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Access to Information in Working Memory: Exploring the Focus of Attention

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Participants memorized briefly presented sets of digits, a subset of which had to be accessed as input for arithmetic tasks (the *active set*), whereas another subset had to be remembered independently of the concurrent task (the *passive set*). Latencies for arithmetic operations were a function of the setsize of active but not passive sets. Object-switch costs were observed when successive operations were applied to different digits within an active set. Participants took 2 s to encode a passive set so that it did not affect processing latencies (Experiment 2). The results support a model distinguishing 3 states of representations in working memory: the activated part of long-term memory, a capacity limited region of direct access, and a focus of attention.

Working memory is commonly described as a system for simultaneous storage and processing of information. The relation between "storage" and "processing," however, is rarely specified. Resource models generally posit a common resource (e.g., activation) that must be shared between the two functions (Just & Carpenter, 1992). Evidence from dual task studies, however, casts doubt on the resource-sharing hypothesis: There are numerous examples in the literature of processing that is largely unimpaired by a concurrent short-term memory demand, even when the memory demand is close to the maximum span (e.g., Foos & Wright, 1992; Klapp, Marshburn, & Lester, 1983; Logan, 1978, 1979, 1980; Oberauer, Demmrich, Mayr, & Kliegl, 2001).

It has occasionally been noted (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Garavan, 1998) that the interplay of storage and processing is mediated by selective attention to the subset of elements in working memory that must be manipulated at any moment. For example, when the task is to add three-digit numbers without paper and pencil, one must focus on the ones in the first step, while holding the other digits in memory at the same time. The distinction between information that is accessed at any moment for further processing on the one hand, and the information held available in the background for later use on the other hand, is readily accommodated by a model like Cowan's (1995, 1999). Cowan distinguished between the activated part of long-term memory and the focus of attention. Only the focus of attention is assumed to have limited capacity. The activation of representations in long-term memory is not capacity limited, but it can get lost through decay or interference. In a model of this kind (for a similar construction, see Anderson & Lebiere, 1998), information can be processed in the focus without being impaired by the demand to hold other information in the activated part of long-term memory.

Evidence pertaining to the interaction of storage and processing functions of working memory comes from a recent study by Oberauer et al. (2001). In two experiments we asked young and old adults to work on a mental arithmetic task while simultaneously remembering a list of three or six digits briefly presented before each arithmetic problem. In one condition, the memory list was unrelated to the arithmetic task. In another condition participants had to substitute variables in the arithmetic task with specific digits from the memory list. As long as the memory task and the processing task were unrelated, there was no effect of memory load on arithmetic problem solving. Speed and accuracy of the arithmetic task were impaired by the simultaneous memory demand only in the substitution condition, where participants had to access the memory contents during processing. This result can be interpreted in the framework offered by Cowan (1988, 1995, 1999): As long as no access to a memory list is required, the list can be held in the activated part of long-term memory, so that it does not use up capacity of the focus that processes the arithmetic task. An effect of the memory set on processing is observed, however, when access to the memory list is required. This can be the case either because the whole list must be moved into the focus of attention (the *broad focus interpretation*) or because the focus must selectively pick out one element from a set, and this selection is more difficult when the set is larger (the *selection interpretation*).

A study using a modified Sternberg recognition task (Oberauer, 2001) provides additional support for the distinction between Cowan's (1995) "focus of attention" and the activated part of long-term memory. In this task, participants memorized two lists of words, after which a cue was given that declared one of the lists as relevant, whereas the other list could be forgotten. When the recognition probe appeared immediately after the cue, the reaction times (RTs) were a function of the length of both lists. When the probe appeared 1 s or more after the cue, RTs increased only with the length of the relevant list but were independent of the length of the irrelevant list. This indicates that the irrelevant list no longer occupied part of the capacity of working memory. The irrelevant list apparently could be removed from the focus of attention within 1 s after the cue, such that only the relevant list was held in the focus for comparison with the probe. Nonetheless, the irrelevant

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list still had an indirect effect on the recognition decision: Probes stemming from the irrelevant list were rejected more slowly than completely new words, and this intrusion effect was measurable up to 5 s after the cue. The intrusion effect can be attributed to residual activation of the irrelevant list elements in long-term memory: Activated representations generate a familiarity signal that provides preliminary evidence for a "yes" response, which later is overridden by a more reliable but slower process of recollection.

