The distance effect in numerical memory-updating tasks

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Abstract Two experiments examined the role of numerical distance in updating numerical information in working memory. In the first experiment, participants had to memorize a new number only when it was smaller than a previously memorized number. In the second experiment, updating was based on an external signal, which removed the need to perform any numerical comparison. In both experiments, distance between the memorized number and the new one was manipulated. The results showed that smaller distances between the new and the old information led to shorter updating times. This graded facilitation suggests that the process by which information is substituted in the focus of attention involves maintaining the shared features between the new and the old number activated and selecting other new features to be activated. Thus, the updating cost may be related to amount of new features to be activated in the focus of attention.

Keywords Working memory · Updating · Numerical distance

Updating is a process which allows people to replace and modify the content of working memory (WM) in order to hold new information (Morris & Jones, 1990), and it is considered a fundamental executive function in cognitive architecture (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). To investigate this process, tasks have

been designed which involved simultaneously maintaining different elements in memory, some of which have to be replaced by new information. Many studies have examined the mechanisms involved in the selective access to the content of WM or in replacing outdated information (Garavan, 1998; Gehring, Bryck, Jonides, Albin, & Badre, 2003; Li, Bao, Chen, Zhang, Han, He, & Hu, 2006; Kessler & Meiran, 2006, 2008; Oberauer, 2002, 2003; Oberauer, Wendland, & Kliegl, 2003; Unsworth & Engle, 2008; Voigt & Hagendorf, 2002). However, little study has been given to the possible role played by the relationship between the information maintained in memory and the new information that replaces it. This study aims to address this question by investigating how the numerical distance between the stored and the new numerical information influences the updating process.

Updating tasks have been used to study selective access in WM since Garavan (1998) introduced the double counter task. In this task, participants had to keep two counters in memory for two different figures. Participants updated the appropriate mental count by adding one unit when the corresponding figure was presented. Garavan's main finding was that the time used to update the information was longer when there was a switch from one counter to the other, that is, when the counter to be updated was different from the counter previously updated. These results suggest that people do not have simultaneous access to all of the content of WM, but can only attend to one stimulus at a time. This effect fits the theoretical models which conceive WM as a hierarchical system of active representations in long-term memory (Cowan, 1995; Oberauer, 2002). In this system, Oberauer (2002) has proposed the existence of a focus of attention in WM which maintains the representation which a person is aware of at a given moment and on which the next

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cognitive operation is performed. Along the same lines, Oberauer found greater switching costs when the number of elements in WM increased (see also Oberauer, 2003; Oberauer et al., 2003; Voigt & Hagendorf, 2002). This indicates the greater difficulty in selecting one item to be focused from different candidates when the number of candidates increases. According to Oberauer's (2002) model, these different elements are thought to be activated in the direct access region, which means that they are available and ready for selective access and processing in the focus of attention.

In previous studies updating and selective access were not dissociated, since in all the trials it was necessary to update information. Subsequent efforts have been made to differentiate the costs associated with selective access to contents and those associated with the actual updating of the information. Oberauer (2003) studied separately the processes of updating and selective access to working memory contents in order to determine their possible roles in the switching effect. His results showed that switching cost was present when the contents of WM had to be accessed but not updated, and also when updating was required but no retrieval of previous information was needed. Therefore, these experiments revealed that both selective access and updating influence the switching effect.

To further dissociate these processes, Kessler and Meiran (2006) manipulated simultaneously updating and object switching in a numerical task. Their results confirmed that even in non-updating trials there was an appreciable switching effect. In addition, the authors found an interesting result when they compared two conditions which did not require a switch of object: in one condition there was only one updateable element (simple lists), in the other condition there were two updateable objects (mixed lists), although only one of them was updated. The updating cost was higher when there were two updateable elements (mixed lists) than when there was only one updateable element (simple lists), even when in neither case object switching was required and only one object was updated in each trial. Based on this result, the authors considered that there is a global updating mechanism which acts on all the elements stored in WM, even though only one of them may be updated. This mechanism would give stability to the representations of the different objects held in WM.

In addition to global updating, Kessler and Meiran (2008) proposed a local updating mechanism that modifies only some elements in WM. They showed that the time required for updating was related to the number of items that had to be substituted. This selective updating would provide flexibility to WM, allowing modification of the information. It could be argued that selective updating occurs not only at the level of the different elements stored in WM, but also at the level of a representation associated

with a single element or object in WM. Thus, updating could be affected by the relationship between the representation of an element in WM and the new representation. The more similar the new representation is to that previously stored, the faster the updating should be. This is the hypothesis which we aim to explore in this study.

The relationship between stored and new numerical information

Updating studies mentioned above have mostly used numerical information, and in fact new information is generally obtained after performing an operation based on stored information. New and stored information may be related to a greater or lesser extent through the operations carried out. For example, the easiest arithmetical operations give results which are closer to the previously stored information than do more difficult operations. It is possible that the proximity of the numbers involved in the updating may influence the time needed to carry out the updating.

