Fast and obligatory updating of working memory representations

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Abstract

Attending to items facilitates their encoding into working memory (WM), implying that the contents of WM are updated as we direct attention to the environment. Conversely, much research shows that WM updating is slow and effortful, suggesting that shielding against incoming input, rather than updating, is the default. To resolve this discrepancy, we suggest that updating item-to-context associations is costly, whereas updating a single item is fast and automatic. Participants performed a choice task in which the need for updating was manipulated. Experiment 1 (N=25) showed that updating was slower than not updating with a set-size of two items that required item-context binding, but faster when the set-size only involved one item. Experiment 2 (N=28) replicated this finding. Experiment 3 (N=20) showed that the slower no-update trials are due to removing erroneously updated information. In contrast to previous findings, these results suggest that updating is frequently effortless and obligatory.

To keep track of our ever-changing environment, we constantly need to update our working memory (WM) with goal-relevant information. WM updating is considered a core "executive function" (Miyake et al., 2000), which plays an essential part in goal-directed behavior. Over the past three decades, a large body of research has investigated the behavioral and neural underpinning of WM updating. A key finding is that updating is behaviorally costly. Specifically, studies that manipulated the need for updating observed that performance in trials that required updating was longer than in no-update trials (Kessler & Meiran, 2006, 2008; Kessler & Oberauer, 2014, 2015). Experimental paradigms that enable a finer-detailed analysis of the processes involved revealed that this cost is due to the operation of several distinctive and time-consuming sub-process involved, including opening the "gate" to WM (Rac-Lubashevsky & Kessler, 2016a,b), substitution (Ecker, Lewandowsky, Oberauer & Chee, 2010), and removing outdated information (Ecker, Lewandowsky & Oberauer, 2014).

However, the latency of WM updating, its proneness to error (Frischkorn, von Bastian, Souza & Oberauer, 2022), and its associated self-reports of mental effort (Westbrook, Kester & Braver, 2013) are all at odds with the common view that attention plays a role in determining the contents of WM. According to this view, orienting attention toward novel stimuli lead to their automatic encoding into WM (Cowan, 1999). While mere attention is not a sufficient condition for encoding items into WM (Chen & Wyble, 2015), directing attention to items facilitates this process (Oberauer, 2019). This view implies that updating may take place as part of, or as a result of, other attention-consuming processes, such as response selection (Oberauer, Souza, Druey & Gade, 2013; Szmalec, Vandierendonck & Kemps, 2005). It follows that updating is often the default outcome of attending to items and hence should be relatively effortless and automatic. If so, then it is the *resistance* to updating, rather than updating, that is controlled and difficult.

Here we suggest that resolving the above discrepancy relies on differentiating between updating items and item-context associations. Typical updating tasks require participants to keep track of the most recent item that corresponds to each of several contexts, being locations on the screen (Ecker et al., 2010; Kessler & Meiran, 2006, 2008; Oberauer 2002), serial positions (Kessler & Oberauer, 2014, 2015; Morris & Jones 1990), or semantic categories (Miyake et al., 2000). These tasks involve the simultaneous maintenance of several items that differ in their associated context. Therefore, correct performance is dependent on forming, maintaining, and retrieving these item-to-context associations. For example, in the n-back task, participants must compare the item presented on the screen to the one that appeared n trials before. Even in its easiest variant, the 1-back task, in which each item should be compared to the immediately preceding one, two items should be held in WM during the comparison process: the present and the previous one. Confusing between them is detrimental to task performance. Hence, each item should be associated with its role or context, being the present or previous item. It follows that this and other updating tasks require updating item-context binding rather than items per se. While updating these bindings is costly, we suggest that merely updating items without the need to bind them into a context is seamless and even obligatory, a by-product of their attention-consuming processing.