Further evidence for the existence of a focus of attention within working memory comes from the study of Garavan (1998). He asked participants to count squares and triangles that appeared sequentially, in random order, on the screen. Thus, participants had to remember and update two running counts simultaneously. The sequence of geometrical figures was self-paced, so that the latency of individual counting operations could be measured. Garavan observed that a switch from one mental counter to the other (e.g., when a triangle followed a square) took 300–500 ms longer than updating the same counter again (e.g., when a square followed a square). This indicates that participants hold one counter in the focus of attention while memorizing the other outside the focus. The cost of switching counters reflects the time it takes to move the focus of attention within the memory set from one item to the other.

McElree and Dosher (1989) observed that the last item of a short word list presented for a Sternberg recognition task was accessible much faster and more accurately than the other list items. They interpreted this as evidence for a focus of attention holding the last list item, which can be compared to an immediately following probe much quicker than earlier list elements. McElree (1998) showed that the focus could be extended to the last three items when the list is presented in groups of three categorically related words.

Taken together, these studies and their interpretations reveal an ambiguity with respect to the role of the focus of attention. According to Cowan (1995, 1999), the focus holds several items simultaneously (with a limit of about four items; see Cowan, 2001), which can be directly accessed by a central executive for processing. This characterization is compatible with the use of the concept as applied to the modified Sternberg task (Oberauer, 2001) and in the broad-focus interpretation of the mental arithmetic study by Oberauer et al. (2001). On the other hand, Garavan (1998) and McElree and Dosher (1989) suggested a more narrow focus that is usually restricted to a single object. Here, the role of the focus is not to hold a set of memory elements ready for access by the processor but to hold the memory content (usually a single object) already selected for processing. This latter use of the term (also implied in the selection interpretation of Oberauer et al., 2001) bears more similarity to the notion of a focus in the visual attention literature (e.g., Eriksen & Murphy, 1987).

In this article, I argue that the two interpretations of the term *focus of attention* in fact point to two different functional states of information in working memory. Therefore, I propose to conceptualize working memory as a concentric structure of representations with three functionally distinct regions (see Figure 1).

1. The activated part of long-term memory can serve, among other things, to memorize information over brief periods for later recall.

2. The region of direct access holds a limited number of chunks available to be used in ongoing cognitive processes.

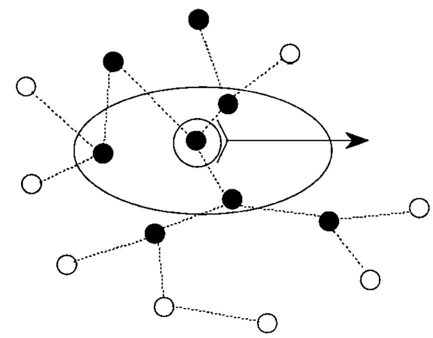

Figure 1. A concentric model of working memory. Nodes and lines represent a network of long-term memory representations, some of which are activated (black nodes). A subset of these items is held in the region of direct access (large oval). Within the region of direct access, one item is selected for processing by the focus of attention (small oval). Activated items outside the region of direct access form the activated part of long-term memory, which is accessible only indirectly via associative links (dotted lines) to representations in the more central regions.

3. The focus of attention holds at any time the one chunk that is actually selected as the object of the next cognitive operation.