Numerical distance has been found to be related to different effects in studies dealing with numerical cognition. It has been shown that the latency in naming a one-digit number is lower when a close prime is presented than when the prime is more distant (Brysbaert, 1995; Den Heyer & Briand, 1986; Koechlin, Naccache, Block & Dehaene, 1999; Reynvoet, Brysbaert, & Fias, 2002). Distance is also involved in the split effect which is found in verification tasks of simple mental calculation. In these tasks, a simple arithmetical operation is presented (e.g., $4 + 2$), along with a number which may (e.g., 6) or may not (e.g., 7) be the correct solution. Results show that the response times for incorrect solutions are greater, and the accuracy is lower when the incorrect answers presented are close to the correct solution (e.g., 7) rather than more distant (e.g., 9) (Ashcraft & Battaglia, 1978; Ashcraft & Stazyk, 1981; Stazyk, Ashcraft, & Hamann, 1982; Zbrodoff & Logan, 1990). Similarly, in Stroop numerical tasks the degree of interference is inversely related to the numerical distance between the irrelevant digits and the number of items shown on screen (Pavese & Umiltà, 1998, 1999). In memory tasks as well the distance between the information stored in memory and that presented may also influence performance. Using the Sternberg recognition task, Morin, DeRosa, and Stultz (1967) showed that the response times to negative probes decreased according to the distance of the negative probe from the member of positive set nearest in size. All the results described above may be due to the fact that numbers are represented as an ordered continuum, and that the activation of a number spreads along this continuum, affecting the other numbers which are used later in the task. Therefore, numerical distance may also

influence updating based on numerical operations, since the number maintained in memory and the new one may be more or less distant.

From the results described, a possible hypothesis is that updating could be easier if the number presented is closer to the number stored in memory. This assumption can also be made from proposals which consider that the information in WM is represented as sets of features (Nairne, 1990; Oberauer & Kliegl, 2001, 2006). From this perspective, two items which are stored in WM can overlap as long as their representations share certain features. It has been found that when two items have to be maintained simultaneously in WM, their representational overlap produces interference (Oberauer & Lange, 2008). This interference is the result of the competition between both representations for common features and of the subsequent degradation of the representation which loses these features. Nevertheless, in the case of updating, when one item replaces another, there should be a facilitation effect related to the number of shared features. In this case, the features which are common to both representations would remain active, whereas the new features which change with respect to the information stored in memory should be selectively activated and bound to the rest of the features. Therefore, the higher the number of new features to be activated the greater the updating cost.

In a previous experiment (Lendínez, Pelegrina, & Lechuga, 2007) we used Kessler and Meiran's (2006) task in which new information to be memorized was obtained after an arithmetical operation was carried out on a value stored in memory. Participants had to maintain a digit number (e.g., 4) in memory, then an arithmetical operation (e.g., + 1 or + 2) indicated that the original number had to be replaced with the result of applying the operation (i.e., 5 or 6). Our results showed that numerical operations affected the time needed to update information. In the example shown, more time was spent with the operation + 2 than with + 1. This could indicate that in this task, more difficult operations increase the updating cost. However, although the operation + 2 is more difficult than + 1 (Ashcraft 1992), it should also be considered that these operations produce results which are more or less distant from the original (6 is further than 5 from 4). That is, it is possible that the results may be due to the numerical distance between the two numbers involved in the updating.

Present study

In the present study we aimed to further investigate to what extent numerical distance between information stored in memory and newly presented information influence updating. To do this, the possible effect of numerical distance and the difficulty of the operations should be disentangled. To this end, in the first experiment we designed a task in which the

difficulty of the operations was inversely related to numerical distance. Specifically, we used a numerical comparison as the basis for updating. Studies of mental arithmetic show that response times in numerical comparisons are faster as the distance between numerical values increases (Dehaene, Dupoux, & Mehler, 1990; Moyer & Landauer, 1967). Hence, in numerical comparisons difficulty and distance are inversely related because the most difficult operations involve the shorter distances. Therefore, if difficulty were to influence updating times, these times should be higher when the distance is small. In contrast, if it is the similarity of the information which were to influence performance, then the updating times should be lower for closer numbers. The second experiment was designed to better exclude a possible role of the operations that are usually presented in numerical updating studies. In this experiment participants do not have to carry out any numerical operations; they simply have to memorize numbers which are more or less related to the information stored in memory. Therefore numerical distance was not associated with any numerical operation, and its possible effect would be due to the representational similarity.

First experiment

In the first experiment we used an updating task based on Carretti, Cornoldi, and Pelegrina (2007), in which the participants had to memorize the smaller number which appeared in each of two shapes. Here, the criterion for updating or not updating depends on a numerical comparison between the number maintained in memory and the number presented. Therefore, both updating conditions involve similar numerical comparisons, but differ in the need to replace information stored in memory with new information. The use of the same operations in the two updating conditions enables us to manipulate the distance in both.

If numerical distance were to influence performance through the similarity between the numerical representations stored in memory and that presented, the time needed should be lower with closer numbers, since they share more features. In addition, if representational similarity were to have a specific effect on updating, this effect should be more evident in the condition in which information must be substituted than in the non-updating condition. However, if distance were to affect performance through the difficulty of the comparison, more time should be spent in comparisons between closer numbers, and this effect should be equivalent in both updating conditions, as analogous comparisons are performed in both conditions.

This experiment follows the procedure used by Kessler and Meiran (2006) in which two types of lists are included: mixed and simple. In mixed lists two active elements which

may be updated are stored in WM, so that the participant has to switch from one element to another throughout the list. In simple lists there is only one element which may be updated. The inclusion of these single lists in which all the cognitive operations are performed on the same element allows us to observe the possible distance effect without the influence of other effects involved in the switching or maintenance of various active elements in memory. In addition, this condition is more similar to numerical tasks in which the participant has to compare a number on the screen with another number stored in memory (e.g., Dehaene et al., 1990).