To test this idea, we designed a minimal updating task. Experiment 1 required maintaining either 1 (set-size = 1; SS1) or two (set-size = 2; SS2) items in WM (see Figure 1). In each trial, participants performed a choice reaction-time (RT) task based on the presented item. The memory of the items presented in previous trials was not required for responding correctly. In addition, in each trial, the participants were prompted whether to update the presented item into WM or not. After a few trials, they had to recall the item held in their WM. While minimal in its processing requirements, this task shares all the features of more complex updating tasks:

holding items in memory over several trials, selectively updating them upon demand, frequently updating the information throughout a sequence of trials, and filtering out distractors when updating is not required. To anticipate the results, updating was slower than no-updating in SS2, reflecting the need to associate each item to its context and update these associations in update trials. However, updating was faster in SS1, in which no item-binding associations needed to be updated.

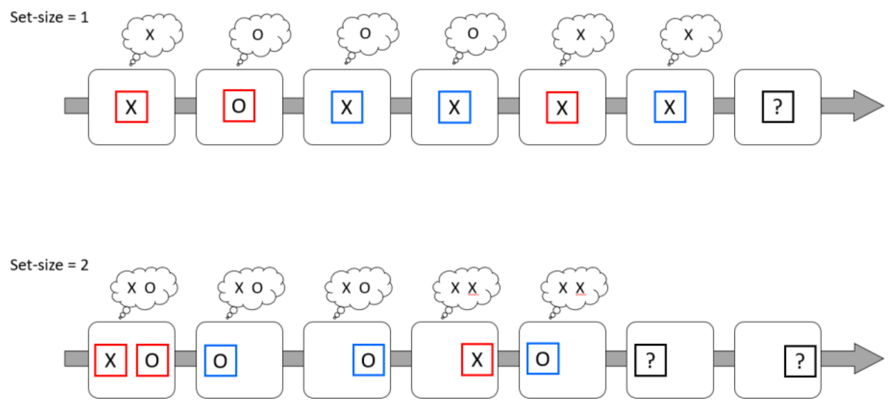

Figure 1. Experiment 1: Trial sequences in SS1 (top) and SS2 (bottom). Bubbles represent the content of WM in each trial.

Experiment 1

Method

Participants

Thirty-four students from Ben-Gurion University of the Negev participated in the experiment in return for course credit. Nine participants were excluded from the analysis due to low accuracy (<80%) in either the choice RT trials or the recall phase. 25 participants (22 women, age: M = 23.280, SD = 2.441) were therefore included in the analysis.

Procedure

Stimuli presentation was programmed in OpenSesame (Mathôt, Schreij & Theeuwes, 2012). The study was run using JATOS (Lange, Kühn & Filevich, 2015). Participants performed the experiment online using their personal computers through their internet browsers.

The experiment was composed of two parts, corresponding to SS1 and SS2, respectively. 25 sequences of trials were administered in SS1 and 50 sequences in SS2. Each part was preceded by two practice sequences.

Participants performed a choice RT task (Figure 1). In each trial of SS1, the letter X or O appeared on the screen, and the participants needed to respond with the keys *p* or *q*, respectively. Each letter appeared within a red or a blue frame. Throughout each sequence, participants were required to remember the letter that appeared in the most recent red frame, and to report it at the end of the sequence. Accordingly, a red frame required updating WM with the letter that appeared inside it ("update" condition), while a blue frame did not ("no-update" condition). The first trial in each sequence was always an update trial. The updating condition in each of the subsequent trials was chosen at random with equal probabilities for update and no-update. The duration of each trial was terminated by the response. The inter-trial interval was 500ms. Each trial had a 10% probability of being the last in the sequence. Accordingly, the number of trials in each sequence followed a geometric distribution, so that the participants could not expect the end of the sequence. A recall probe appeared at the end of each sequence, in the form of a question mark within a black frame. The participants needed to indicate the letter they remember, namely the last letter that appeared within a red frame, using the *x* and *o* keys.

