counter switching cost in the update condition was 71 ms and nonsignificant in the short cue–target interval, *F*(1, 21) = 1.15 (*MSE* = 47,842.00, 95% CI = −42, 184), and 123 ms and nonsignificant in the long cue–target interval, *F*(1, 21) = 1.59 (*MSE* = 103,390.03, 95% CI = −42, 288). The cue repetition gain in the update condition was 183 ms in the short cue–target interval, *F*(1, 21) = 11.55 (*MSE* = 31,964.29, 95% CI = 91, 275). In the long cue–target interval of the update condition, there was a pattern of cue repetition *cost* of 92 ms, *F*(1, 21) = 1.77 (*MSE* = 51,822.02, 95% CI = −25, 209), which was nonsignificant, however. These object switching cost subcomponents are not reported for the non-update condition because object switching costs were nonsignificant.

A reliable object mixing cost was found in the update condition in both the short cue–target interval, 886 ms, *F*(1, 21) = 238.67 (*MSE* = 72,300.48, 95% CI = 748, 1,024), and the long cue–target interval, 709 ms, *F*(1, 21) = 270.71 (*MSE* = 40,837.85, 95% CI = 605, 813). This reduction in mixing cost by advance preparation (177 ms) was also significant, *F*(1, 21) = 14.00 (*MSE* = 24,547.48, 95% CI = 96, 258).

The mixing cost in the non-update condition was significant in the short cue–target interval, 154 ms, *F*(1, 21) = 29.66 (*MSE* = 17,518.45, 95% CI = 86, 222), and marginally significant in the long cue–target interval, 99 ms, *F*(1, 21) = 3.93 (*MSE* = 54,426.90, 95% CI = −21, 219), *p* = .06. The mixing cost reduction in the cue–target interval was nonsignificant, however, *F*(1, 21) = .88 (*MSE* = 38,159.05, 95% CI = −46, 156).

Discussion

The results demonstrate dissociation between object switching cost and updating cost. Specifically, switching cost was eliminated by advance preparation, whereas updating cost in the mixed-object condition was only slightly reduced. This reduction may be due to a reduction in conflict or ambiguity regarding the upcoming object. Another reason for this might be the reduced cognitive load in the long cue–target interval, which may result in a greater degree of parallel processing (Luria & Meiran, 2005).

The results imply that the major part of the updating cost in the mixed-object condition stems from the updating process, which could not be performed in advance because the relevant information was not yet provided. These findings rule out the aforementioned alternative account that the updating cost in the mixed-object condition reflects object selection. The reason is that the literature and our results suggest that object selection is presumably reflected in the object switching cost and not in the object mixing cost.

Experiment 4

The results of Experiments 2 and 3 were interpreted as evidence that updating acts upon all objects within WM. Therefore, updating takes longer when more objects are present, namely in the mixed-object condition compared with the single-object condition. However, the overadditive interaction between object mixing cost and updating may be explained in an alternative way. According to this alternative hypothesis, the updating process is not changed qualitatively between the single and mixed conditions. In other words, updating acts upon the relevant updated object only. The larger updating cost in the mixed-object condition can be explained by a processing–storage trade-off (Baddeley & Hitch, 1974; Daneman & Carpenter, 1980; Just & Carpenter, 1992). The mixed-object condition requires the storage of an extra object relative to the single-object condition. Therefore, this additional WM load slows the updating process due to sharing of resources between processing and storage.

Experiment 4 addressed this alternative account of our results. The experiment included the single-object conditions as in Experiment 2 and a mixed-object block in which one object was relevant for further updating throughout the miniblock (“active set”; e.g., Oberauer, 2002) and the other was passive and never updated. At the end of each miniblock, both the active and passive object values had to be reported. Consequently, the mixed condition was similar to the single-object condition, with an added memory load of one digit. If the larger updating cost in the mixed-object condition stems from enlarged storage demands, one would expect a larger updating cost in the mixed-object condition of this experiment as well.

In contrast to the processing–storage trade-off hypothesis, we follow Oberauer’s (2002) claim that the distinction between the region of direct access and activated LTM is functional and not dependent on load. In the mixed conditions of our Experiments 1–3, both objects were kept in the direct access region because they were both relevant throughout the trial sequence. However, when a passive object is included, it is expected that it will be stored as activated LTM. Therefore, although the same amount of load is involved, we predict an additive interaction between mixing cost and updating in Experiment 4 because only one object is active in both the single- and mixed-object conditions.