Method

Participants

The participants were 24 psychology students (23 women) between the ages of 18 and 22 ($M = 18.92$; $SD = 1.50$). In all the experiments, they received course credits for their participation.

Materials

The task was made up of 90 lists of 12 items. Each item consisted of a shape (rectangle or triangle) in the centre of which was a number between 11 and 99. The first item was always a rectangle and the second a triangle. There were two types of lists: 30 simple and 60 mixed. In the simple lists, all the items following the initial ones had the same shape: either a rectangle or a triangle. Half the lists had a rectangle, while the other half had a triangle. The mixed lists contained items with both shapes (see Fig. 1). In each experimental session the lists were organized in three blocks. The first and the third block had 15 simple lists each. The second block was made up of 60 mixed lists.

The items in each of the lists could be different types according to the switching and updating conditions. In the non-switching condition, the shape associated with an item was always the same as for the previous item, while in the switching condition the shape was different. In the simple lists all the items were nonswitch, whereas in the mixed lists half the items were of each type. In the updating condition each number was lower than the previous smallest number associated with the same shape. In the non-updating condition the number was larger than the previous smallest number.

In addition, the distance between the two numbers associated with the same shape was manipulated. Therefore, in each of the updating conditions, the distance could be large when the two numbers differed by 5 or 6 units, or small if the numbers differed by 1 or 2 units. Each of the lists had approximately the same number of items with large and small distance.

Fig. 1 Schematic representation of a mixed list in Experiments 1 and 2. Initially, two items were presented with the initial values for each shape. Then a sequence of items was presented. In the first experiment (*left*), the participant had to compare the number presented inside the shape with the number maintained for the same shape in order to memorize the smallest number. In the second experiment (*right*), the participant had to memorize the number inside the shape according to the cue that masked the number. When the cue was green (represented as a circle with solid line) the number had to be memorized. With red cues (represented as a circle with broken line) the number did not have to be memorized. At the end of the list, participants had to type the final value associated with each shape

Procedure

Each list began with the consecutive presentation of the two initial items, first a rectangle and then a triangle, both with a number in the centre. Once the participants had memorized the initial values associated with each shape they had to press a key. The rest of the items were then shown in sequence. For each one, the participants had to memorize the number when it was lower than that

memorized for the presented shape, and then press a key. When participants pressed a key, a blank screen was shown for 250 ms followed by the next item (see Fig. 1).

At the end of the list, each of the shapes was shown successively with an indicator (“_”) which indicated to the participants that they should type the smallest number associated with that shape. As with the initial items, the rectangle was always shown first. After the results were recorded, the participant was informed of the number of correct answers. The latency between the moment each item was displayed and the moment the participant pressed a key was recorded. The presentation of the stimuli as well as the registration of latencies and responses were controlled using the program *E-prime* (Schneider, Eschman, & Zuccolotto, 2002).

The instructions indicated to the participants that they should perform the comparison and memorize the result as quickly as possible, while trying to be accurate. Before the experimental session, the participants performed eight practice trials with both types of lists, so that they were familiar with the procedure.

Results

The participants completed correctly 80.07% of the mixed lists and 85.97% of the simple lists. Response times from practice lists and from the incorrectly reported lists were excluded from analyses. Response times lower than 200 ms and those exceeding the participant's mean in each condition by more than 3.5 standard deviations were also removed from data analysis (1.22%).

A repeated measures ANOVA 3 (type of object switch) $\times$ 2 (updating) $\times$ 2 (distance) showed the main effects of type of object switch, $F(2, 46) = 231.41$, $p < 0.001$, $\eta^2 = 0.910$, updating, $F(1, 23) = 61.35$, $p < 0.001$, $\eta^2 = 0.727$, and distance, $F(1, 23) = 75.41$, $p < 0.001$, $\eta^2 = 0.766$. The distance effect was qualified by a significant interaction with updating, $F(1, 23) = 160.68$, $p < 0.001$, $\eta^2 = 0.875$. Furthermore, there were significant interactions between type of object switch and updating, $F(2, 46) = 5.88$, $p < 0.005$, $\eta^2 = 0.204$, type of object switch and distance, $F(2, 46) = 18.78$, $p < 0.001$, $\eta^2 = 0.450$, and the third order interaction: type of object switch $\times$ updating $\times$ distance, $F(2, 46) = 3.64$, $p < 0.05$, $\eta^2 = 0.137$. The results are shown in Fig. 2.

The three-way interaction was further specified with a separate two-way ANOVA 3 (type of object switch) $\times$ 2 (distance) for each condition of updating. The separate analysis for the updating trials showed that the main effects of type of object switch, $F(2, 46) = 161.73$, $p < 0.001$, $\eta^2 = 0.875$, and distance, $F(1, 23) = 143.41$, $p < 0.001$, $\eta^2 = 0.862$, as well the interaction, $F(2, 46) = 13.99$, $p < 0.001$, $\eta^2 = 0.378$, were significant. This interaction point-

ed to a differential effect of distance on each level of type of object switch. The difference between large and small distance was 122 ms in single lists, $F(1, 23) = 40.72$, $p < 0.001$, $\eta^2 = 0.639$; in the non-switching condition in mixed lists it was 326 ms, $F(1, 23) = 154.93$, $p < 0.001$, $\eta^2 = 0.871$; and in the switching condition in mixed lists it was 270 ms, $F(1, 23) = 41.83$, $p < 0.001$, $\eta^2 = 0.645$. The interaction was due to the fact that the distance effect in non-switching trials from mixed lists was higher than in non-switching trials from single lists, $F(1, 23) = 41.68$, $p < 0.001$, $\eta^2 = 0.644$.