SS2 was similar but included two frames, one presented on the left side of the screen and the other on the right. In the first trial, both frames were presented in red, with the letter X or O within each of them. Then, in each trial, one of the frames appeared on the screen in either red or blue, with a letter inside. Participants were required to respond to the letter as in SS1, and remember the last letter that appeared within a red frame on each of the sides. Accordingly, two letters needed to be memorized throughout the sequence. After a random number of trials, the participants were prompted to recall the most recent red letter that appeared in each side in random order using the X and O keys.

Design and Analysis

The main analysis focused on RT and accuracy in the choice RT task as a function of Set-Size (1 vs. 2) and Updating (update vs. no-update). We also examined the effect of Update-Switch, defined as whether or not the updating condition in Trial N differed from Trial N-1. Switch trials are update trials following no-update trials or vice versa. Repeat trials are update following an update, and no-update following a no-update. This variable is interesting based on the finding that switching between update and no-update trials results in a substantial behavioral cost, attributed to switching the state of the gate to WM (Kessler & Oberauer, 2014; Rac-Lubashevsky & Kessler, 2016a,b). Additional analyses examined performance as a function of lag-2 switch vs. repetition (Experiment 3) and in the recall phase (Experiments 2 and 3). The analysis only included trials from sequences in which the final recall step was correct. Error and post-error trials were removed from the RT analysis. RTs that deviated more than 2sd from the mean of their condition within each subject were dismissed as outliers. All analyses were carried out in R (R Core Team, 2017) using the RStudio IDE (RStudio team, 2022; version 4.1.2) using "afex" (Singmann et al., 2021; version 1.0-1), "emmeans" (Lenth, 2022; version 1.7.2), and "tidyverse" (Wickham et al., 2019; version 1.3.1) packages.

Results

Choice trials RT

An ANOVA was conducted with Set-Size (1,2), Updating (update, no-update), and Update-Switch (switch, repeat) as within-subject variables. Significant main effects were observed for Set-Size, $F(1,24)=20.35$, $p<.001$, $\eta_p^2=.46$, Updating, $F(1,24)=36.62$, $p<.001$, $\eta_p^2=.60$, and Update-Switch, $F(1,24)=48.03$, $p<.001$, $\eta_p^2=.67$. The two-way interaction between Updating and Update-Switch was significant, $F(1,24)=4.63$, $p=.042$, $\eta_p^2=.16$, reflecting a larger switching effect in update trials (245ms) than in no-update trials (179ms). Finally, the two-way interaction between Updating and Set-Size was significant, $F(1,24)=63.12$, $p<.001$, $\eta_p^2=.73$ (see Figure 2). In SS2, update trials were 279ms *slower* than no-update trials, $F(1,24)=59.99$, $p<.001$. In SS1, by contrast, update trials were 49ms *faster* than no-update trials, $F(1,24)=8.37$, $p=.008$. The two-way interaction between Set-Size and Update-Switch, as well as the three-way interaction, were both non-significant (p=.194 and .637, respectively).

Choice trials accuracy

The main effect of Updating was significant, $F(1,24)=14.28$, $MSe= .0007$, $p<.001$, $\eta_p^2=.37$, reflecting a larger error proportion in no-update trials (4.1%) than in update trials (2.7%). In addition, the main effect of Set-Size was significant, $F(1.24)=7.61$, $MSe=.0019$, $p=.011$, $\eta_p^2=.24$, reflecting a larger error proportion in SS2 (4.3%) than in SS1 (2.6%). Finally, the two-way interaction between Updating and Update-Switch was significant, *F(1,24)=7.14, MSe=.0007, p=.013,* $\eta_p^2=.23$. Specifically, the simple main effect of Updating was significant in repetition trials, *F(1,24)=13.78, p=.001*, but not in switch trials, *F(1,24)=1.06, p=.312*.