Method

Participants

Eight students from Ben-Gurion University were paid 30 NIS (New Israeli Sheqel) (about $6.50) for participating in this experiment.

Procedure

The general procedure was similar to that used in Experiment 2, with three changes. First, the mixed condition involved nonswitch trials only. The participants were told in advance that only the number associated with the rectangles would have to be remembered, without any updating throughout each miniblock. Second, both single conditions included triangles only as object cues. This was done to constantly map the triangles as updateable objects and rectangles as nonupdateable objects. Third, the number of miniblocks in each block was reduced to 5 in each single block and to 25 in the mixed block.

Results and Discussion

The participants performed correctly in 82% of the mixed-object miniblocks and in 88% of the single-object blocks, $t(7) = 1.54$, $p = .08$.

RT

A three-way ANOVA was conducted with load (one or two objects), cue switching, and updating as within-participants variables. Only the main effect for updating was significant, reflecting an updating cost of 505 ms, $F(1, 7) = 50.63$ ($MSE = 80{,}665.41$, 95% CI = 220, 790). No other effects were significant (see Figure 5).

Most important, there was no effect for load, $F(1, 7) = .05$ ($MSE = 65{,}894.74$), and no significant interaction between load and updating, $F(1, 7) = 1.12$ ($MSE = 23{,}224.68$). Accordingly, this result failed to support the prediction of a processing–storage trade-off. We further analyzed the first trial of each miniblock to rule out the possibility that the additional load was more demanding at the beginning of the trial sequence. Two participants were excluded from this analysis due to an incomplete factorial design resulting from insufficient data points. Updating costs were 428 and 426 ms for the mixed- and single-object conditions, respectively, $F(1, 5) = .00$ ($MSE = 33{,}913.04$, 95% CI = −183, 187),

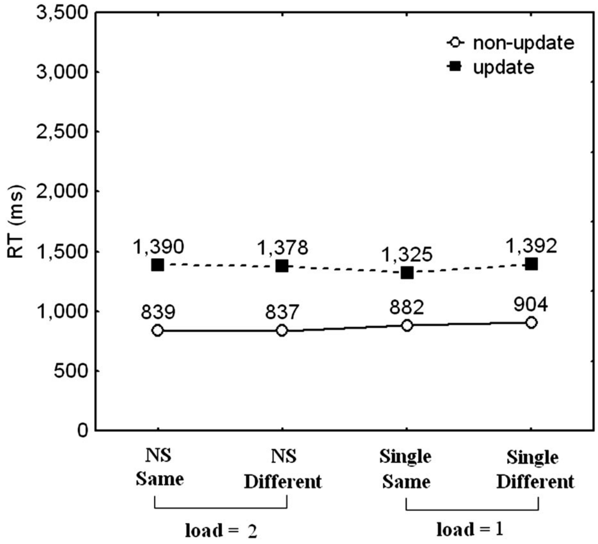

Figure 5. Experiment 4: mean reaction times (RT) as a function of object switching and updating. No effect for working memory load was found when holding a non-updateable object. NS = nonswitch.

for the interaction between load and updating. This result gives further support against a general processing–storage account for our results because it shows that the interaction was additive even in the first trial, when WM was just loaded.

It might be argued that an additional passive object does not load WM and that Experiment 4 thus does not serve as a good examination of the trade-off hypothesis. For example, it has already been extensively demonstrated that a small passive memory load does not affect the performance of an ongoing task (e.g., Anderson, Reder, & Lebiere, 1996; Baddeley & Hitch, 1974; Carlson, Sullivan, & Schneider, 1989; Klapp, Marshburn, & Lester, 1983; Oberauer, 2002; Oberauer, Demmrich, Mayr, & Kliegl, 2001). Oberauer et al. claimed that passive memory load does not degrade the performance because no access to the stored memory information is required. The performance is affected by load when such access is required as part of the ongoing task. This point corresponds to the distinction between the region of direct access and the other parts of activated LTM in Oberauer's concentric model. When an object needs to be accessed or updated to perform the task, it is kept in an accessible state, namely the region of direct access. Otherwise, it is kept as activated LTM, but outside the region of direct access.

We argue that the functional state of the representation, rather than load per se, determines its effect on updating. It is not a general load that slows the updating process, but a specific load of one functional form of representations, namely the direct access region. In this experiment, we showed that the direct access region and activated LTM could be distinguished already in the first trial of the miniblock. Accordingly, the effect of load is moderated by the goal state or by intentions regarding future operations on the respective representations. Therefore, a general processing–storage trade-off cannot account for our results.