The analogous analysis for the non-updating trials revealed the significant effects of type of object switch, $F(2, 46) = 208.79$, $p < 0.001$, $\eta^2 = 0.901$, and distance, $F(1, 23) = 7.74$, $p < 0.05$, $\eta^2 = 0.252$, as well as their interaction, $F(2, 46) = 9.09$, $p < 0.001$, $\eta^2 = 0.283$. Again this interaction indicated that there was a differential effect of distance on each level of type of object switch. Specifically, the difference between large and small distance was only significant for the non-switching condition in mixed lists (114 ms), $F(1, 23) = 15.85$, $p < 0.005$, $\eta^2 = 0.408$ (see Fig. 2).

The inclusion of mixed and single lists allows for the analysis of two aspects inherent in these updating tasks. The first is the switching cost, i.e., the time necessary to carry out a cognitive operation increases when there is object switching in WM, compared to when the operation is carried consecutively on the same object. The second is the mixing cost, i.e., the response time increases with the number of active elements in WM, even when the number of updated elements remains constant. Previous analyses have indicated that the distance effect varied according to type of switch object. This could have an impact in switching and mixing costs. Additional analyses showed that the switching cost in updating trials in the large

Fig. 2 Response time as a function of type of object switching, updating and distance in Experiment 1

distance condition was 233 ms, whereas in the small distance condition it was 289 ms; although, these switching costs were not different statistically ($p > 0.2$). In non-updating trials, the switching cost was lower for the large (141 ms) than for the small distance condition (232 ms) since the interaction was significant, $F(1, 23) = 9.92$, $p < 0.005$, $\eta^2 = 0.301$. Regarding the mixing effect, in the updating trials the mixing cost was lower in the small distance condition (321 ms) than in the large distance condition (526 ms), as indicated by the interaction, $F(1, 23) = 41.68$, $p < 0.001$, $\eta^2 = 0.644$. Also, in non-updating trials the mixing cost was lower in the small distance condition (329 ms) than in the large distance condition (447 ms), $F(1, 23) = 15.76$, $p < 0.005$, $\eta^2 = 0.407$. In sum, the mixing cost was higher in large distance trials than in small distance, whereas switching cost was greater in small distance than in large distance condition for the non-updating trials. The next experiment gave us the opportunity to replicate these results.

Discussion

The most important results are those related to the distance effect and its differential impact in both updating conditions. First, it has been shown that a smaller distance between the number stored in memory and the number presented implies a smaller time cost than when the distance is greater. This effect can be seen both in mixed lists and in simple lists. Simple lists represent a condition which is more similar to numerical comparison tasks in which a number (e.g., 55) stored in memory has to be compared with another presented number. These results cannot be explained by the difficulty effect observed in studies on numerical comparisons, as in this case the comparisons with closer numbers produce longer response times. (e.g., Dehaene et al., 1990; Moyer & Landauer, 1967). Therefore, the manipulation of distance may reflect similarity-based facilitation.

Second, it has been found that distance affects the two updating conditions differently. In the updating trials, there was a clear distance effect, whereas in the non-updating trials, distance either had no influence (switch items in mixed lists and items in simple lists), or its effect was much less pronounced (non-switching items in mixed lists). This confirms that the distance effect is not solely due to the numerical comparisons performed, as if this were the case, this manipulation should have produced an opposite effect, and also should have been equally effective in both updating conditions in which similar comparisons had to be made. Furthermore, the consistent effect of distance in updating trials compared with non-updating trials suggests that this manipulation influences the storage of new information for future use.

Second experiment

The aim of the second experiment was to determine whether the distance between numbers affects the speed with which the updating is performed, even when the task does not require any numerical operation, and therefore does not have any associated difficulty. If the distance effect is obtained when no operation is necessary, this effect may be explained in terms of representational similarity.

To better rule out the possible effect of the numerical operations, a task was designed in which an external cue indicated whether or not to update the information. The task is similar to other updating tasks such as the Keeping-Track task (Yntema & Mueser, 1962) or that used by Oberauer (2003, Exp. 2). The use of external cues avoids the need to access information stored in memory in order to decide when information has to be updated. Also, in this experiment the numbers to be stored are not necessarily the lowest, as they may also be higher than the number stored in memory.

Method

Participants

The participants were 22 psychology students (19 women) between the ages of 18 and 28 ($M = 20.68$; $SD = 2.51$). None of them had participated in the previous experiment.

Materials

The task contained 36 simple lists and 72 mixed lists which were presented in three blocks: 18 simple, 72 mixed, and 18 simple. The lists were of different lengths to prevent participants from predicting the end of the list and therefore which item had to be recalled. As well as the two initial items, a third of the lists had four items, a third six items, and the remaining third had eight items. Each of the items was a shape (rectangle or triangle) with a number in the centre between 11 and 99. The type of object switch and distance were manipulated as in the previous experiment. In this experiment, updating was also manipulated. However, in contrast to the previous experiment, the number to be updated could be lower or higher than the previous number associated with the same shape, as the updating was indicated by a signal.

