Selective Attention to Elements in Working Memory

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Abstract. Three experiments with an arithmetic working memory task examine the object switch effect first reported by Garavan (1998), which was interpreted as evidence for a focus of attention within working memory. Experiments 1a and 1b showed object switch costs with a task that requires selective access to items in working memory, but did not involve counting, and did not require updating of working memory contents, thus ruling out two alternative explanations of Garavan's results. Experiment 2 showed object switch costs with a task that required no selective access to working memory contents, but involved updating, thus providing evidence for a second component to the overall object switch costs. Further analyses revealed that the object switch cost increased with memory set size; that there were (smaller) switch costs when the switch was to an item of the same type; that repeating an arithmetic operation does not have the same effect as repeating the object it is applied to; and that object switching is not mediated by backward inhibition of the previously focused object.

Key words: working memory, attention, switching, mental model, anaphor resolution, spatial distance effect

One function of working memory is to hold a number of units of information available for processing. Processing often requires selection of a subset of the working memory contents as the object of a manipulation. For example, mental addition of two three-digit numbers involves first adding the ones, then the tens, and so on. During these steps, some digits are selected for specific roles (e.g., first addend) in the addition operation, while the others are held in working memory, but not used in the current operation.

Selective access to contents of working memory suggests that there is a focus of attention within working memory analogous to the focus of visual attention (e.g., Eriksen & St. James, 1986; Treisman, 1988). A representation in the focus of attention is in a state of increased availability for cognitive operations, such that any cognitive operation set up by the current task set or action plan will be applied to the representation in the focus and not to the other representations currently held in working memory. In the course of an addition task, for example, working memory could execute the operation "add four" while the digit three is in the focus, thus generating seven as a result, which might replace the previous digit in the focus. The next step could then be the execution of "add two". If this operation is to be applied to the seven, it can be executed immediately. If the operation must be applied to a different object, however, (e.g., when switching from the ones to the tens) the new object must be taken into the focus first.

Garavan (1998) has investigated the focus of attention in working memory with a memory-updating task. He presented participants a sequence of geometrical figures, either rectangles or triangles, and asked them to keep a running count of the two categories. Reaction times were about 500 ms larger following a switch of the figure category (e.g., when a triangle followed a square) than following a repetition (e.g., a triangle following a triangle). Garavan interpreted this difference as the cost for shifting the focus of attention from one counter to the other within working memory.

In Garavan's task the hypothetical focus of attention has two functions. One is to provide selective *access* to the counter to be updated by retrieving its current value from working memory. The other is to selectively *update* this counter by establishing its new value in working memory at the required posi-

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tion within the memory set. The main goal of the present series of experiments is to disentangle these two functions of the focus of attention and to investigate their characteristics separately.

Experiments 1a and 1b investigate object switching with a task that requires selective retrieval of elements in working memory but no updating. Participants had to apply an arithmetic operation to one of a set of digits held in working memory and report the result without changing the content of working memory. Experiment 2 uses a complementary task involving updating but no retrieval. Elements of the memory set are replaced by the results of equations displayed on the screen, with the equation's location determining which element has to be replaced. In the switch condition, the position of the element to be replaced in a given updating cycle differs from the one replaced before. This task requires no access to a new element in working memory in the case of an object switch, because the computation of the new digit does not require the old digit as input. In fact, a new digit can be remembered instead of the old one even if the old digit had been forgotten before. The object switch, however, might still be associated with a time cost. This cost could, for example, reflect the time needed for focusing the representation of the new position, that is, accessing the appropriate context representation to which the new item is associated (for a computational model of short-term memory based on context representations see, e.g., Burgess & Hitch, 1999).

Separating access to working memory from updating of working memory also serves to test a potential alternative explanation of Garavan's (1998) experiment in terms of the rescheduling of a process sequence. Participants in his experiment, when asked to rehearse and count aloud, typically rehearsed both counters in the same order in every updating cycle. For example, when a triangle was presented, they repeated the current number of rectangles, and then articulated the updated number of triangles. When a rectangle was presented, they first articulated the new number of rectangles, then the old number of triangles. In the first case, the sequence of operations to be done could be "articulate rectangles, increment triangles, articulate triangles." In the second case, the sequence would have to be "increment rectangles, articulate rectangles, articulate triangles." Thus, a switch from one category to the other implies a rescheduling of cognitive operations. This could require extra executive processes, which need extra time (c.f., Baddeley, 1996, Meyer & Kieras, 1997). This explanation makes no reference to a focus of attention as a mechanism that selectively picks one object at a time.

The rescheduling account of object switch costs would predict such costs in Experiment 2, where articulation of the updated item must wait until the computation process is finished. A switch to a new position for updating therefore would most likely involve a new ordering of rehearsal and computation operations. No such rescheduling is required in Experiments 1a and 1b, because here the rehearsal of the constant set of memory items can proceed independently of the computation process. Thus, regardless of which object must be accessed for the arithmetic operation, rehearsal of the whole memory set can proceed either before or after the computation. Therefore, a rescheduling account would not predict object switch costs in Experiments 1a and 1b.

When object switch costs reflect the time it takes the focus of attention to shift to a new object, we can expect that this time increases with the number of objects among which the focus must select the right one. Switch costs should therefore increase with memory load. Consistent with this, Oberauer, Demmrich, Mayr, and Kliegl (2000) found that the time taken to retrieve an item from working memory for processing strongly depended on the size of the memory set. Voigt and Hagendorf (2002) varied memory load from two to three in Garavan's paradigm and found larger switch costs with three counters than with two. The present experiments investigate the effect of memory load on the two hypothesized component processes, selective access to a new element in working memory, and selective updating of an element at a new position in working memory.