The limits of working memory capacity, as measured by various tasks (see, e.g., Cowan, 2001; Oberauer, Süβ, Schulze, Wilhelm, & Wittmann, 2000), presumably reflect the limited number of independent elements that can be held in the region of direct access at the same time. This region, therefore, corresponds most closely to what Cowan (1995, 1999) named the *focus of attention*. The capacity limit of working memory probably arises from two factors, partial overwriting of representations in working memory and crosstalk between the elements in the region of direct access when one of them must be selected for processing (Oberauer & Kliegl, 2001). *Overwriting* means that representations sharing features tend to overwrite each other's feature codes (e.g., as in the feature model of Nairne, 1990). *Crosstalk* refers to the competition among items in the region of direct access when it comes to selectively retrieve one of them at the exclusion of others. Elements held in the activated part of long-term memory do not contribute to crosstalk because they are not part of the set from which the focus selects one element.

Retrieving an item from working memory, either for recall or for manipulation, means bringing this item into the focus of attention. The focus of working memory therefore has a function with respect to memory that is equivalent to the function of a focus of attention in perception. Following Allport (1987), we can characterize this function as "selection for (cognitive) action" (p. 395). Whereas the focus of attention can directly retrieve items from the region of direct access, recall of items from the activated part of long-term memory must be mediated by retrieval structures that help to bring the to-be-recalled chunks into the region of direct access (Ericsson & Kintsch, 1995). Only objects within the region of direct access are regarded as selection candidates by the focus of attention. Therefore, only objects in the direct access region contribute to crosstalk, thereby slowing down the selection process.

To summarize, I see working memory as an organized set of representations characterized by their increased state of accessibility for cognitive processes. Representations belonging to the contents of working memory can be distinguished with respect to their access status. Capacity limits on "simultaneous storage and processing" arise not from the need to share a limited resource, but from the difficulty of selective access when several distinct mental objects must be held immediately available.

The goal of the present study was to provide evidence for the concentric model of working memory specified above. Two experiments extending the memory-updating paradigm of Garavan (1998) show three different functional states of working memory contents simultaneously: There are items memorized for later recall but not accessed during a concurrent processing task; these items do not affect the speed of the processing task. There are other items which are held available for direct access and which affect the processing latencies. Finally, there is a single item at any moment that is actually selected as the object of a cognitive process.

Experiment 1

The memory-updating task used in this study was originally designed by Salthouse, Babcock, and Shaw (1991). Participants first memorized a varied number of digits presented in different frames on the screen (see Figure 2). These initial values had to be updated according to arithmetic operations (e.g., "+3" or "–6") presented sequentially in selected frames. After a total of 9 updating operations, displayed in self-paced mode, the final values for each frame were probed for recall in a random order. In the task version used here, two rows of frames were presented. In one condition, both rows were declared as "active," that is, elements from both rows would be updated. In another condition, one row was declared "active" and the other "passive." The items in the passive row are never updated, so that participants only had to remember the initial values until the final recall. To manipulate setsize for the active and the passive sets, both rows could consist of either one or three items.

I assumed that items in a passive set would be memorized in the activated part of long-term memory. The setsize of a passive set therefore does not affect latencies for the updating operations. Active sets, in contrast, would be held in the region of direct access, and therefore their setsize would have an effect on updating latencies. Within an active set, the current value of the frame that is presently updated would be selected as the object of updating by bringing it into the focus of attention. Shifting the focus of attention from one mental object to another within the active set or sets can be expected to yield extra time costs similar to those observed by Garavan (1998). I refer to this effect as *object switching costs*. An additional prediction is that the object switching costs are a function of the difficulty of selection from the elements in the direct access region. This implies that object switching costs increase with the total number of elements in active sets, but not with the number of elements in a passive set.