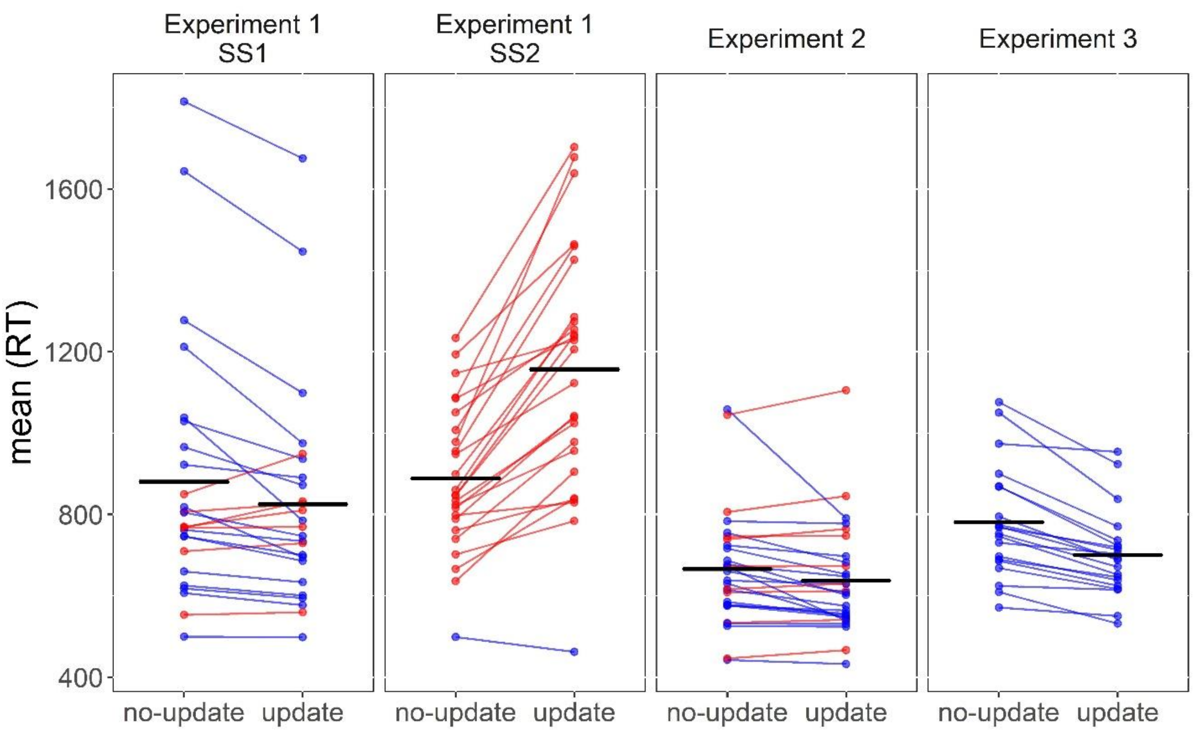

Figure 2: RT by Updating for Experiments 1, 2, and 3. Horizontal black lines represent grand averages across participants. Red lines represent participants with updating cost, whereas participants showing an updating benefit are represented by blue lines. SS = Set-Size.

Experiment 2

Whereas the longer updating latencies in SS2 are consistent with previous findings in the WM updating literature, the finding in SS1 is novel and surprising. The goal of Experiment 2 was to replicate this finding.

Method

Participants

Thirty students from Ben-Gurion University of the Negev participated in the experiment in return for course credit. Two participants were excluded from the analysis due to low accuracy (<80%) in either the choice RT trials or the recall phase. 28 participants (16 women, age: *M* = 23.250, *SD* = 1.379) were therefore included in the analysis.

Procedure

The procedure was identical to that of Experiment 1, except for the following changes. First, this experiment only tested SS1, in which the novel finding was previously observed. Second, the number of trial sequences in SS1 was increased to 55. Third, the same response keys were now used for both the choice task and the recall phase, namely p and q for X and O, respectively. Accordingly, the participants did not need to move their fingers between the choice and recall trials, enabling to measure RT at recall. Unlike Experiment 1, this experiment was conducted in the lab.