A further goal of this work is to throw some light on the mechanisms of object selection in working memory. For selection of task sets in a switching paradigm, Mayr and Keele (2000) have provided evidence that selection of one task set is supported by inhibition of the previous task set. Their evidence for *backward inhibition* comes from comparing sequences of choice reactions in a paradigm where participants switched between three sets A, B, and C. In a sequence like ABA, task set A would be inhibited when switching to B. When a switch back to A follows immediately, A is still inhibited and reaction times will be particularly slow. Over time, inhibition is assumed to decay, so that switching from B to A will be easier when the last use of A occurred longer ago in the sequence. Consistent with this idea, Mayr and Keele (2000) found longer times on the last reaction of sequences ABA compared to CBA. In general, backward inhibition predicts that access to a new task set (or object) becomes easier with longer lags between the current reaction and the last reaction using the same task set (object). The experiments reported here provide an opportunity to test for backward inhibition in object switching by analyzing latencies as a function of lag between successive retrievals of the same object.

To summarize, the main goals of the experiments reported here were: (1) to separate the access component from the updating component in the hypothesized focus shift in working memory as reported by Garavan (1998); thereby (2) test one alternative explanation of the object switch cost in terms of rescheduling of operations; (3) to investigate the effect of memory set size on object switch costs; and (4) to test whether backward inhibition is involved in selecting a new object in working memory.

Experiments 1a and 1b

In the first two experiments, participants had to remember one, two, three, or four digits. In Experiment 1a, each digit was associated with a frame on the screen. In Experiment 1b, each digit was associated with a different color. Arithmetic operations like "+2" or "−4" were then presented in individual frames (Experiment 1a) or in one of the colors (Experiment 1b). Participants had to apply each operation to the digit in the respective frame or to the digit with the corresponding color, respectively, and key in the result as quickly as possible. The main variable of interest (for memory demands larger than one) is whether an operation is applied to the same digit as the previous operation (no object switch) or to a new one (object switch).

During the sequence of arithmetic operations required in one trial the memory set was not changed. Thus, this task did not require memory updating, and therefore the processing operation and potential rehearsal processes can proceed independently. There is no reason to assume a reordering of these processes in case of an object switch. Therefore, if switching between objects has an effect on reaction times, this can be attributed to the retrieval of a new element from working memory. Insofar as retrieval of an element from working memory means bringing this item into the focus of attention, finding objects switch costs in these experiments would support the notion of a focus of attention in working memory.

The two versions of the experiment (1a and 1b) were designed to provide a direct comparison between a situation where the objects in working memory are distinguished by the spatial position of stimuli, as in my previous experiments on object switching (Oberauer, 2002), and a situation where they are distinguished by a feature such as the form of geometrical objects (Garavan, 1998, Voigt & Hagendorf, 2002) or the color of the stimuli. Such a comparison is necessary because with a spatial separation of the objects and the corresponding updating operations, a switch between objects always involves a shift of visual attention in space as well. Only findings that are consistent over both versions can unambiguously be attributed to object switching in working memory, instead of shifting visual attention.

If a digit is retrieved into the focus of attention, we could ask whether the focused memory element is a token or a type representation (see Henson, 1998). For instance, a memory list such as "2 4 3 2" contains two tokens of the type "2" at different list positions. If the focus of attention picks out a specific token, there should be a switch cost even if the switch is to another instance of the same type, for instance, from the "2" at the first list position to the "2" at the final list position. If the generic type is focused, on the other hand, there should be switch costs only when the focus switches to a different type. To distinguish these possibilities, there was a repeated item in the memory set in every second trial with a memory demand of three or four. Some of the object switches in these trials therefore were switches to another token of the same type.

A further issue concerns repetitions of arithmetic operations. The task of the participant is to compute the result of a simple equation, with the first addend or subtrahend coming from working memory and the second, together with the plus or minus sign, being read from the screen. If the first component of the equation is brought into a focus of attention, this could be true for the second one as well. In this case, a change from one operation to another in successive updating cycles would also mean a shift of focus, whereas a repetition of the previous operation would require no shift of focus to another second addend or second subtrahend. To investigate this question, repetitions of operations were coded as a further independent variable.

Method

Participants

Participants were high school students from Potsdam (N = 24/20 for Experiment 1a and 1b, respectively). Their mean age was 19.8/18.6 years (SD = 1.81/1.90), and 17/10 of them were female. They were paid 10 DM (about US $4) for their participation in a one-hour session.

Materials and Procedure

Each trial of Experiment 1a began with the presentation of one, two, three, or four rectangular frames on the computer screen, depending on the memory set size. For set size one, the frame was placed in the center of the screen, and for the other set sizes they were arranged equidistantly on an imaginary circle. One digit was displayed in each frame. The digits were all presented simultaneously until the partici-

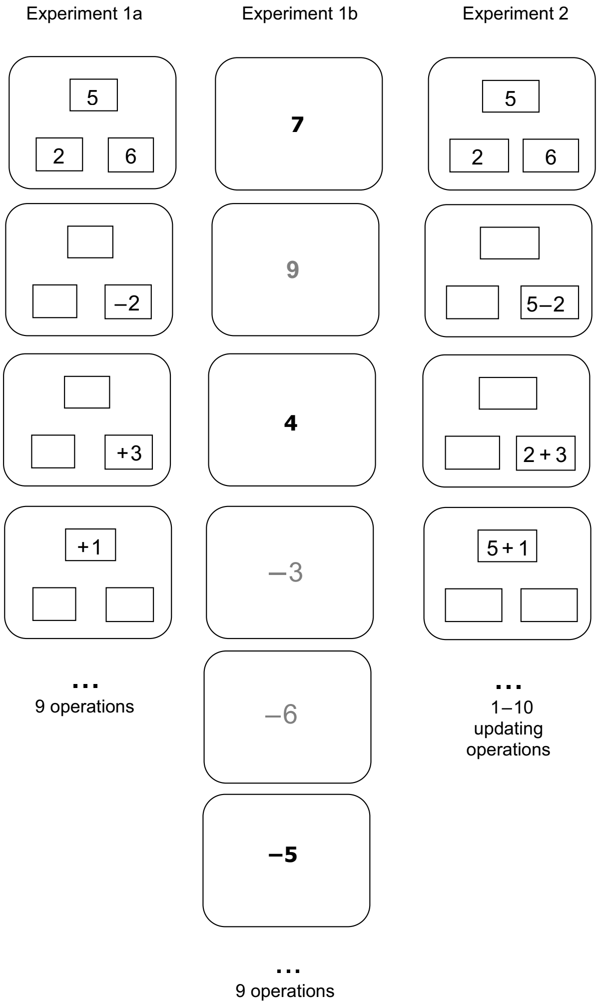

Figure 1. Schematic examples of trials used in Experiment 1a (left), 1b (middle), and 2 (right) with set size three. Frames represent successive screen displays following each other from top to bottom each time the participant pressed the appropriate key (space bar or a number key). The figure illustrates the presentation of initial values and the first three operations. The second operation is a nonswitch operation, whereas the third one is a switch operation. Different colors used in Experiment 1b are illustrated through different font types. In Experiment 2, the sequence of updating operations is followed by a recall request.