Another important argument against the processing–storage trade-off account is the amount of additional load involved. WM load was one object in the single-object condition and two objects in the mixed-object condition. It is highly unlikely that the large difference in updating cost (e.g., 672 ms in Experiment 2, in which the updating cost was more than doubled in the mixed-object condition) can be attributed solely to loading WM with one additional object only. For example, Baddeley and Hitch (1974) showed that processing–storage trade-off existed when more that three items had to be retained while performing the focal task. Also, we are unaware of any study that found such a dramatic effect of single-object load addition on performance. Accordingly, we regard the trade-off explanation as highly implausible. It should be noted that we do not totally deny the possibility that processing–storage trade-off existed to a limited extent in our results. However, it can account for only a very small portion of the effect we report.

Experiment 5

In the above experiments, we defined updating cost as the difference in RT between update and non-update trials. One might argue that this difference reflects more than updating per se. Besides updating, two other processes are conceivable. First, update trials involve an arithmetic computation, which is unnecessary in the non-update condition. Therefore, our estimate of updating cost is inflated by the extra processing stage of computation. Second, it is plausible that no access to or retrieval from WM is needed in the non-update condition. To perform the task correctly, the relevant object's value does not have to be retrieved in the non-update condition. Therefore, it might be the case that retrieval, rather than updating, is responsible for the larger updating cost in the mixed-object condition.

To overcome this difficulty, we used a modified memory updating paradigm in which the participants had to decide in each trial whether the outcome of the computation was odd or even. This manipulation removes the confounding with retrieval because parity judgments require retrieval in every trial. In addition, this modification addresses another shortcoming of the memory updating paradigm, namely the self-paced RT measurement, which relies on self-reported introspection. In our Experiments 1–4, as well as in other experiments using this paradigm (Garavan, 1998; Gehring et al., 2003; Oberauer, 2002, Experiment 1, 2003, Experiment 1), the participants were required to press a key when they finished their mental updating. Properly speaking, the measurement was therefore of subjective readiness times rather than objective reaction times. The inherent assumption in the above studies is that readiness times reliably reflect the duration of the relevant inner cognitive processes, such as updating and shifting, and these only.

In contrast to this assumption, it has been argued that participants fail to correctly report the inner processes that have led them to action (Nisbett & Wilson, 1977). This general principle was experimentally demonstrated by Meiran, Hommel, Bibi, and Lev (2002) in a task switching study in which the tasks were randomly ordered and indicated by a cue. After the cue was presented, the participants had to report whenever they were ready for processing the target, applying the indicated task. The main finding was that longer readiness times (presumably indicating better readiness) were paradoxically accompanied by longer reaction times. This suggests that the participants had no conscious awareness of their inner control processes and therefore could not reliably report the completion of their performance. In the present experiment, the need for a parity judgment in every trial resolved the RT measurement issue by forcing the participants to carry out an actual decision and by measuring the time needed for its execution.

Using a performance-based measure solved another limitation of the previous studies. The use of subjective measure of response time forced us, as it forced previous researchers, to use an intertrial interval of 0 ms. If longer intertrial intervals were used, then the participants could respond before completing their mental operation and use the intertrial interval to complete the process. The way to prevent this strategy was to present the next stimulus immediately after the response (intertrial interval of 0 ms). This solution prevented past researchers from manipulating the intertrial interval and from using longer intertrial intervals. The manipulation of intertrial interval is relevant to the investigation of the effect of decay on object switching cost (for the measurement of decay in a task switching paradigm, see Meiran, Chorev, & Sapir, 2000). When a performance-based measure is used, as in this experiment, the participants are forced to complete their mental process before responding.

Another limitation of the updating paradigm is that it is impossible to perform an error analysis at the level of individual responses, which makes it impossible to assess speed–accuracy trade-off, for example. With the performance-based measure, a response selection is made in every trial, thus enabling the standard analysis of error proportions. Accordingly, Experiment 5 compared the performance-based measure and the subjective measure of response time using an intertrial interval of 1,000 ms.

Method

Participants

Thirty-seven participants from the same subject pool as in Experiments 1–3 participated in the experiment as part of their course requirements. Five participants were omitted from the analysis: Two participants decided to stop in the middle of the experiment; one participant was removed because of equipment failure; and two participants committed too many errors (the proportions of correct miniblocks in the mixed-object blocks were 21% and 9%, respectively). Eventually, the responses of 32 participants were analyzed, with 16 participants in each of two groups.