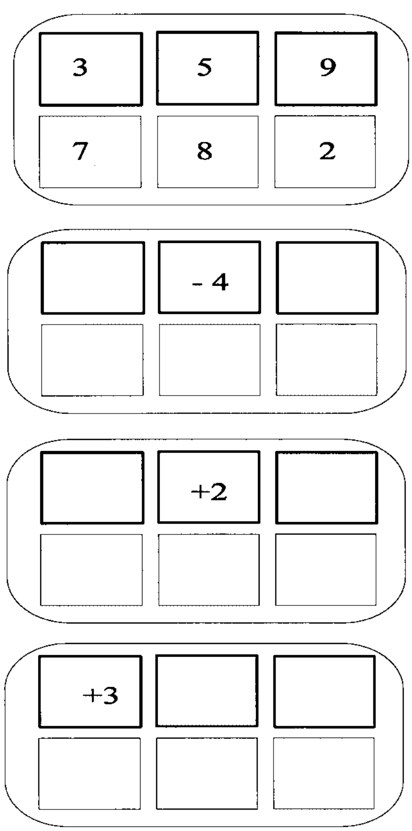

Figure 2. Partial sequence of displays in a trial of the memory updating task used in Experiment 1. The example is from the active-passive condition, and both setsizes are three. The active set was displayed in red on the screen (denoted by thick lines in the figure). The second operation illustrates a nonswitch operation, and the third operation involves an object switch.

Method

Participants

Eighteen students from the University of Potsdam participated in this study. Their mean age was 22.4 years (SD = 2.6), and 16 of them were women.

Design and Procedure

Participants worked on memory-updating tasks modeled after Salthouse et al. (1991). Each trial began with the presentation of two rows of frames, one in the upper and one in the lower half of the computer screen (see Figure 2). Each row consisted of either one or three frames. Within each frame, a digit between 1 and 9 was presented. All digits were presented simultaneously until the participant had memorized them and pressed the space bar. A series of nine arithmetic operations was then displayed sequentially in individual frames. Participants were asked to update the current value of the respective frame according to the operation and press the space bar when finished, after which the next operation was displayed. After nine operations, question marks were presented one at a time in all frames, and participants were required to type the current value of the respective frame. Order of recall of the rows, as well as of the frames within each row, was randomized for each trial. Participants knew that all intermediate and final results were digits between 1 and 9.

There were three practice blocks and 16 test blocks, each consisting of 10 trials. Two conditions were realized. In the active–active (AA) condition both rows of frames contained "active" values that were updated during the trial. In the active–passive (AP) condition only one row was "active," whereas the other was declared "passive." The passive row was not updated, and the nine updating operations in this condition were concentrated on the active row. Frames and digits of active rows were displayed in red, whereas passive frames and digits were displayed in white on a black background. Condition was varied over blocks in an alternating pattern. Between the blocks of the AP condition, the active row alternated between the top and the bottom row.

The setsizes of both rows were varied independently in a random order within blocks. Each row could have a setsize of one or three digits. Switching between the objects of updating was varied according to two orthogonal factors: "Horizontal" switching from one frame to another within a row, and "vertical" switching from a frame in one row to the corresponding frame in the other row. Within each trial there were two updating operations without switch (i.e., the operation was applied to the same object as before), two with an object switch within the row, two with a row switch to a corresponding object, and two with both within- and between-row switch. (The first operation in each sequence of nine was not categorized as switching or nonswitching.) Not all switching conditions could be realized in all trials. In condition AP, the row switch was not realized, so that there were four operations without switching and four with a horizontal object switch. In all trials of condition AP where the active setsize was 1, there was no switch at all. Likewise, there was no horizontal switch in the AA condition when both setsizes were 1. In this case, half of the operations involved no switch, and the other half involved a row switch. In effect, then, switching was varied as two factors nested within condition and the setsize factors according to logical constraints.

The whole experiment was conducted in three 1 hr sessions. During the first session, participants worked on three practice blocks introducing the AA condition and the two versions of the AP condition (active set above vs. below passive set), respectively, which were followed by four test blocks. The remaining two sessions consisted of six test blocks each.

Results

Report of the results is ordered by hypotheses. The first block of hypotheses concerns setsize effects; the second block concerns the effects of object switching. For the RT analyses, I excluded all RTs from individual operations for which the recalled final value in the respective frame was erroneous. *Outliers* were defined as RTs smaller than 300 ms and RTs exceeding individual participant's means in a condition cell by three standard deviations; these outliers were also excluded from analysis (eliminating between 1 and 3% of RTs per condition). For the recall latencies, there were too few data points per condition cell for this treatment; therefore, outliers were removed by absolute criteria (300 and 10,000 ms) at both ends. For all statistical tests, an alpha level of .05 was adopted.