pant pressed the space bar. Immediately afterwards, the first operation was displayed in one of the frames. Operations could range from "–8" to "+8" (excluding 0), with the restriction that the result was a digit between one and nine. Participants were asked to type the result as fast as possible on the set of number keys of the computer keyboard. Each response was immediately followed by another operation displayed in the same or another frame. There were nine successive updating cycles in each trial. For the memory demands larger than one, change or no change of the frame was determined at random with the restriction that half of the cycles in each trial (except the first one) were switching cycles and half were not.

In Experiment 1b, the initial digits were displayed one by one in the center of the screen, each one in a different color. Each digit was displayed until the participant pressed the space bar. The initial digits were always presented in the order blue, red, green, yellow, until the set size of the trial was reached (e.g., with set size 2, the first digit always was blue, the second red). Following presentation of the initial digits, nine successive operations were displayed in the center of the screen. Their color indicated to which digit they had to be applied. In all other respects the procedure was exactly as in Experiment 1a.

Every second trial with a set size larger than two involved a memory set with one repeated item. For these trials, two switch cycles were switches to a digit of the same type (i.e., display of an operation in a new frame/color that contained the same digit as the frame/color used before), whereas the other two switch cycles were switches to a different type of digit. Repetitions of operations occurred as a by-product of the random selection of operations with a probability of 1/16.

Two sets of 128 trials each were generated at random by a computer program following the design and constraints outlined above. Participants were assigned to one of the two sets in alternation. Both sets began with four practice blocks of eight trials each, followed by eight test blocks, each consisting of 12 trials. Memory set size was varied between blocks. The practice blocks were presented with increasing set size. The test blocks in the first set of trials were ordered in a sequence of set sizes 1–2–3–4–4–3–2–1, those in the second set formed the sequence 4–3–2–1–1–2–3–4. The same set of trials was used for Experiment 1a and 1b.

Results

Reaction times associated with false responses, reaction times shorter than 300 ms, and times that exceeded an individual's mean in a design cell by more than three standard deviations were excluded from analysis. The alpha level was set to .05 for all experiments reported in this article.

Object Switch Costs and Set size Effects

Reaction times were submitted to an ANOVA with memory set size (set sizes 2 to 4) and object switching (switch vs. no switch) as factors. Only switches

Table 1. F Statistics for Analyses of Reaction Times in Experiments 1a and 1b

Effect	Experiment 1a		Experiment 1b	
	F(*df*1, *df*2)	*MSE*	*F*(*df*1, *df*2)	*MSE*
Set size (2–4)	72.4(1.5, 33.4)	10,136	80.1(1.4, 26.2)	29,223
Switch	95.8(1, 23)	44,721	188.6(1, 19)	79,277
Set size × Switch	50.4(1.7, 38.4)	7,538	65.0(1.6, 30.9)	23,523
Set size Nonswitch (1–4)	20.6(2.37, 54.4)	7,143	28.0(2.1, 40.9)	11,919
Contrast 1: Lag 0 vs. 1,2,3+	91.5(1, 23)	80,883	98.0(1, 19)	198,799
Contrast 2: Lag 1 vs. 2,3+	5.8(1, 23)	53,058	16.8(1, 19)	111,638
Set size × Contrast 2	5.4(1, 23)	38,267	4.9(1, 19)	64,111
Contrast 2 (Set size 3)	5.0(1, 23)	47,133	11.1(1, 19)	143,657
Contrast 2 (Set size 4)	7.1(1, 23)	381,528	7.8(1, 19)	115,780
Item Repetition	16.1(1, 23)	16,164	7.9(1, 19)	25,920
Token Switch	46.9(1, 23)	14,420	120.3(1, 19)	71,490
Token vs. Type Switch	43.53(1, 23)	34,909	17.7(1, 19)	64,245
Set size (3–4) × To-Ty Switch	13.42 (1,23)	13,884	25.9 (1,19)	23,260
Operation Repetition	56.0(1, 23)	81,075	31.8(1, 19)	159,002
Switch × Operation Repetition	96.6(1, 23)	65,343	73.4(1, 19)	106,905

Note. Noninteger *df*'s are due to Greenhouse-Geisser correction for nonsphericity.

to different digit types were included in this analysis. For both experiments, there was a main effect of set size, a main effect of object switch, and an interaction. The effects are illustrated in Figure 2, and the test statistics are summarized in the first three lines of Table 1. Reaction times were several hundred milliseconds larger following an object switch than following no switch. This switch cost increased with memory set size.

In fact, the switching reactions were responsible for the largest part of the set size main effect for set sizes from two to four. The set size effect for reaction times without switching was small. In Experiment 1a it just failed to reach significance, $F(1.62, 37.3) = 3.13$, $MSE = 5977.8$, $p = .065$ (the noninteger *df*s here and in the remainder of the paper are due to Greenhouse-Geisser correction for nonsphericity). The linear contrast, however, reached the significance level with $F(1, 23) = 4.55$, $MSE = 5878.2$. In Experiment 1b, neither the main effect nor the linear contrast was significant ($F < 2$). In both experiments, however, a pronounced set size effect on nonswitch reactions was observed when the trials from set size one were included in the analysis (Table 1, line 4). Thus, while switching reactions increase continuously with set size, nonswitch reactions seem to increase mainly from set size one to two, reaching a relatively stable plateau thereafter until at least set size four.