Procedure

The participants were randomly assigned to two groups, subjective report and performance-based. The procedure for the subjective report group was identical to that used in Experiment 2, except that the intertrial interval was now 1,000 ms. The difference between the groups was in their response types. In the performance-based group, the participants had to indicate in every trial whether the outcome number was odd or even. The *L* key served to indicate "even," and the *A* key served to indicate "odd." Once an error was conducted, the Hebrew word for *error* appeared for 1,000 ms; the miniblock was terminated; and the final value screens appeared.

Analytical Procedure and Design

The analytic procedure was similar to that used in Experiment 2. In addition, incorrect trials were not analyzed for RT in the performance-based group. The major analysis focused on the effect of group on object switching and updating. This design was intended to replicate the basic findings also within the performance-based group. Another analysis was conducted that focused on the effect of intertrial interval on object switching and updating. This analysis compared the group in Experiment 2 with the subjective report group in Experiment 5. These two experiments used the subjective measure and differed only in the intertrial interval (0 ms in Experiment 2 and 1,000 ms in Experiment 5). The rationale behind the second analysis was to examine the hypothesis that the intertrial interval can be used for processing in the subjective measure paradigm. This hypothesis predicts longer response times in the short intertrial interval.

Results and Discussion

The proportions of correct miniblocks were 72% and 93% for mixed- and single-object miniblocks in the subjective report group, respectively. In the performance-based group, the proportions were 76% and 88% for mixed and single miniblocks, respectively. The main effect for mixing (single vs. mixed miniblocks) was significant, $F(1, 30) = 16.43$ ($MSE = .0292$, 95% CI = .09, .23). The main effect for group was nonsignificant, $F(1, 30) = .07$ ($MSE = .0276$, 95% CI = −.06, .08), and so was the interaction, $F(1, 30) = 1.38$ ($MSE = .0272$).

RT

All effects in the design were significant. Main effects were found for group, $F(1, 30) = 12.71$ ($MSE = 940{,}142.08$); object switching, $F(4, 120) = 109.20$ ($MSE = 103.458.70$); and updating, $F(1, 30) = 169.52$ ($MSE = 249{,}823.75$). Two-way interactions were observed between group and object switching, $F(4, 120) = 4.07$ ($MSE = 103{,}458.70$); group and updating, $F(1, 30) = 4.20$ ($MSE = 249{,}823.75$); and object switching and updating, $F(4, 120) = 46.74$ ($MSE = 34{,}543.97$). The three-way interaction was also significant, $F(4, 120) = 7.14$ ($MSE = 34{,}543.97$; see Figure 6).

The simple interaction between group and object switching in the update condition was nonsignificant, $F(4, 120) = .64$ ($MSE = 68{,}925.63$). Specifically, both switching cost and mixing cost were statistically the same for both groups, $F(1, 30) = 2.38$ ($MSE = 67{,}455.30$), $p = .13$, and $F(1, 30) = .35$ ($MSE = 120{,}988.28$), $p = .56$, respectively. Coupled with the significant main effect of group, this last result can be interpreted as showing that response selection, manifested by the need to select an actual response in the performance-based group, was an inserted processing stage in the update condition.

In the update condition, switching cost was 127 ms in the subjective report group, $F(1, 15) = 4.63$ ($MSE = 27{,}849.63$, 95% CI = 23, 231), and 327 ms in the performance-based group, $F(1, 15) = 8.01$ ($MSE = 107{,}060.97$, 95% CI = 123, 531). The difference between these switching costs was nonsignificant, $F(1, 30) = 2.38$ ($MSE = 67{,}455.30$, 95% CI = 92, 308), $p = .13$.

In the non-update condition, the simple interaction between group and object switching was significant, $F(4, 120) = 9.02$ ($MSE = 69{,}077.04$). Switching cost was larger in the performance-based group than in the subjective report group, 646 and 182 ms, respectively, $F(1, 30) = 9.94$ ($MSE = 86{,}748.29$, 95% CI = 341, 587). Switching costs were significant for both the performance-based group, $F(1, 15) = 26.57$ ($MSE = 125{,}646.14$, 95% CI = 425, 867), and the subjective report group, $F(1, 15) = 5.52$ ($MSE = 47{,}850.43$, 95% CI = 46, 318).

Regarding the object switching cost subcomponents, in the update condition, pure counter switching cost was 149 ms and nonsignificant in the subjective report group, $F(1, 15) = 2.35$ ($MSE = 75{,}816.78$, 95% CI = −22, 320), and 269 ms in the performance-based group, $F(1, 15) = 9.35$ ($MSE = 61{,}734.49$, 95% CI = 114, 424). In the non-update condition, pure counter switching cost was 112 ms and nonsignificant in the subjective report group, $F(1, 15) = 1.92$ ($MSE = 52{,}481.33$, 95% CI = −31, 255), and 638 ms in the performance-based group, $F(1, 15) = 20.39$ ($MSE = 159{,}583.06$, 95% CI = 389, 887).