Effects of Condition and Setsize

RTs for updating operations. The first hypothesis tested was that remembering a second passive set (condition AP) slows updating operations less than remembering an additional active set of equal length (condition AA). A second, related hypothesis was that the setsize of an active row, but not a passive row, would have an effect on updating latencies. Only RTs for nonswitch operations were included in the analysis to avoid confounds of switching with condition and setsize. RTs were submitted to an analysis of variance (ANOVA) with three factors: condition (active–active vs. active–passive), the setsize of the row in which the updating operation was displayed (the *updated* set), and the setsize of the other row (the *not updated* set). In condition AP, the not updated set always was the passive row. The results are shown in Figure 3.

There was a main effect of condition, $F(1, 17) = 53.81$, $MSE = 876{,}666$, reflecting longer RTs when both rows were active. Both setsizes had significant main effects, $F(1, 17) = 53.16$, $MSE = 629{,}029$, for the updated set and $F(1, 17) = 48.15$, $MSE = 322{,}658$, for the not updated set. The setsize effect of the not updated set, however, interacted with condition, $F(1, 17) = 26.98$, $MSE = 468{,}938$. As can be seen in Figure 3, in the AP condition the not updated (i.e., passive) row had no setsize effect at all, whereas there was a sizeable effect of the not updated set's size in the condition where this set was active. The setsize effect of the updated set was also larger in condition AA than in condition AP, $F(1, 17) = 7.95$, $MSE = 337{,}262$. The interaction of the two

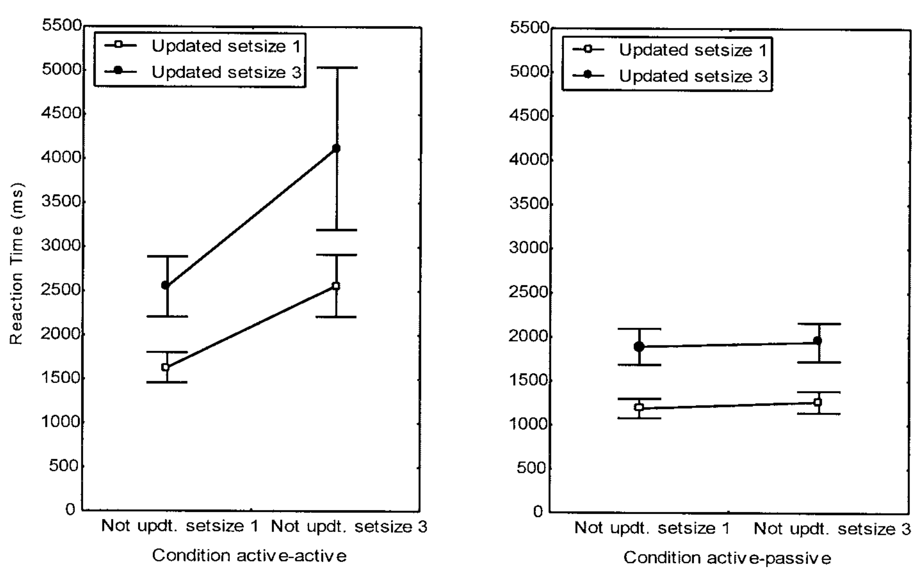

Figure 3. Experiment 1: Setsize effects on reaction times (in milliseconds) for updating operations. Updated setsize is the setsize of the set from which one element is updated by the operation; this is always an active set. Not updated (Not updt.) setsize is the setsize of the other set, which is also active in the active–active condition but passive in the active–passive condition. Only nonswitching operations are included. Error bars represent two standard errors.

setsize effects as well as the three-way interaction fell just short of significance (Fs = 4.03 and 3.75, respectively, with ps = .06 and .07).