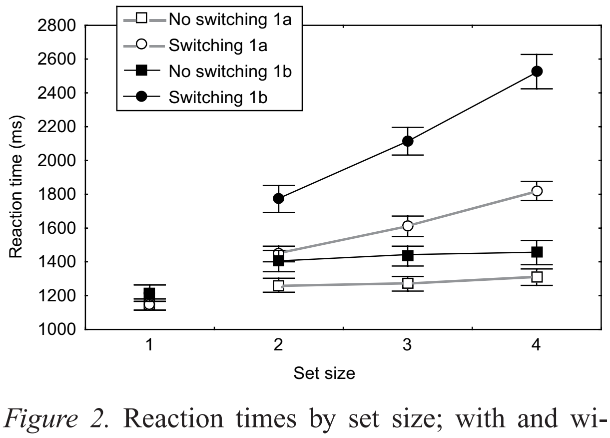

Figure 2. Reaction times by set size; with and without object switching, Experiments 1a (grey lines) and 1b (black lines). Error bars represent one standard error.

Lag Analysis

A more fine-grained picture of object switch effects can be obtained by analyzing runs of successive reactions in which an object is refocused after a variable lag. For example, in a trial with three frames/colors A, B, and C, a run like AA means that the last reaction focuses on the item in frame A with lag 0 (i.e., a nonswitch reaction). Switching reactions can refocus an item with lag 1 (e.g., ABA), lag 2 (e.g., ABCA), or lag 3 (e.g., ABCBA); higher lags are not considered here because they were too rare. The interesting comparison is between reaction times for the last reaction in runs with lags 1, 2, or 3. If the focus holds exactly one item at a time in an all-or-none fashion, there should be no difference between these three lags, because once the item A is out of the focus, it does not matter how long it stays out until it is focused again. Alternatively, being in the focus could be a matter of degree, such as when focusing an item means giving it more activation than other items in working memory. In this case the extra activation could fade only gradually after an item is removed from the focus, and when the same item is refocused after a short lag, there could be residual activation from the first focusing. Thus, reaction times after lag 1 should be shorter than after lag 2 and 3. A third possibility is that removing an item from the focus of attention involves active backward inhibition of this item (Mayr & Keele, 2000).

I categorized reaction times from serial positions five to nine in each trial into one of four lag categories (lag 0, lag 1, lag 2, and lag 3 or higher), separate for set sizes two to four. The mean latencies are plotted in Figure 3. These means were submitted to an ANOVA with set size (3) and lag (4) as factors. I computed Helmert contrasts on the lag factor to test the hypotheses outlined above. The results were very consistent over both experiments. The first Helmert contrast compares lag 0 to the mean of lags 1 to 3+; this contrast was significant, reflecting the object switch effect. The second contrast compares lag 1 to the mean of lag 2 and 3+, thereby testing for the empirical signature of backward inhibition (i.e., longer RTs at lag 1 than at longer lags). Reaction times with lag 1 were significantly shorter than those with higher lags. The third contrast (lag 2 vs. 3+) was not significant ($F < 2.6$ in both experiments).

The first Helmert contrast interacted with set size, reflecting the set size by object switch interaction already noted above. The second Helmert contrast also interacted with set size (Table 1). Separate ANOVAs for the three set sizes with lag (4) as factor showed that the second Helmert contrast (lag 1 vs. the higher lags) was significant for set sizes three and four, but not for set size two (both $F < 1$). The reason for this difference could be that with set sizes three and four, higher lags can mean that two or three *different* items are focused between the first and the second retrieval of the critical item (e.g., in runs like ABCA or ABCDA). This can never happen with set size two, where a longer lag always results from a run of the form ABB[B]A. Thus, the interaction of the lag effect with set size could be a hint that the number of *different* items focused between two retrievals of a particular digit, and not the intervening lag per se, is the critical factor. Unfortunately, the number of reactions with higher lags was too small to differentiate them further into different kinds of runs.

Object Switches to Repeated Items

The next set of analyses concerned the effect of repeated items. First, the general effect of repeated items in the memory set was evaluated with an ANOVA involving set size (2), switching (2), and item repetition (2) as factors. Item repetition had a significant main effect on reaction times, but did not enter in any interactions. Reaction times were 74 and 82 ms faster with than without a repeated item in Experiment 1a and 1b, respectively.

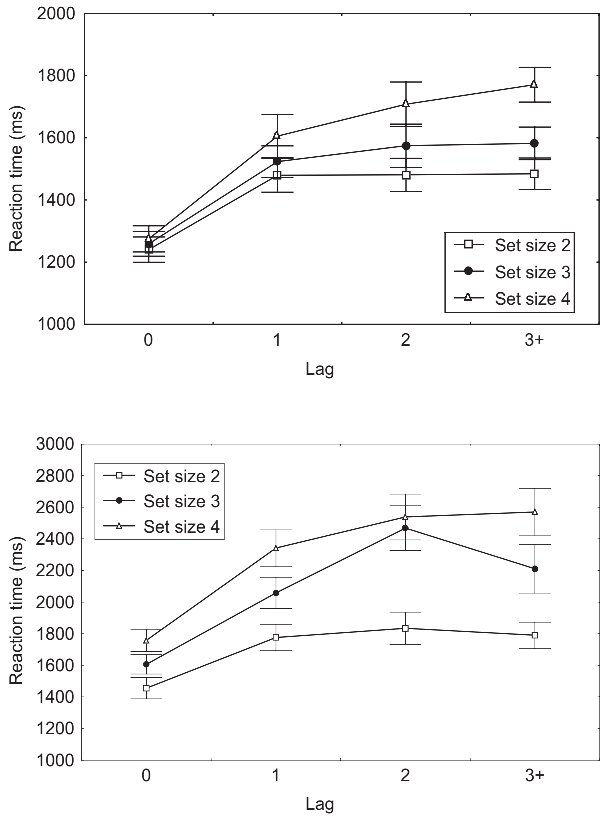

Figure 3. Reaction times for computation with an item as a function of lag since last use of the same item in a sequence of operations (data from operations 5–9). Top panel: Experiment 1a; bottom panel: Experiment 1b. Error bars represent one standard error.