Cue repetition gain in the update condition was 22 ms and nonsignificant in the subjective report group, $F(1, 15) = .13$ ($MSE = 30{,}602.68$, 95% CI = −87, 131), and 58 ms and nonsignificant in the performance-based group, $F(1, 15) = 1.78$ ($MSE = 15{,}485.44$, 95% CI = −19, 135). Cue repetition gain in the non-update condition was 70 ms and marginally significant in the subjective report group, $F(1, 15) = 3.01$ ($MSE = 12{,}816.00$, 95% CI = 0, 140), and 8 ms and nonsignificant in the performance-based group, $F(1, 15) = .01$ ($MSE = 76{,}592.68$, 95% CI = −164, 180).

This result is consistent with the above hypothesis (see Experiment 2) that the relevant object is not accessed or the access process is aborted before completion in the non-update condition. When access is necessary to perform the parity judgment, switching cost becomes observable even in the non-update condition.

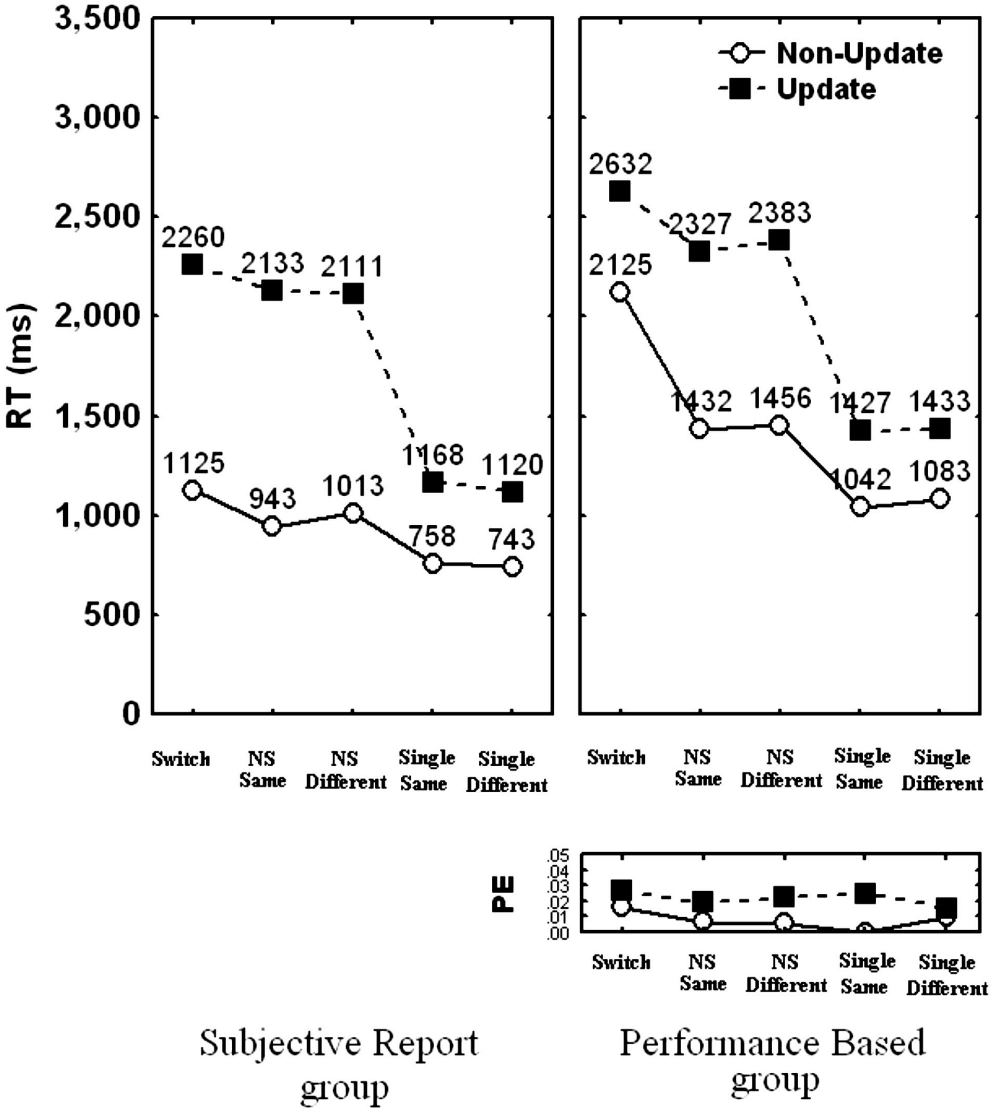

Figure 6. Experiment 5: mean reaction times (RT) as a function of group, object switching, and updating. Error proportions (PE) are provided for the performance-based group, in which a parity judgment was required in every trial. The subjective report group replicated the previous findings of Experiment 2 with an intertrial interval of 1,000 ms. The overadditive interaction between object mixing cost and updating was observed in the performance-based group as well. NS = nonswitch.

An interesting result was that, in the performance-based group, switching cost was larger in the non-update condition than in the update condition, 646 versus 327 ms, $F(1, 15) = 14.47$ (MSE = 28,035.95, 95% CI = 215, 423). A possible explanation for this result is that, in non-update trials, the same response is repeated when the object is repeated. Therefore, response selection might be performed by retrieving the previous response, and access is not necessarily needed. When the object is switched or updated, a parity judgment should be performed using the current object's value. Therefore, nonswitch RTs in the non-update condition might be underestimated due to use of the response repetition strategy.

The overadditive interaction between updating and mixing cost was significant in both the subjective report group, $F(1, 15) = 52.39$ (MSE = 86,035.17), and the performance-based group, $F(1, 15) = 79.48$ (MSE = 24,686.59). The updating cost in the mixed condition was 1,144 ms in the subjective report group, $F(1, 15) = 72.21$ (MSE = 290,064.37, 95% CI = 809, 1,479), and 880 ms in the performance-based group, $F(1, 15) = 162.25$ (MSE = 76,351.56, 95% CI = 708, 1,052); however, the difference between the groups in updating cost was only marginally significant, $F(1, 30) = 3.05$ (MSE = 183,207.97, 95% CI = 79, 449), $p = .09$.

Intertrial Interval Effects