Results

Choice trials RT

The main effect of Updating was significant, *$F(1,27)=5.78$, $p=.023$, $\eta_p^2=.18$*, reflecting faster RTs in update than in no-update trials (638 vs. 666ms, respectively). This finding replicates Experiment 1. Also, the main effect of Update-Switch was significant, *$F(1,27)=47.85$, $p<.001$, $\eta_p^2=.64$*, reflecting a switch cost of 101ms. The 2-way interaction was non-significant, $F(1,27)<1$.

Choice trials accuracy

The main effect of Updating was significant, *$F(1,27)=12.96$, $p=.001$, $\eta_p^2=.32$*, as well as the two-way interaction, *$F(1,27)=5.36$, $p=.028$, $\eta_p^2=.17$*. Specifically, update trials were more accurate than no-update in repetition trials (3.8% vs. 6.4%, respectively), *$F(1,27)=14.42$, $p<.001$*, but the two did not significantly differ in switch trials (4.3% vs. 5.0%, respectively), *$F(1,27)=1.73$, $p=.20$*.

Recall performance

We examined RT for the recall trials to see whether the duration of recall was sensitive to the number of trials that took place since the presentation of the last red frame. Such a finding could imply that participants did not update their WM throughout the trial sequence but rather retrospectively tried to recall the letter in the last red frame when prompted to do so. Such a reactive control strategy (Braver, 2012) is already implausible since it predicts no RT difference between update and no-update trials during the choice trials. Still, we aimed to test its prediction that RT will be longer the further away was the most recent red frame. To test this, we examined RT for probes that appeared following 1, 2, or ≥3 no-update trials in a row.

Probes that immediately followed an update trial were excluded from the analysis, because responding to the probe in these cases involves a stimulus- and response-repetition. RTs for correct probes following 1, 2, and ≥3 no-update trials in a row were 785, 831, and 805ms. Apart from being non-monotonic, this trend was clearly non-significant, $F(2,54)=1.28$, $p=.287$, $\eta_p^2=.05$. The effect on recall accuracy was also non-significant, $F(2,54)=.13$, $p=.881$. These results support the idea that updating took place in the choice trials and not retroactively.

Experiment 3

Why is updating faster than not updating? One possibility is that attending to an item during response selection facilitates its updating into WM, whether updating is required or not. Removal (Lewis-Peacock, Kessler & Oberauer, 2018) then applies to the items that did not require updating, namely those in the blue frames, to prevent interference with the goal-relevant content of WM, namely the letter in the most recent red frame. We capitalized on the lag-2 repetition effect (Mayr & Keele, 2000; Kessler, 2018) to examine this possibility. If removal takes place, then responding to an item that appeared two trials ago across a different intervening item (e.g., X preceded by O that was preceded by X; n-2 repetition) is expected to be slower than responding to an item that differed from the one that appeared two trials ago (e.g., X preceded by O that was preceded by Z; n-2 switch). This is because moving from X to O entailed suppressing X as part of its removal from WM, which impairs the response to X in the following trial. Accordingly, a removal account of our results predicts n-2 repetition cost in no-update trials.

Method

Participants

Thirty-two students from Ben-Gurion University of the Negev participated in the experiment in return for course credit. Twelve participants were excluded from the analysis due to low accuracy (<80%) in either the choice RT trials or the recall phase. 20 participants (18 women, age: M = 23.60 SD = 1.27) were therefore included in the analysis.

Procedure

The procedure of Experiment 2 was used with the following changes. In each trial, the letter X, O or Z appeared on the screen, and the participants needed to respond with the keys *j, k* and *l*, respectively, using their index, middle, and ring fingers. In order to ensure we get enough sequences for the analysis, each trial had an 80% chance of having the same colored frame (namely, Updating condition) as the previous trial. In addition, each sequence had a minimum of 3 trials. The experiment was conducted online as in Experiment 1.