Is there a switch cost when the switch is to a digit of the same type? This question was investigated by comparing no-switch reactions with reactions after a switch to a new item that was identical in type with the old one. An ANOVA with token switch (2) and set size (2) as factors revealed a significant effect of token switch, but no effect of set size and no interaction (all $F < 1$). A second ANOVA contrasted the switch to a digit of the same type with switching to a different digit type (token vs. type switch in Table 1). There was a significant difference of the two switching conditions, together with a reliable effect of set size and an interaction of the switching contrast with set size. The results are summarized in Figure 4. Consistent over both experiments, switching to a new token of the same type was associated

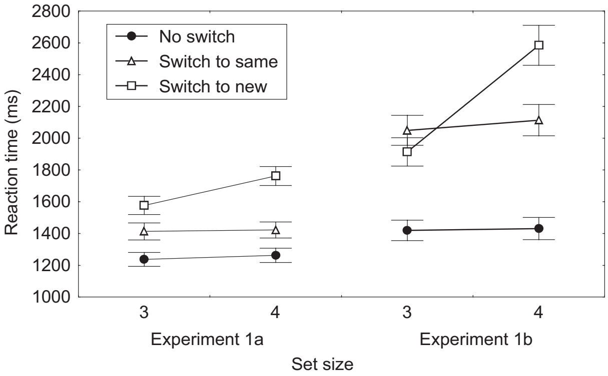

Figure 4. Object switching costs for the switch to a digit of the same type vs. to a digit of a different type, Experiments 1a and 1b. Only trials with a repeated digit are included. Error bars represent one standard error.

with a switch cost, which was smaller than switching to a new type. A set size effect was observed only for the reactions involving a switch to a new type.

Repeated Operations

A final analysis concerned the effect of a repeated operation. I computed ANOVAs with set size (3), object switch (2) and operation repetition (2) as factors, including only trials without item repetitions. The new factor, operation repetition, showed a main effect and interacted with the switching factor. Repetition of an operation yielded a reaction time advantage (547 and 652 ms for the two experiments) when no object switch was involved, but a (nonsignificant) cost (46 and 71 ms) when combined with an object switch. Thus, repetition or change of the operation shows a different pattern than the repetition or change of the item to which the operation is applied. Reaction times following repetition of an object (i.e., no switch) were faster than RTs following a switch, even when the operation was changed (as in most cases). Reaction times for repeated operations, however, were faster than RTs with new operations only when applied to the same object. There was no general advantage of repeating the operation even when the first addend/subtrahend was changed.

Errors

There were 4.6% errors overall in the arithmetic computations in Experiment 1a. Probably due to a ceiling effect, only the effect of operation repetition was significant in Experiment 1a, $F(1, 23) = 7.92$, $MSE = 37.02$, which was qualified by an interaction with object switching, $F(1, 23) = 4.37$, $MSE = 42.32$. Accuracy was highest for operation repetition combined with no object switch (98.4 %).

In Experiment 1b, participants made a mean of 6.6% errors. An ANOVA of set size (3) with object switch (2) showed no main effect of set size ($F = 2.5$), but a main effect of switching, $F(1, 19) = 5.7$, $MSE = 19.2$, and an interaction, $F(2, 38) = 4.2$, $MSE = 10.8$. Whereas accuracy for nonswitch reactions remained between 93 and 94% for all setsizes, those for switches declined from 93.2% (set size two) over 92.5 (3) to 89.3% (4). No other effect, including those involving operation repetition, was significant. To summarize, the few significant effects on accuracy data matched those found in the latencies.

Discussion

Experiments 1a and 1b replicated and extended the object switch effect reported by Garavan (1998) and by Voigt and Hagendorf (2002). The results of both experiments are remarkably consistent. Apart from generating slower reaction times overall [1642 vs. 1377 ms, $F(1, 42) = 13.3$, $MSE = 231{,}325$], the version distinguishing items by color showed precisely the same effects as the version distinguishing items by spatial position. In addition to providing a replication of all theoretically interesting effects, this allows us to attribute the effects to attentional processes in working memory, not to shifts of visual attention in space: Instead of adding costs for shifts of visual attention, using spatial positions to identify items and operations made the task easier, probably because spatial positions were more efficient retrieval cues than colors.

Since no updating of working memory contents was involved, an explanation of the object switch costs in these experiments in terms of rescheduling of operations can be ruled out. Reordering of operations might still occur, since participants were free to do computation and rehearsal operations in any order, but there is no reason to assume that reordering would happen more frequently after a switch than without a switch of the object. Therefore, the object switch costs observed in the present experiments must be interpreted as reflecting retrieval of a new item in working memory.

Retrieval from Working Memory and the Focus of Attention

Retrieval of an element from working memory could mean two things. First, it could mean that the item is selected as input for a particular cognitive operation. In the production system architecture ACT-R (Anderson & Lebiere, 1998), for example, retrieval of some piece of information is equivalent with binding this information to a variable in a production rule. The retrieved information is usable only for the specific operation it is retrieved for. In this case, there would be no use for the concept of a focus of attention. Alternatively, an item retrieved from working memory could be brought into a general state of privileged availability relative to other items in working memory. Thus, any operation could be applied faster to the retrieved item than to another item in working memory. This is essentially a functional description of what it means to bring an item into the focus of attention. The advantage of nonswitch reactions observed in the present experiments was obtained even when the operation applied to the current object changed from one reaction to the next. This implies that an item, once retrieved, is available for all addition and subtraction operations. Whether the availability advantage generalizes also to non-arithmetic operations is an open question for future research. At any rate, the present data strongly support the concept of a focus of attention within working memory that makes its contents available beyond the specific operation they were originally selected for.

The object switch effect implies that repeating the first addend/subtrahend provides a general advantage even when a new operation was applied to it. Repeating the operation, on the other hand, led to an advantage only when the whole equation (including the first addend or subtrahend) was repeated. Thus, the element retrieved from working memory and the operation displayed on the screen have different cognitive roles. There is no evidence that the operation is held in a focus of attention that makes it more available than other operations regardless of which item it is applied to. The very specific repetition advantage observed for operations most likely is not an effect of repeating an operation per se. Instead, it is due to the fact that when the whole equation is repeated, people just recall the previous result instead of computing it anew.