The subjective report group in Experiment 5 was compared with the group in Experiment 2, with intertrial interval (0 or 1,000 ms) as a between-participants independent variable. RTs were slower by 259 ms in the short intertrial interval, $F(1, 22) = 7.23$ ($MSE = 494{,}555.11$, 95% CI = −94, 612). Intertrial interval did not interact with object switching or updating, $F < 1$ for all interactions. A planned comparison was conducted to reveal differences between the intertrial intervals in switching cost in the update condition. This contrast is important to check the hypothesis that, in the long intertrial interval, the participants might not complete the cognitive process before indicating their response. Switching cost did not differ significantly between intertrial intervals, $F(1, 22) = .25$ ($MSE = 29{,}148.44$). This result shows that switching cost was not absorbed into the intertrial interval. In contrast, mixing cost in the non-update condition was larger in the long intertrial interval (228 ms) than in the short intertrial interval (44 ms), $F(1, 22) = 3.96$ ($MSE = 45{,}894.94$, 95% CI = 77, 291).

Error proportions

Error analysis was possible only in the performance-based group. Note, however, that an error in a given trial stemmed only from response selection when the object value was correctly calculated, but the odd–even decision was wrong. This is because only miniblocks in which the final values were correct were entered into the analysis. A two-way ANOVA included condition and updating as independent variables. Only the main effect for updating was significant and reflected an updating cost of 1%, $F(1, 15) = 6.59$ ($MSE = .0013$, 95% CI = −.01, .03).

To summarize the findings, the basic results obtained in Experiment 2 of a substantial overadditive interaction between updating and object mixing cost were replicated using the performance-based measure. The absence of interaction between intertrial interval and switching cost indicated that, in using the subjective measure, the participants did not use the proposed strategy of responding before mental processing was completed.

General Discussion

In this work, we investigated updating in verbal WM. We found a sizable RT difference between conditions that involved updating and those that did not. Moreover, we found this updating cost to be larger when two objects were updateable than when only one object was updateable. This finding is interpreted as evidence that the updating process encompasses both objects in the region of direct access within WM, even though only one of them is actually updated. We argue that this feature of updating all objects applies to the region of direct access because we have shown that it applies only to objects in an updateable state. Objects that served only as passive memory load did not affect the updating cost even immediately following the loading of WM. Therefore, the larger updating cost in the mixed condition cannot be explained by WM load per se.