Procedure

The procedure was similar to that of the previous experiment with some modifications because the participants did not have to perform comparisons. Each item was

shown for 500 ms, during which the participant could read the number. Then a signal was superimposed on the number, which indicated whether or not this number should be recalled. The signal was a circle approximately 1 cm in diameter which covered the number completely, so it was impossible to read the number after its onset. If the number was to be updated, the circle was green, and for numbers which had to be disregarded immediately (non-updating), the circle was red (see Fig. 1). The signal remained on the screen until the participant pressed a key. Then a blank screen was shown for 250 ms followed by the next item. The time elapsed between the presentation of the signal and the pressing of the key was recorded. In other respects the procedure was the same as in the previous experiment.

Results

The participants completed correctly 86.55% of the mixed lists and 87.50% of the simple lists. Response times from practice lists and from the incorrectly reported lists were excluded from analyses. Also, response times exceeding the participant's mean in each condition by more than 3.5 standard deviations or shorter than 200 ms were excluded from data analysis (2.46%).

The ANOVA 3 (type of object switch) $\times$ 2 (updating) $\times$ 2 (distance) yielded main effects for all factors: type of object switch, $F(2, 42) = 30.29$, $p < 0.001$, $\eta^2 = 0.591$, updating, $F(1, 21) = 107.52$, $p < 0.001$, $\eta^2 = 0.837$ and distance, $F(1, 21) = 46.44$, $p < 0.001$, $\eta^2 = 0.689$. Two way interactions were found between type of object switch and updating, $F(2, 42) = 42.72$, $p < 0.001$, $\eta^2 = 0.670$, type of object switch and distance, $F(2, 42) = 6.08$, $p < 0.01$, $\eta^2 = 0.225$, and updating and distance, $F(1, 21) = 40.31$, $p < 0.001$, $\eta^2 = 0.657$. Also the three-way interaction was significant, $F(2, 42) = 8.23$, $p < 0.005$, $\eta^2 = 0.282$. It is important to note that as in the previous experiment, but here without numerical operations, larger distance implied longer times (766 ms) than smaller distance (699 ms). Another result which is replicated is that the difference between large and small distance was greater in updating trials (123 ms) than in non-updating (11 ms). The results are shown in Fig. 3.

The three-way interaction was further examined by carrying out a separate two-way ANOVA 3 (type of object switch) $\times$ 2 (distance) for each condition of updating. For the updating trials, the ANOVA revealed the main effect for type of object switch, $F(2, 42) = 41.90$, $p < 0.001$, $\eta^2 = 0.666$, and distance, $F(1, 21) = 45.39$, $p < 0.001$, $\eta^2 = 0.684$, as well as their interaction, $F(2, 42) = 7.09$, $p < 0.005$, $\eta^2 = 0.253$. Subsequent analysis showed that the distance effect was significant in each condition of type of object switch. Specifically, the difference between the small and the large distance in switching condition in mixing lists

was 113 ms, $F(1, 21) = 21.16$, $p < 0.001$, $\eta^2 = 0.502$; in the non-switching condition in mixed lists that difference was 191 ms, $F(1, 21) = 34.45$, $p < 0.001$, $\eta^2 = 0.621$; and in the non-switching condition in single lists it was 65 ms, $F(1, 21) = 9.07$, $p < 0.01$, $\eta^2 = 0.302$. The interaction was due to a greater distance effect in non-switching trials from mixed lists than that found both in switching trials from mixed lists, $F(1, 21) = 4.59$, $p < 0.05$, $\eta^2 = 0.180$, and in single lists, $F(1, 21) = 16.11$, $p < 0.005$, $\eta^2 = 0.434$.

For the non-updating trials, the ANOVA showed a main effect of distance, $F(1, 21) = 8.57$, $p < 0.01$, $\eta^2 = 0.290$, and the interaction between type of object switch and distance, $F(2, 42) = 4.76$, $p < 0.05$, $\eta^2 = 0.185$. The analysis of distance in each condition of object switching indicated that this effect was only significant in the switching condition from mixed lists, $F(1, 21) = 12.85$, $p < 0.005$, $\eta^2 = 0.380$. In this condition the difference between large and small distance was 30 ms.

As in the previous experiment, distance influenced the switching and mixing effects. In updating trials, the switching cost was lower in the large distance condition (59 ms), than in the small distance condition (136 ms), as indicated by the interaction between switching and distance, $F(1, 21) = 4.59$, $p < 0.05$, $\eta^2 = 0.180$. In non-updating trials the switching cost was markedly reduced (19 ms), although it did not disappear completely, $F(1, 21) = 7.95$, $p < 0.05$, $\eta^2 = 0.275$. However, in these trials the interaction with distance was not significant ($p > 0.09$). Regarding the mixing effect, in the updating trials, it was found that mixing cost increased with distance. In the small distance condition it was 151 ms, $F(1, 21) = 19.26$, $p < 0.001$, $\eta^2 = 0.478$, while in the large distance condition it was 277 ms, $F(1, 21) = 31.46$, $p < 0.001$, $\eta^2 = 0.600$. In non-updating trials neither the mixing and distance effects nor their interaction were significant ($p > 0.2$).

Fig. 3 Response time as a function of type of object switching, updating and distance in Experiment 2

Discussion

The results again show a distance effect even when no numerical comparison was involved. As in the previous experiment, there was a clear distance effect when information had to be updated, suggesting that it is related to the storage of new information. In contrast to non-updating trials, the distance effect was only found in switching trials and was much less marked. This could indicate a not entirely consistent priming effect through which the representations stored in memory make it easier to process the number presented.