Set size Effects

As expected, the object switching costs increased with set size. This is compatible with the idea that object switch costs in the present experiment reflect the difficulty of selecting the correct item for retrieval. In addition, there was an unexpected but interesting discontinuity in the set size effect for nonswitch reactions. A marked increase in reaction times from set size one to two was followed by practically constant latencies from set size two to four. This pattern could be due to a qualitative difference between set size one and the higher set sizes: In the set size one condition no object switch could occur during the whole trial, whereas in the other conditions, an object switch could occur at any moment, even when in fact it did not. The elevated level of reaction times in set sizes two to four could be due to this uncertainty: Even though no *new* item must be selected in a nonswitch reaction, the selected item must still be discriminated from the other items in the memory set to avoid confusions. No such confusions could happen in the set size one condition. Thus, the increase in RTs from set size one to the nonswitch reactions of set size two could reflect the cost of keeping an item in the focus of attention in the presence of distracters in working memory.

Another unexpected modulation of set size effects is apparent in Figure 5: Latencies increased from set size 3 to 4 only when there was a switch to a new type. There was no set size effect with a switch to a new token of the same type. This seems to imply that the increase of reaction times with set sizes > 2 is not just specific for object switch trials but even more specifically limited to trials where one has to switch to a new *type*. At present it is not clear what specific process is involved in accessing a new type and why it should be particularly sensitive to an increase in working memory load. This highly specific effect of load, however, is a challenge for all theories involving general resources to account for working memory load effects.

Tokens and Types

A reliable object switch cost was observed even when the element switched to was the same digit type as the element left behind. On the other hand, the switch effect was larger when the digit type changed. Both effects can readily be explained when object switching reflects retrieval from working memory. Every object switch first leads to a new list position in working memory (i.e., a new frame or a new color), which acts as retrieval cue for the item linked to it. This retrieval takes time, thereby generating switch costs in any case. The time to retrieve an item can be shortened, however, by repetition priming. The remaining activation of the old item's type representation (i.e., the lexical representation of a digit in semantic memory) will activate the representation of the new item when it is of the same type.

A more radical version of the priming idea would state that the representation of the item *is* its type representation in semantic memory, and the tokens are individuated only through temporary links of the type representations to different episodic contexts (i.e., the list positions). This interpretation fits well with theory and data regarding the Ranschburg effect (see Henson, 1998). In forward serial recall of lists with a repeated item, people tend to forget the second occurrence of the repeated type. This is probably due to response suppression; that is, inhibition of each item after it has been recalled. If this inhibition affects the type, not just the token, it results in an omission of the second occurrence of the same type.

Backward Inhibition?

The analysis of lag effects tested whether the empirical signature for backward inhibition reported by Mayr & Keele (2000) for task-set switching could also be obtained for object switching. This was not the case. There is no evidence that items are removed from the focus of attention by actively inhibiting them to a level below other out-of-focus items in working memory.

In fact, for set sizes larger than two, the opposite pattern was observed: An item could be retrieved faster when it was refocused after a short lag than when its last retrieval dates farther back. This might suggest that being in the focus of attention is a matter of degree – the most recently accessed item might be the most activated, and activation gradually decreases over time or the number of intervening arithmetic operations. A gradual increase of reaction times over lags larger than 1, however, was never observed for set size two (Garavan, 1998; Voigt and Hagendorf, 2002; the present Experiments 1a and 1b; and another unpublished experiment from the Potsdam cognitive lab). This implies that neither time nor the number of intervening processing steps leads to a gradual decrease of accessibility of an item after switching away from it – a finding that is interesting in itself because it contradicts theories assuming time-based decay as an important source of forgetting in working memory (Hitch, Towse, & Hutton, 2001; Towse, Hitch, & Hutton, 2000).

Rather, it might be the number of *different* memory objects that is accessed for processing during the lag that could increase the time needed to access an object in working memory. This would be predicted by a theory incorporating retroactive interference, such as the feature model (Nairne, 1990): Memory objects accessed after a given object overwrite features of that object's representation, and the degree of overwriting is a function not of the number of interfering objects, but of the number of different features they involve.

Before drawing strong conclusions, however, it should be noted that Voigt and Hagendorf (2002) reported a marginally significant *decrease* of reaction times at lags > 1 compared to lag 1 in their set size three condition, contrary to the pattern observed here. This suggests that the gradual increase of times with lag observed here is not such a robust phenomenon after all. At present, the only safe conclusion from the lag analyses is that there is no equivalent to the backward inhibition pattern of Mayr and Keele (2000) in switching between numerical objects in working memory.

Experiment 2

Experiment 2 explores object switching with a working memory task that involves memory updating, but no retrieval of previous memory elements (for an early precursor of this task see Yntema & Mueser, 1962). This task isolates the second component involved in Garavan's (1998) original counting task, which was stripped from the task of Experiments 1a and 1b. A similar condition isolating the updating component was realized by Voigt and Hagendorf (2002, Experiment 2).

Only the spatial version was used in this experiment. Participants memorized a number of digits associated with frames on the screen. Then they solved equations displayed in individual frames and used the results to replace the previous digits in the respective frames. Thus, the memory set is continuously updated by the results of cognitive operations, but the operations do not use information that must be retrieved from working memory. If the object switch effect is exclusively due to the cost of retrieving a new item from working memory, then there should be no switch costs in Experiment 2. On the other hand, if retrieval of a new position representation or other processes involved in updating working memory contents play a role, there should be object switch costs in this experiment as well.

Method

Participants

Participants were 24 high school and university students from Potsdam. Their mean age was 19.8 years (*SD* = 3.46), and 9 of them were female. They were paid 10 DM (about US $ 4) for their participation in a one-hour session.