Mechanisms for Updating

In this section, we provide two possible mechanisms that may account for this phenomenon, updating-triggered rehearsal and binding by synchronization. These mechanisms are not mutually exclusive, but may support two different levels of explanation.

The first mechanism that may account for our results is updating-triggered rehearsal, which is closely related to short-term memory consolidation. Jolicœur and Dell'Acqua (1998) defined short-term memory consolidation as "a process that mediates the transfer of information generated from sensory input to storage in durable storage (probably STM)" (p. 175; STM = short-term memory). To account for our results, this definition should be broadened to include also information generated within WM, such as the results of the internal acts of updating. We shift from describing consolidation as gating perception and short-term memory to the definition of consolidation as a process that continuously acts to support active representations. Consolidation is not the gate to WM, but acts inside WM itself. Specifically, we argue that consolidation is triggered by the updating requirement derived from the environment. Updating takes place either when new information enters WM or when a modification of existing representation is required. The result of the updating process is new material represented in WM. Then, consolidation is required to protect this information against the corroding processes of decay and interference.[1]

Previous studies have shown that short-term memory consolidation occurs within the first few seconds after the presentation of the to-be-remembered stimuli (Jolicœur and Dell'Acqua, 1998; Klapp et al., 1983; Naveh-Benjamin & Jonides, 1984; Oberauer, 2001, 2002). Specifically, consolidation is capacity limited and thus interferes with a concurrent task at its initial stages. Also, its duration is proportional to the amount of information that has to be consolidated (Jolicœur and Dell'Acqua, 1998). However, the capacity limitation of consolidation exists for only few seconds. Once the stimuli are consolidated into a stable form of representation, they can be retained without slowing the performance of a concurrent task. The duration of consolidation was estimated to be around 2 s using the memory updating paradigm (Oberauer, 2002).

The results of Experiment 2 support the hypothesis that WM consolidation encompasses all WM objects in the region of direct access whenever any of them has to be updated. This is the reason why the updating cost increases with an increasing number of updateable objects. However, in contrast to previous studies in which the consolidated material had to be retained passively until the end of the trial, in our paradigm, the updated object could have become relevant again in the following trials. To meet this requirement, both updateable objects are stored in an active state, which enables direct access and retrieval. This state corresponds to the direct access region in Oberauer's (2002) concentric model.

What is the mechanism that carries out consolidation? The capacity limitation of consolidation might suggest that it is performed by the focus of attention. However, several studies have shown that updating is independent of object switching cost, the most profound marker of the focus of attention (Garavan, 1998; Gehring et al., 2003; Voigt & Hagendorf, 2002). In our experiments, for example, the existence of object switching cost above and beyond updating cost shows that these two processes depend on different mechanisms or on different combinations of mechanisms. Although accepting the idea that the focus of attention serves for selection of the relevant object and therefore for switching among objects, we argue that verbal WM consolidation is done through rehearsal. *Maintenance rehearsal* is a strategy of repeating

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[1] We have not discussed these alternatives here or differentiated between them. See Nairne (2002) for an extensive review.

verbal material to keep it in an immediately accessible form (Nairne, 2002) or to facilitate its encoding into LTM (Naveh-Benjamin & Jonides, 1984). Maintenance rehearsal is carried out by programming a motor articulation program that produces phonological verbal codes (Baddeley, 1986, 2003). This claim is supported by imaging studies showing that rehearsal activates speech-related brain areas (Paulesu, Frith, & Frackowiak, 1993; Smith & Jonides, 1999). In the mixed-object condition of our paradigm, participants tended to rehearse both object values in each trial (Garavan, 1998), that is, the motor program included both object values in each trial and therefore had to be reprogrammed whenever any of them changed. Accordingly, reprogramming was longer in the mixed-object condition than in the single-object condition. Because non-update trials did not require a modification of the rehearsed material, reprogramming was limited to update trials only.

The second mechanism that may account for our results is binding by synchronization. WM is associated with the integration and binding of information (e.g., Baddeley, 2000; Luck & Vogel, 1997; Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000; Wheeler & Treisman, 2002). For example, several inputs from different sensory systems that are activated simultaneously contribute to the creation of a composed integrated representation. The same logic applies to the activation of LTM representation, which forms an integrated WM representation. It has been suggested that, although each representation is characterized by a distinctive pattern of cell firing activity, binding is achieved by a temporal synchronization of these patterns (e.g., Klimesch, 1999; Ruchkin et al., 2003; Singer & Gray, 1995). Synchronization also serves to account for the capacity limitations of WM by imposing a restriction on the number of distinguishable cycles of synchronization that can be effectively maintained simultaneously (Hummel & Holyoak, 1997; Lisman & Idiart, 1995; Luck & Vogel, 1998; Shastri & Ajjanagadde, 1993). We claim that once synchronization is achieved, the synchronized elements must stay stable. Any modification of a specific object causes desynchronization, and after the modification is completed, the synchronization needs to build up again. Updating of a specific object is therefore carried out by desynchronization followed by resynchronization. Thus, updating cost might reflect the time required to achieve resynchronization.