Results

Choice trials RT

An ANOVA was conducted with Updating and Update-Switch as within-subject variables. The main effect of Updating was significant, $F(1,19)=25.26, p<.001, \eta_p^2=.57$, again demonstrating faster RTs in update than no-update trials, 733 vs. 835ms, respectively. The main effect of Update-Switch was also significant, $F(1,19)=25.99, p<.001, \eta_p^2=.58$, reflecting longer RTs in switch than in repetition trials, 862 vs. 705ms, respectively. The two-way interaction was non-significant, $F(1,19)=3.56$, $p=.074$, $\eta_p^2=.16$.

Choice trials accuracy

None of the main effects was significant, $F(1,19)=2.18$, $p=.157$, $\eta_p^2=.10$ for Updating, and $F(1,19)=.42$, $p=.523$, $\eta_p^2=.02$ for Update-Switch. The two-way interaction was also non-significant, $F(1,19)=3.60$, $p=.073$, $\eta_p^2=.16$.

Lag-2 repetition RT

Only trials that were preceded by at least two trials of the same updating condition (either update or no-update) entered the analysis. We compared lag-2 repetition trials (e.g., XOX) to switch trials (e.g., ZOX). An ANOVA was conducted with Updating and Lag-2 as within-subject variables. The main effect of Updating was significant, $F(1,19)=16.40$, $p<.001$, $\eta_p^2=.46$, reflecting faster RTs in update than no-update trials, 738 vs. 805ms, respectively. The effect of Lag-2 was non-significant, $F(1,19)=3.79$, $p=.067$, $\eta_p^2=.17$. However, the 2-way interaction was significant, $F(1,19)=9.91$, $p=.005$, $\eta_p^2=.34$ (see Figure 3). Specifically, the simple main effect of Lag-2 in update trials was significant, $F(1,19)=10.59$, $p=.004$, reflecting faster RTs in lag-2 repetition trials than in switch trials, 709 vs. 767ms, respectively. The simple main effect of Lag-2 in no-update trials was non-significant, $F(1,19)=.24$, $p=.632$.

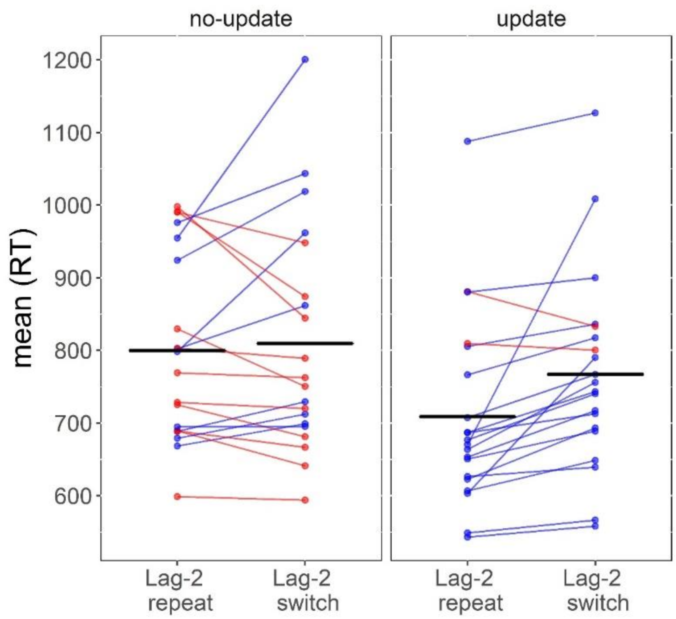

Figure 3: Experiment 3: Lag-2 repetition benefit was found in update trials, whereas no effect was observed in no-update trials. Horizontal black lines represent grand averages across participants. Red lines represent participants with a repetition cost, whereas participants showing a repetition benefit appear in blue.

Lag-2 repetition accuracy

Only the main effect of Lag-2 was significant, $F(1,19)=5.63$, $p=.028$, $\eta_p^2=.23$, reflecting more errors in repetition trials (4.5%) than in switch trials (2.7%). However, this was not qualified by a 2-way interaction, $F(1,19)=1.08$, $p=.312$, $\eta_p^2=.05$. The main effect of Updating was also non-significant, $F(1,19)=.79$, $p=.384$, $\eta_p^2=.04$.