These results show a setsize effect of the not updated row only if it was an active row (i.e., in condition AA). One might wonder whether this setsize effect was already there at the beginning of a trial, before the not updated row had ever been accessed for an operation. If both active rows in condition AA were held in the direct access region of working memory, they should produce a setsize effect regardless of whether they had already been accessed before. To investigate this, I selected the nonswitch RTs from condition AA before the first row switch, that is, before the not updated set was updated the first time. For this subset of latencies, I conducted an ANOVA with updated setsize (1 vs. 3) and not updated setsize (1 vs. 3) as factors. Both factors were significant, $F(1, 17) = 20.06$, $MSE = 851{,}668$, for the updated setsize and $F(1, 17) = 40.98$, $MSE = 801{,}314$, for the not updated setsize. Thus, an active row yielded a setsize effect even before it had been accessed for the first time.

Chunking strategies. In an informal postexperimental interview most participants reported using chunking strategies, which were applied mainly to the passive sets. The most frequent strategies reported were coding a three-digit set as a month–year combination or finding a mathematical relation between the three digits, like "2 * 4 = 8". Could chunking of the passive set explain why the passive set had so little effect on RTs? If chunking reduces the memory load of a passive three-digit list to one item, this could explain the absence of a setsize effect of the passive set. Could this also explain the main effect of condition? In this case, there should be no difference between conditions in those trials where the not updated row was only one digit long, because then chunking could not reduce its load further. This was not the case. When the analysis was restricted to items with not updated sets of length 1, the main effect of condition was still significant, $F(1, 17) = 74.95$, $MSE = 73{,}134$. Thus, even in cases where chunking could play no role, holding a further active digit in mind yielded longer RTs than remembering an additional passive digit.

Accuracy and latency of recall. Recall of final values was much better in condition AP (92%) than in condition AA (82%), $t(17) = 5.13$. In condition AA, accuracy decreased with increasing memory load (95%, 86%, and 65% for two, four, and six active elements, respectively). The linear trend, $F(1, 17) = 61.71$, $MSE = 127.2$, as well as the quadratic trend was significant, $F(1, 17) = 8.57$, $MSE = 43.6$. For condition AP, accuracy data were analyzed by an ANOVA with active setsize (1 vs. 3), passive setsize (1 vs. 3), and recalled set (active vs. passive) as factors. The only significant effect was a main effect of passive setsize, $F(1, 17) = 8.41$, $MSE = 28.77$. Even this effect was relatively small (4%) compared to the drop in accuracy observed with increasing setsizes in the AA condition. Most important, the interaction of active and passive setsize was not significant ($F < 1$). An interaction could have been expected by comparison with the AA condition, where an increase of memory load by two digits had a larger effect when the baseline load was already high, as reflected by the quadratic trend. To conclude, the number of items to be held in memory clearly had different effects in the AP condition than in the AA condition.

Analogous ANOVAs were applied to the latencies of final recall. For the AA condition, there was a strong linear increase with setsize (2, 4, and 6), $F(1, 17) = 127.2$, $MSE = 30{,}814$, but no quadratic trend ($F < 2$). For the AP condition, latencies increased with both setsizes, $F(1, 17) = 9.7$, $MSE = 59{,}801$, for active setsize and $F(1, 17) = 38.3$, $MSE = 40{,}080$, for passive setsize. The two setsizes interacted underadditively, $F(1, 17) = 10.7$, $MSE = 19{,}969$, with a passive setsize effect of 287 ms when active setsize was 1 but only 129 ms when it was 3. More important, latencies were longer for recall of the passive row (1,809 ms) than of the active row (1,433 ms), $F(1, 17) = 43.87$, $MSE = 116{,}100$. An additional time demand for recall of the passive set would be expected if the passive set has to be retrieved from long-term memory.

Effects of Object Switching

I expected that switching from one frame to another during successive updating operations would yield higher RTs than updating the same value as before. In addition, the cost of switching from one object to another should be larger with larger active setsizes but independent of passive setsize, because only elements in the active row contribute to crosstalk when the focus of attention selects a new object.