Another interesting result is the switching effect obtained in updating trials even though, in this task, it is not necessary to retrieve the content of the object stored in memory. This confirms that in order to update information the participants need to access the object in memory even when they do not need to recall the information (Oberauer, 2003; Voigt & Hagendorf, 2002). This access may be necessary to bind the new information to the appropriate object in WM. On the other hand, in non-updating trials the switching effect was much reduced. This contrasts with the switching effect obtained in the analogous condition in Experiment 1. In that experiment, access to the content of the object stored in memory was a necessary step in both updating conditions in order to decide whether or not the number should be updated. However, in the second experiment, with external cues, participants may simply interpret the non-updating signal as an instruction to press a key to present the following item. The absence of mixing cost in non-updating trials also supports the idea of disrupted access.

General discussion

This study aimed to investigate whether the relationship between the information stored in memory and the new information presented has an effect on updating. Over two experiments we have analyzed the effect of numerical distance on updating. In the first experiment the updating was based on the result of a numerical comparison whereas in the second on an external signal, which removed the need to perform any numerical operation. In both cases we found that updating times were faster when the distance between the number stored in memory and the number replacing it was smaller than when this distance was large.

The first experiment showed that this effect did not depend on the difficulty of the numerical operation to be performed. In numerical comparisons the larger distance is associated with easier numerical comparisons (Moyer & Landauer, 1967). Therefore, if the distance effect were affected by the difficulty of the comparisons there should

have been the opposite result. However, it was the larger distance which implied greater cost. The second experiment showed that the distance effect remained even when the task required no numerical operations, but only to memorize the number shown with the corresponding signal. These results support the idea that the distance effect is not due so much to the processing difficulty, but rather to the relationship between the information stored in memory and the information presented.

Another main result is that the distance effect is modulated by updating. In the updating condition the distance effect is consistently present, whereas in the non-updating condition the effect is less evident, and in some conditions is not even clearly present. The slight facilitation effect in the non-updating trials may occur in the identification stage of the numbers presented, whereas the greater effect in the updating trials would also involve the storage of the new information. Prior information in memory may pre-activate to a greater or lesser extent the new information to be presented regardless if an updating is requested. Thus, the facilitation effect in non-updating trials would be similar to that obtained in other numerical tasks which did not involve memorizing new information, such as priming tasks (Brysbaert, 1995; Den Heyer & Briand, 1986; Koechlin et al., 1999; Naccache & Dehaene, 2001; Reynvoet & Brysbaert, 1999, 2004; Reynvoet et al., 2002) and even recognition tasks in short term memory (Morin et al., 1967). We can assume that these effects are due to the overlapping of the representations of the numbers involved. Other authors have found a facilitation effect which is associated not with the number, but with the physical appearance of the stimuli used to identify the object (the shape) to be updated (Gehring et al., 2003; Li et al., 2006).

The previous priming effect may influence both updating and non-updating trials. However, in updating trials the distance effect cannot be due merely to factors such as the facilitation in the identification of the numbers, as in that case the effect would be similar to that observed in non-updating trials. In addition, it is noteworthy that this effect is found irrespective of whether the person has to use the content of memorized information in order to perform an operation (Experiment 1) or whether this is not necessary (Experiment 2). This suggests that an additional mechanism is involved, which is related specifically to how information is updated.

We propose that such a mechanism may operate on information represented in WM in terms of features, enabling these features to be updated selectively. In the context of WM, some authors consider that information in WM is represented by sets of features which are activated at the same time (Nairne, 1988, 1990; Neath, 2000; Oberauer & Kliegl, 2001, 2006). Given that the sets of features of

two items overlap to various extents, the more similar the items, the greater the degree of overlap. When it is necessary to update a number which shares many features with that stored in memory, the process can be performed more quickly, as fewer features of the second number need to be activated, because all shared features are already activated. The idea of a selective process of updating is in line with the results obtained by Kessler and Meiran (2008) (see also, Vockenberg, 2006 with other material), showing that updating cost increased along with the number of new items to be memorized. It is noteworthy that in our case, there was only one item to be updated in each trial. However, this item could be more or less similar to the information previously stored in memory. Therefore, we can assume that selective updating here acts not so much on various elements stored independently in WM, but rather on a subset of features of the representation associated with a single element. A selective process of updating of features may be also present in visual short-term memory. Ko and Seiffert (2009) found that updating affects exclusively the visual features which have to be replaced. Specifically, they showed that after updating there was facilitation for recognition of the updated features, but not for the rest of the features of the object.

In addition, certain results suggest that updating an element in memory may be affected by other content stored simultaneously in the WM. In both experiments we have found that the distance effect is higher in the non-switching condition in mixed lists. It is possible to suppose that the more marked effect in this condition may be due to the fact that the quantity of information which is active may be more than in the other conditions. This non-switching condition differs from the non-switching condition in simple lists in that an additional item needs to be stored (that associated with the other object). In addition, in this condition more information associated with an object may be active at the same time compared to in the switching condition in mixed lists. When two consecutive items associated with the same object are presented, some irrelevant information related to the first of the two items (i.e., the number previously substituted) may maintain a certain degree of residual activation when the second item is shown. Oberauer (2001, 2005) concluded that more than one second is necessary to eliminate information which has been active in the direct access area of WM. Therefore, this additional load in the non-switching condition in mixed lists may interfere with the new information, and this may happen to a greater extent when the new and stored information is more different. This effect could therefore be considered as a case of proactive interference between the contents of WM, in which outdated information which is still active in WM interferes with new information. This interference would take place

over a short time window, i.e., the time during which the features which are no longer relevant retain some residual activation.