Recall performance

Six participants were removed from the RT analysis and 2 from the error analysis due to empty cells. RTs were 947, 922 and 851ms for probes following 1, 2, or ≥3 no-update trials in a row, respectively, *$F(2,26)=1.36$, $p=.274$, $\eta_p^2=.10$*. Error rates 14.7, 5.9 and 15.3%, respectively, *$F(2,34)=1.26$, $p=.297$, $\eta_p^2=.07$*. As in Experiment 2, no evidence was found to support a retroactive control strategy.

Discussion

The basic finding of quicker update RTs was again replicated. Lag-2 repetition facilitated performance in update trials but did not have an effect in the no-update condition. The effect in update trials reflects priming from previous trials, suggesting that continuously updating a single item in WM does not result in long-lasting after-effects of removal. While we did not observe a repetition cost in no-update trials, the abolished repetition gain in this condition is consistent with the notion of suppressing not-updated information. A similar result was reported by Ecker et al. (2014), who found that the repetition benefit in a memory updating paradigm was reduced but not eliminated, following a removal cue.

General Discussion

Previous studies addressed the apparent conflict between the role of WM in shielding the maintained information against interference and its effective updating with goal-relevant information upon need (Frank, Loughry & O’Reilly, 2001; Hazy, Frank & O’Reilly, 2007; O’Reilly, Braver & Cohen, 1999). Ample work suggests that these seemingly opposing computational goals are coordinated by a gating mechanism that regulates the flow of information into WM (Braver & Cohen, 2000; Chatham & Badre, 2015; McNab & Klingberg, 2008). The gate is closed by default to protect the maintained information against interference and is transiently opened to update WM with new, goal-relevant information. Control over the gate state is associated with activation in dopaminergic brainstem nuclei (D'Ardenne et al., 2012) and in the basal-ganglia (Nir-Cohen et al., 2020). Since the default gate-state is closed, updating requires a cascade of processes that include opening the gate and encoding the new information, possibly while forming new item-context associations and removing old ones. Carrying these processes out is time-costly and non-obligatory. In contrast to the above, we suggest that under simple conditions that involve the concurrent processing and maintenance of one item only, updating can be quick and obligatory. Slower RTs in no-update trials are due to removal, as reflected by a diminished lag-2 repetition benefit in this condition.

The finding of an update-switch cost in SS1 calls for a reinterpretation of this effect. Previous studies have shown that switching between no-update and update trials, or vice versa, results in a substantial RT cost, ascribed to opening or closing the gate, respectively (Kessler & Oberauer, 2014; Rac-Lubashevsky & Kessler, 2016b; Rac-Lubashevsky, Slagter & Kessler, 2017). Our findings of obligatory updating in SS1 imply that the gate remained open throughout performance, both in updating and no-updating trials, and hence the need for removal in no-update trials. Accordingly, the finding of an update-switch cost in SS1 thus cannot be attributed to gating, and presumably reflects switching between two tasks, namely updating and not-updating. Previous findings using the reference-back task indicated that update-switching is not merely task-switching, as demonstrated by asymmetrical brain activity when switching in the two directions (Nir-Cohen et al. 2020; Rac-Lubashevsky & Kessler, 2018.). Also, update-switching was observed even in tasks where the difference between update and no-update trials was not made explicit to the participant (Kessler & Oberauer, 2014). However, based on the findings in SS1, we contend that the RT cost of update-switch in earlier studies may partially reflect task switching.

To conclude, we identified a condition in which updating is the default mode of WM. When holding only one item in mind, updating is a by-product of attention, which in our case is manifested in the response selection as part of the choice RT task. Notably, recent evidence had shown that when given the opportunity to choose the number of items held in WM, people tend to rely on one item only (Draschkow, Kallmayer & Nobre, 2021). Accordingly, the situation of our SS1 condition is very common during natural “real world” behavior, implying that most of the time, updating our WM is fast and effortless.

Authors' note

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