The main analysis focuses on "horizontal" switches between frames within a row, because only these switches are comparable over both conditions. Therefore, only trials where such switches occurred (i.e., trials where the updated row had three items) were included in the analysis. An ANOVA with condition (AA vs. AP), switching (yes vs. no), and setsize of the not updated set (1 vs. 3) was conducted on the RTs. The main effects of condition and setsize and their interaction were already discussed above and are not detailed again. In addition, there was a main effect of switching, $F(1, 17) = 32.91$, $MSE = 409{,}863$, which interacted with condition, $F(1, 17) = 11.42$, $MSE = 174{,}061$, and also with the setsize of the not updated set, $F(1, 17) = 5.35$, $MSE = 215{,}933$. The predicted three-way interaction was also significant, $F(1, 17) = 4.03$, $MSE = 189{,}283$, $p = .03$ (one-tailed[1]): The switching effects increased with setsize in the AA condition, where *setsize* refers to the size of an active set, but it did not increase with the setsize of the passive set in the AP condition (see Figure 4).

In addition, I analyzed the effect of switches between rows in condition AA by an ANOVA with updated setsize, not updated setsize, and row switch as factors. Only RTs involving no switch within a row were considered to keep the "horizontal" switches constant across all design cells. There was a significant effect of switching, $F(1, 17) = 32.27$, $MSE = 827{,}697$, which interacted with both setsizes, $F(1, 17) = 28.60$, $MSE = 3{,}616{,}867$, and $F(1, 17) = 34.17$, $MSE = 2{,}519{,}758$. The three-way interaction was not significant.

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[1] A three-way interaction in a 2 × 2 × 2 ANOVA is a contrast comparing two sets of four design cells each; in this case the first set includes from condition AA the nonswitch RTs with passive setsize 1 and the switch RTs with setsize 3, and from condition AP the nonswitch RTs with setsize 3 and the switch RT with setsize 1. The second set is built from the remaining four cells. A t test comparing the means of these sets is equivalent to the F test for the three-way interaction. I formulated a precise prediction for this three-way interaction, which can be restated as expecting the first set to be larger than the second. Therefore, a one-tailed test is warranted here.

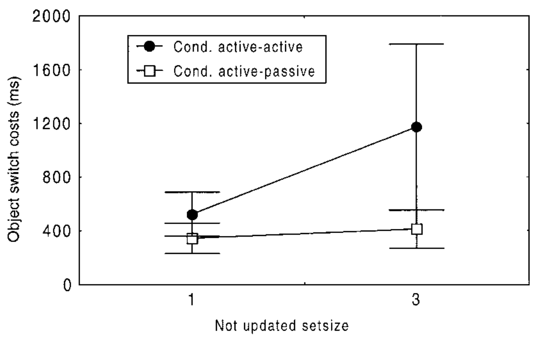

Figure 4. Experiment 1: Object switch costs as a function of an active setsize (condition [cond.] active–active) versus a passive setsize (cond. active–passive). Error bars represent two standard errors.

Discussion

The results generally confirmed the predictions of the concentric model of working memory outlined above. The distinction between items in the activated part of long-term memory and items held in the region of direct access was supported by the differences between active and passive sets in the experiment. Holding a passive set in memory along with an active set resulted in faster overall reactions than memorizing two active sets. This should be expected when active but not passive elements draw on the limited capacity of the direct access region. Further supporting this assumption, RTs were affected by the not updated set when it was an active set, but not when it was a passive set.