Implications for WM

The results obtained have implications for understanding how the information elements stored at various levels of WM interact among themselves and with the new information presented during the task. The similarity-based facilitation obtained is a consequence of the representational overlap between the information which has been activated in the focus of attention and that associated with new presented stimulus. This proactive and graded facilitation indicates that what is substituted in the focus of attention is not a whole representation (i.e., of the new number), but the new features that are not present in the old representation. Thus when an item is substituted by another, the shared features will remain in a state of activation while a subset of new features will be activated. Then the set of features which are finally activated has to be bound together and also to the context in order to form a unitary representation of the object differentiated from other objects stored at other levels (i.e. the direct access region). This mechanism could be generalized beyond updating tasks and numerical information such as those analyzed in this study. Indeed, it could be applied to situations which involve merely the storage of new information in the focus of attention (cf. Jonides, Lewis, Nee, Lustig, Berman, & Moore, 2008, p. 203). In general, this situation would represent a very low similarity condition in which the majority of the features to be activated would be new.

Our results indicate that the overlap between the information held in the focus and the new information leads to facilitation in response time. In contrast, the representational overlap between the information stored simultaneously in the direct access region has a detrimental effect on recall accuracy. This overlap may be present between the material in a processing task (distracter) and that which has to be stored in WM (Lange & Oberauer, 2005; Oberauer & Lange, 2008, Exp. 1; Oberauer, 2009) or it may be found among the different items to be remembered in a list (Oberauer, 2009, Exp 2). Consistent with this idea, our findings also suggest that it is more difficult to activate the appropriate features in the focus of attention in the presence of other sets of different activated features. This may reflect a competition between the representations active in the focus of attention and other representations for shared features. These other representations may come from the direct access region (e.g., other numbers maintained) or from outdated information with a certain level of residual activation.

In summary, our results indicate that updating in WM occurs faster when the numerical information to be updated is closer to that stored in memory, probably owing to a representational effect of shared features. A future objective will be to determine the nature of the features which play a role in the distance effects and to quantify their effect in relation to updating. The information in WM which is associated with an item is stored in the form of multiple traces, containing features which are semantic, visual, orthographic, phonological, articulatory, etc. The distance effect may be due to the activation of features of different types, such as semantic or phonological.

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References

- Ashcraft, M. H. (1992). Cognitive arithmetic: a review of data and theory. *Cognition*, 44, 75–106. doi:10.1016/0010-0277(92)90051-I
- Ashcraft, M. H., & Battaglia, J. (1978). Cognitive arithmetic: evidence for retrieval and decision processes in mental addition. *Journal of Experimental Psychology: Human Learning and Memory*, 4, 527–538. doi:10.1037/0278-7393.4.5.527
- Ashcraft, M. H., & Stazyk, E. H. (1981). Mental addition: a test of three verification models. *Memory & Cognition*, 9, 185–196
- Brysbaert, M. (1995). Arabic number reading: on the nature of the numerical scale and the origin of phonological recoding. *Journal of Experimental Psychology: General*, 124, 434–452. doi:10.1037/0096-3445.124.4.434
- Carretti, B., Cornoldi, C., & Pelegrina, S. (2007). Which factors influence number updating in working memory? The effects of size distance and suppression. *British Journal of Psychology*, 98, 45–60. doi:10.1348/000712606X104175
- Cowan, N. (1995). *Attention and memory: An integrated framework*. New York: Oxford University Press.
- Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 626–641. doi:10.1037/0096-1523.16.3.626
- Den Heyer, K., & Briand, K. (1986). Priming single digit numbers: automatic spreading activation dissipates as a function of semantic distance. *The American Journal of Psychology*, 99, 315–340.
- Garavan, H. (1998). Serial attention within working memory. *Memory & Cognition*, 26, 263–276.
- Gehring, W. J., Bryck, R. L., Jonides, J., Albin, R. L., & Badre, D. (2003). The mind's eye, looking inward? In search of executive control in internal attention shifting. *Psychophysiology*, 40, 572–585. doi:10.1111/1469-8986.00059
- Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., & Moore, K. S. (2008). The mind and brain of short-term memory. *Annual Review of Psychology*, 59, 193–224. doi:10.1146/annurev.psych.59.103006.093615
- Kessler, Y., & Meiran, N. (2006). All updateable objects in working memory are updated whenever any of them are modified: evidence from the memory updating paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32, 570–585. doi:10.1037/0278-7393.32.3.570
- Kessler, Y., & Meiran, N. (2008). Two dissociable updating processes in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34, 1339–1348. doi:10.1037/a0013078
- Ko, P. C., & Seiffert, A. E. (2009). Updating objects in visual short-term memory is feature selective. *Memory & Cognition*, 37, 909–923. doi:10.3758/MC.37.6.909
- Koechlin, E., Naccache, L., Block, E., & Dehaene, S. (1999). Primed numbers: exploring the modularity of numerical representations with masked and unmasked priming. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 1882–1905. doi:10.1037/0096-1523.25.6.1882
- Lange, E., & Oberauer, K. (2005). Overwriting of phonemic features in serial recall. *Memory*, 13, 333–339. doi:10.1080/09658210344000378
- Lendínez, C., Pelegrina, S., & Lechuga, M. T. (2007). *The role of the numerical operations involved in updating memory tasks on updating costs*. Paper presented at the XV Meeting of the European Society for Cognitive Psychology. Marseille, France.
- Li, Z. H., Bao, M., Chen, X. C., Zhang, D. R., Han, S. H., He, S., et al. (2006). Attention shift in human verbal working memory: priming contribution and dynamic brain activation. *Brain Research*, 1078, 131–142. doi:10.1016/j.brainres.2006.01.032
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” tasks: a latent variable analysis. *Cognitive Psychology*, 41, 49–100. doi:10.1006/cogp.1999.0734
- Morin, R. E., DeRosa, D. V., & Stultz, V. (1967). Recognition memory and reaction time. *Acta Psychologica*, 27, 298–305.
- Morris, N., & Jones, D. M. (1990). Memory updating in working memory: the role of central executive. *British Journal of Psychology*, 81, 111–121.
- Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature*, 215, 1519–1520. doi:10.1038/2151519a0
- Naccache, L., & Dehaene, S. (2001). Unconscious semantic priming extends to novel unseen stimuli. *Cognition*, 80, 223–237. doi:10.1016/S0010-0277(00)00139-6
- Nairne, J. S. (1988). A framework for interpreting recency effects in immediate serial recall. *Memory & Cognition*, 16, 343–352.
- Nairne, J. S. (1990). A feature model of immediate memory. *Memory & Cognition*, 18, 251–269.
- Neath, I. (2000). Modeling the effects of irrelevant speech on memory. *Psychonomic Bulletin & Review*, 7, 403–423.
- Oberauer, K. (2001). Removing irrelevant information from working memory: a cognitive aging study with the modified Sternberg task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 27, 948–957. doi:10.1037/0278-7393.27.4.948
- Oberauer, K. (2002). Access to information in working memory: exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28, 411–421. doi:10.1037/0278-7393.28.3.411
- Oberauer, K. (2003). Selective attention to elements in working memory. *Experimental Psychology*, 50, 257–269. doi:10.1027/1618-3169.50.4.257
- Oberauer, K. (2005). Binding and inhibition in working memory: individual and age differences in short-term recognition. *Journal of Experimental Psychology*, 134, 368–387. doi:10.1037/0096-3445.134.3.368