We argue that the time required to achieve resynchronization is proportional to the number of activated objects. This can be explained in two ways, which are not distinguishable at this stage. First, if all of the activated objects form a singular complex object (cf. Halford, Wilson, and Philips, 1998; Zelazo & Frye, 1997), then resynchronization should be achieved among all of the activated objects. When any object fires in a different pattern of frequencies, the probability of obtaining synchronization decreases when more objects are active. Accordingly, more time is required for resynchronization. Non-update trials are not affected in this way because no resynchronization is required when none of the activated objects is modified. A second possibility is in line with the independent multiobject approach (e.g., Cowan, 1988; Oberauer, 2002), suggesting that synchronization does not act among all active objects, but only within each object. In our paradigm, for example, object cues and object values are synchronized for each object separately to form an object. In contrast to the first possibility, here only the relevant updated object has to be resynchronized. However, when other synchronized objects are maintained, the probability of reaching a distinctive pattern of synchronization is reduced. Again, this would increase the resynchronization cost, which is required only in the update condition. More research is required to distinguish between the above two explanations and to further relate updating to resynchronization.

Broader Theoretical Implications

Our results constitute important evidence contributing to the controversy over the capacity of the focus of attention. Cowan (2001) reviewed a large body of research that supports a limitation of four objects. In contrast, phenomena such as object switching cost (e.g., Garavan, 1998) and immediate recall of the last item studied compared with previous items (e.g., McElree, 2001; McElree & Dosher, 1989) are interpreted as evidence for a one-object limitation. This apparent discrepancy can be resolved in two ways. The first is to differentiate between two concepts of focus of attention, one holding several items and the other holding only one (Oberauer, 2002). The second is that the limitation can be expanded from one to about four objects by practice (Verhaeghen, Cerella, & Basak, 2004).

Our study strongly supports the first option. To our knowledge, no other study, except for Oberauer's (2002) work, has involved all three levels of representations within a single set of experiments. We provide evidence for a one-object focus of attention, marked by an object switching cost; a broader region of direct access, which forms a functional association with the object it holds, as shown by the interaction between updating and object mixing cost; and a passive short-term memory level that holds objects that are marked as non-updateable. Our results support Oberauer's concentric model in two ways. We claim that the direct access region is related to updating and have shown that it undergoes updating as a whole whenever updating is required. Also, we have shown that this update-triggered rehearsal is not performed by the focus of attention. We therefore assume that the focus of attention is required for the actual updating of the relevant object, whereas all of the objects are rehearsed subsequently by a different mechanism. This mechanism is close to Baddeley's (1986) concept of a phonological loop that serves for maintenance of verbal material and might be implemented by the synchronization.

Limitations

Although the effects of updating cost were sizable and stable in our study, we acknowledge that our measurement of updating cost might be confounded with other factors. Specifically, our non-update condition involved the computation of the arithmetic operation $x \pm 0$, which might rely on different rules than those related to the other arithmetic operations used (Baroody, 1985). The possibility that the overadditive interaction between updating and object mixing cost is confounded with this feature of the non-update condition is remote, mainly due to the results of Experiment 5, showing basically the same results by using a more rigorous measure of RTs. Still, additional research is required to provide a more direct measure of updating cost.

Another limitation that was raised by one of the reviewers addresses our notion of a WM object. In our study, we regarded each shape category (e.g., triangle) as a WM object and the concrete perceptual shapes (upward- and downward-pointing triangles) as different retrieval cues for the object's value. Alternatively, it can be claimed that each shape orientation constituted a separate object by itself. Accordingly, one could argue that our mixed-object condition involved four objects rather than only two objects. Although we cannot completely rule out this possibility, we think that it is implausible for two reasons. First, it is unlikely that two perfectly informationally dependent objects (e.g., the upward- and downward-pointing triangles) were kept as separate mental objects especially because they were regarded as one object in the experimental task. Moreover, if this were the case, a cue repetition gain would be expected also in the single-object (or single-shape category) condition, which we did not find. Nonetheless, future work may be required to clarify this point.

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