Materials and Procedure

A trial started with the presentation of the initial digits in their respective frames, as described in Experiment 1a. There were no item repetitions in the sets of initial digits. When the participant pressed the space bar, the first equation appeared in a selected frame. Equations were single-digit addition or subtraction problems with results between one and nine. Participants were asked to compute the result and replace the memory item associated with the frame by it. When ready, they should press the space bar, which immediately triggered the display of the next equation in the same or another frame. Equations directly following each other were always different. The number of successive updating steps in each trial varied randomly between one and ten, so that participants never knew when the updating sequence would stop. This was necessary to encourage them to remember all initial and intermediate memory items. At the end of the sequence, participants had to enter the final values of each frame in random order.

Within each trial, the location of each equation was determined at random, with the probability of switching to a new frame set to .5. Thus, about half the updating latencies were associated with a change to a new frame (i.e., an object switch), and the other half with an update of the same frame as before (i.e., no object switch). Independently of the object switch factor, the result of the equation could be the same as the digit it replaced with a probability of 1/9; this variable was coded as the item change factor.

Memory set size was varied between blocks. There were nine blocks, three for each of the set sizes two, three, and four; each block consisted of eight trials. The first three blocks (one for each set size, in ascending order) were regarded as practice blocks and not included in the analyses. The test blocks were ordered in an upward-downward sequence as in Experiments 1a and 1b; half the participants worked on a set of test trials that began with set size two, the other half worked on a second set of test trials beginning with set size four. The test trials together comprised 180 updating cycles for each set size.

Results

The accuracy of final recall declined with increasing set size, $F(1.5, 34) = 19.6$, $MSE = 13.5$, with 97% correct (set size 2), 96.7 (3), and 91.9 (4). Latencies for updating operations in frames whose content was not recalled correctly later, as well as latencies larger than 5 s or smaller than 300 ms were discarded. The remaining latencies were submitted to an ANOVA with set size (3), object switching (2), and item change (2) as factors. There was a main effect of set size, $F(1.7, 39.7) = 147{,}1$, $MSE = 59{,}544$, a main effect of object switching, $F(1, 23) = 151.0$, $MSE = 68{,}684$, and a main effect of item change, $F(1, 23) = 4.5$, $MSE = 66{,}035$. The object switch effect interacted with set size, $F(1.7, 38) = 5.49$, $MSE = 48{,}057$, but not with item change ($F = 0$), and the three-way interaction also wasn't significant. Figure 5 shows that the switching effect increased with set size. The item change effect consisted of a 64 ms advantage for updating steps in which the new result was equal to the digit it replaced.

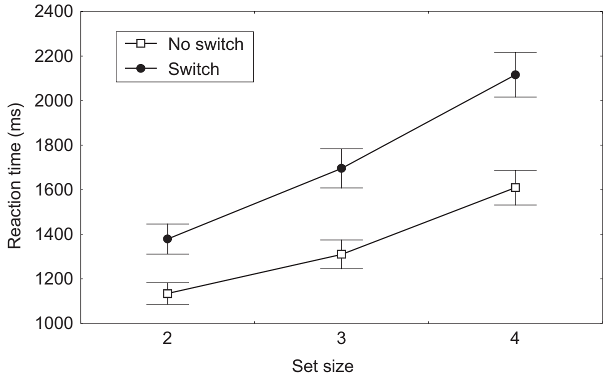

Figure 5. Object switching costs by set size, Experiment 2. Error bars represent one standard error.

Discussion

The main result of this experiment was a sizeable object switch effect on updating latencies, although the updating steps did not require retrieval of an item from working memory. Moreover, this switch effect again increased with set size. An analogous result was reported by Voigt and Hagendorf (2002). They contrasted the original counting task of Garavan (1998) with a substitution version where participants updated their working memory contents by new numbers displayed on the screen. The substitution version yielded smaller, but still substantial switch costs increasing with set size. These findings strongly suggest that the switch effect reported by Garavan (1998) is not *only* a reflection of the selective retrieval of a new element from working memory. The switch costs observed in Experiment 2 must be attributed to a different process.

One explanation for this effect could be that an object switch in the present experiment requires moving the focus of attention to a new spatial position; that is, selectively accessing a new representation of the position the next result must be associated with. This would be a component process of the object switch in Experiments 1a and 1b, where accessing the appropriate position representation is a prerequisite for retrieving the associated item. This interpretation seems unlikely, because the switch costs observed in Experiment 2 were nearly as large as those in Experiment 1a (380 vs. 445 ms, averaged over the three set sizes). Assuming that focusing the new position and retrieving the associated item are sequential processing steps, this would leave only about 65 ms for the retrieval step. However, if we relax the assumption of strictly sequential processing steps, this subtraction logic does not necessarily hold (e.g., McClelland, 1979), so the interpretation of object switch costs as time to bring a new position representation into the focus can't be ruled out for the present experiment.

Another potential explanation is that the object switch costs in Experiment 2 reflect the time needed to reschedule the processing sequence within each updating cycle. In the updating task used here, the arithmetic computation must be coordinated with rehearsal of the memory set. A convenient sequence might be to insert the computation into the rehearsal sequence just before the item that is to be updated. With this schedule, there is no need to keep the result of the equation in mind for some time until it is first rehearsed; the result can be articulated immediately after its generation at the correct position in the rehearsal sequence. Such a schedule requires that with every object switch the computation step is inserted at a new point in the rehearsal sequence. The executive demand of this reorganization could explain the switch costs in the present experiment. A problem with this explanation is that it is not immediately clear why the executive demands should increase with set size. One potential reason could be that finding the right point in the rehearsal sequence where the computation must be done is harder when the rehearsal sequence is longer. Another reason could be that an increase in memory load slows down executive processes (Roberts, Hager, & Heron, 1994).

Finally, the object switch cost could reflect the time required to establish the association or binding of the element currently in the focus of attention with its position in working memory. As long as a representation is kept in the focus of attention, there is no need to establish a representation of the item-position link, because the item in the focus and the position in the focus are linked simply by being in the focus. As soon as the currently focused item must be left behind, its link to a position must be remembered in working memory. Establishing a means to represent this link might take some time. This time would be required when the focus of attention switches to a new position. In a nonswitch cycle, in contrast, the representation held in the focus of attention can immediately be discarded and replaced by the next result. Establishing a binding between an item and a position might require more time with larger set sizes because the binding must be made more robust in the presence of more potential distracters.