- Oberauer, K. (2009). Interference between storage and processing in working memory: feature overwriting, not similarity-based competition. *Memory & Cognition*, 37, 346–357. doi:10.3758/MC.37.3.346
- Oberauer, K., & Kliegl, R. (2001). Beyond resources: formal models of complexity effects and age differences in working memory. *European Journal of Cognitive Psychology*, 13, 187–215. doi:10.1080/09541440042000278
- Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language*, 55, 601–626. doi:10.1016/j.jml.2006.08.009
- Oberauer, K., & Lange, E. B. (2008). Interference in verbal working memory: distinguishing similarity-based confusion, feature overwriting, and feature migration. *Journal of Memory and Language*, 58, 730–745. doi:10.1016/j.jml.2007.09.006
- Oberauer, K., Wendland, M., & Kliegl, R. (2003). Age differences in working memory. The roles of storage and selective access. *Memory & Cognition*, 31, 563–569.
- Pavese, A., & Umiltà, C. (1998). Symbolic distance between numerosity and identity modulates Stroop interference. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 1535–1545. doi:10.1037/0096-1523.24.5.1535
- Pavese, A., & Umiltà, C. (1999). Further evidence on the effect of symbolic distance on Stroop-like interference. *Psychological Research*, 62, 62–71. doi:10.1007/s004260050040
- Reynvoet, B., & Brysbaert, M. (1999). Single-digit and two digit Arabic numerals address the same semantic number line. *Cognition*, 72, 191–201. doi:10.1016/S0010-0277(99)00048-7
- Reynvoet, B., & Brysbaert, M. (2004). Cross-notation number priming investigated at different stimulus onset asynchronies in parity and naming tasks. *Experimental Psychology*, 51, 81–90. doi:10.1027/1618-3169.51.2.81
- Reynvoet, B., Brysbaert, M., & Fias, W. (2002). Semantic priming in number naming. *The Quarterly Journal of Experimental Psychology*, 55A, 1127–1139. doi:10.1080/02724980244000116
- Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime users's guide*. Pittsburgh: Psychology Software Tools, Inc.
- Stazyk, E. H., Ashcraft, M. H., & Hamann, M. S. (1982). A network approach to mental multiplication. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 8, 320–335. doi:10.1037/0278-7393.8.4.320
- Unsworth, N., & Engle, R. W. (2008). Speed and accuracy of accessing information in working memory: an individual differences investigation of focus switching. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 34, 616–630. doi:10.1037/0278-7393.34.3.616
- Vockenberg, K. (2006). *Updating of representations in working memory*. Unpublished doctoral dissertation, University of Potsdam.
- Voigt, S., & Hagendorf, H. (2002). The role of task context for component processes in focus switching. *Psychologische Beiträge*, 44, 248–274.
- Yntema, D. B., & Mueser, G. E. (1962). Keeping track of variables that have few or many states. *Journal of Experimental Psychology*, 63, 391–395. doi:10.1037/h0045706
- Zbrodoff, N. J., & Logan, G. D. (1990). On the relation between production and verification tasks in the psychology of simple arithmetic. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 83–97. doi:10.1037/0278-7393.16.1.83