Replacing a memory element with an identical new element took less time than replacing it with a new element. This effect did not interact with object switching. One reason for the item change effect could be that the previous item memorized at a location acted as a prime for the result of the equation. In this case, the effect would be due to a faster arithmetic computation; it should be eliminated when the new memory element must not be computed, but is presented directly. Alternatively, the advantage of an identical new element could be due to the absence of proactive interference from the old element. According to this interpretation, less time would be required to delete or suppress the old element at a location if the new element is identical with it. In this case, the item change effect should be observable even without arithmetic computation. The present data do not allow a decision between these possibilities.

General Discussion

The experiments reported here help to clarify the nature of the object switch effect first described by Garavan (1998). First, they rule out an alternative explanation left open by Garavan's design. The object switch effect cannot be explained exclusively by the need to reschedule rehearsal and arithmetic operations. Experiments 1a and 1b had no feature that would motivate more extensive rescheduling following an object switch than following an object repetition; in both cases, participants could do rehearsal and computation in any order. Nonetheless, there was a substantial object switch cost.

Second, the object switch costs observed by Garavan (1998) can be decomposed into at least two components. The first component, demonstrated in Experiments 1a and 1b, can be genuinely described as the cost for shifting the focus of attention from one object in working memory to another one. This component can also be described as selective retrieval of an object from working memory. The second component, illustrated in Experiment 2, could reflect the time needed to bring the appropriate position representation into the focus of attention. It could also reflect the time demand for an executive process needed to reschedule the sequence of rehearsal and updating operations. Alternatively, it could reflect the time demand for establishing a link between a new item and its position in working memory. The present data don't allow the differentiation of these three possibilities. Both components probably contributed to the switch costs observed by Garavan (1998) and the analogous experiment by Voigt and Hagendorf (2002). This does not imply, however, that we can predict switch costs in a paradigm involving access *and* updating by summing up the switch costs observed with access (no updating) and those observed with updating (no access). The processes responsible for the two components need not be discrete sequential steps – they might proceed in cascade (McClelland, 1979) or even in parallel (e.g., one could bring a context representation and the item linked to it into the focus simultaneously).

Third, the lag analysis of Experiments 1a and 1b throws some light on the mechanism of selective attention to individual objects in working memory. In contrast to the selection of task sets (Mayr & Keele, 2000), the selection of an object for processing does not seem to involve active inhibition of the previously selected object. Instead, with larger set sizes the object selected just before the one presently focused could still be retrieved slightly faster than other objects that were focused longer ago. This data pattern could be due to a selection mechanism that relies on a passive and gradual removal of a no-longer-needed item from the focus of attention. Alternatively, it could be due to retroactive interference operating in addition to the movement of the focus of attention. Since the gradual increase of reaction times for lags > 1 might not be generalizable (Voigt & Hagendorf, 2002), any further interpretation must await data from a more direct investigation of this issue.

Fourth, the analysis of repeated operations in Experiments 1a and 1b reveals asymmetric roles for the first and the second addend/subtrahend in the tasks used here. The first addend or subtrahend is treated as the object an operation is applied to. This object is selected from a set held in memory by bringing it into the focus of attention, where it is available for any arithmetic operation as long as no other object is focused. The second addend or subtrahend, in contrast, is treated as part of an instruction for an operation to be applied to the selected object. It is not selected beyond its role in specifying a single operation to be applied to a specific object. Thus, there is no advantage in repeating an operation when the object it is applied to is changed. There seems to be a focus of attention that holds an object to which an operation is to be applied, but there is no equivalent focus of attention that holds the operation.

This is remarkable in light of the literature on task-set switching (Allport, Styles, & Hsieh, 1994; Jersild, 1927; Rogers & Monsell, 1995). In task-set switching designs, there is a substantial RT gain when the same task-set is repeated from one reaction to the next, even when the object it is applied to (i.e., the stimulus) is changed. Thus, a task set for a choice reaction time task obviously can be selected independently of the object it is applied to. One might wonder why an operation like "add four," which also could be interpreted as a task set (see, for example, the original task-set switching studies by Jersild, 1927), is not selected independently of the object it is applied to. There are, of course, several differences between my experiments and a typical task-set switching design. The critical difference could be that in the experiments reported here, the operation is displayed on the screen without any distracters, while the object it is applied to must be retrieved from a memory set consisting of several candidates. In task-set switching designs the roles are reversed: The object is displayed singly on the screen, whereas the task set must be selectively retrieved from two (or more) alternatives held in memory. Obviously, there is no need for a selection mechanism like the focus of attention when the information to be used is presented exclusively in the environment, but there is a need for such a selection mechanism when the required information must be retrieved from a set of candidates held in memory. The selection mechanisms for objects and for task sets seem to have in common that they keep their contents selected beyond the processing step they were originally selected for, thus leading to switch costs (or repetition benefits). They differ, as noted above, in that the selection mechanism for task sets seems to employ backward inhibition, whereas the focus of attention for objects in working memory does not.

To conclude, the present data support the suggestion of Garavan (1998) that there is a focus of attention in working memory that serves to select one item at a time as the object of the next processing step. The notion of a focus of attention within working memory is also supported by research on the Sternberg recognition task (McElree & Dosher, 1989): The last item of a serially presented list is accessible faster and with higher accuracy than previous items. McElree (1998) extended this approach, showing that the focus of attention can hold more than a single item when the items are categorically related and presented in temporal groups. It is not clear in this case whether the focus of attention held three distinct items or a single chunk. If the function of the focus of attention is to selectively hold those representations that are required as objects for the next cognitive operation, we should expect that it can hold more than one distinct object in case of operations that require two or more objects (e.g., a comparison of two objects in a memory set). Further research on the object switch effect could, among other things, investigate how the focus of attention manages to provide selective access to working memory contents when more than one object is needed for a cognitive operation.

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