The combination of one active and one passive set also yielded better recall than the combination of two active sets. Whereas the setsize effects of two active sets on recall accuracy interacted, as evidenced by the positively accelerated decrease of accuracy with overall memory load, the setsize effects of one active and one passive set did not interact, lending additional support to the assumption that the two sets do not compete for the same limited capacity. The latencies of recall are consistent with this interpretation. Sharing of a limited capacity would, if anything, lead to an overadditive interaction of active and passive setsize, and such an overadditive effect on RTs was in fact marginally significant in condition AA, $F(1, 17) = 4.05$, $MSE = 453{,}290$, $p = .06$. (See the left panel of Figure 3.) The interaction on recall latencies in condition AP, however, was underadditive. Recall of the passive set took additional time, supporting the hypothesis that the passive set can only be accessed indirectly through retrieval structures. One finding difficult to explain is why the size of the active row or rows had a pronounced effect in condition AA but no effect in condition AP. This inconsistency is difficult to understand from the perspective of any extant theory of working memory, not just the one proposed here; it is probably premature to speculate about its source.

The object switch effects within an active set of three elements document the time cost of moving the focus of attention from one object to another within the region of direct access. As expected, the switch costs were a function of the setsize of an additional active set, but not a passive set. This finding supports the idea that switching costs depend on the difficulty of selecting one item for processing, which increases with the number of eligible candidates, but not with the total number of items held in working memory. The analysis of switches between rows is in accordance with this interpretation: When both sets were active, costs of switching to an object in a new row increased with both setsizes.

The strategies reported by participants suggest that chunking played an important role for memorizing the passive lists. Chunking presumably was less efficient for the active lists, because participants would have been forced to unpack and repack the chunk after each updating operation. The difference between active and passive sets, however, could not be entirely explained by chunking, because they were substantial even for sets of one digit, which cannot be chunked into a smaller unit. Nonetheless, chunking could be responsible for part of the observed effects. This explanation is fully compatible with the concentric model. Chunking means that links between items are built up (or previously existing links used) in long-term memory (cf. Ericsson & Kintsch, 1995). This means that the elements forming a chunk are represented in long-term memory, whereas only a pointer associated to the chunk is held in the region of direct access. The idea of chunking enriches the concept of the activated part of long-term memory as used by Cowan (1995, 1999) by pointing out that elements in long-term memory are not just activated, but also connected with each other.

One problematic aspect of Experiment 1 is that active and passive sets differed in (at least) two important ways. First, the active sets but not the passive sets were continuously accessed during the processing task. Second, the active but not the passive set continuously changed. The second factor alone could have produced the differences between the two conditions: Active sets might lead to slower reactions and to setsize effects on updating latencies because they required more intermediate rehearsal (e.g., one extra rehearsal of all the items in a row when one has changed). Two active sets might lead to worse recall because there is proactive interference from old values in both sets. In Experiment 2, I disentangled the two aspects by using active and passive sets that both stay constant throughout a trial.

Experiment 2

The second experiment was based on a task very similar to the memory-updating task, with the main difference that the values in the active sets were not updated. Again, participants learned digits associated to frames in two rows on the screen and then applied arithmetic operations to selected digits. In this experiment, however, participants were instructed to type the result of each arithmetic operation into the computer, while keeping in memory the original value of each frame. Thus, both active and passive sets remained unchanged over the whole trial.

A second change was that participants were informed which set would be the active one only after they memorized the initial values. This allowed me to vary the cue–stimulus interval (CSI) between the cue indicating the active set and the display of the first arithmetic operation. Previous research with the modified Sternberg task (Oberauer, 2001) suggested that it takes about 1 s before setsize effects of an irrelevant set disappear. This could mean that people first encode all items into the direct access region of working memory. When the cue appears, the items that need not be accessed in the near future are removed from the direct access region, and this takes about 1 s. By varying the CSI from 100 ms to 5 s, I hoped to trace the gradual reduction of the setsize effect of the passive set on RTs for arithmetic computations.

Method

Participants

Twenty-four students from the University of Potsdam participated in this study. Their mean age was 23.3 years ($SD = 2.0$), and 12 were women.

Design and Procedure

As in Experiment 1, each trial began with the presentation of two rows, each consisting of either one or three frames. One digit was displayed in each frame, and participants were asked to memorize these digits. All digits were presented simultaneously for 1.2 s times the number of digits. After the digits disappeared, one of the rows was indicated as the "active" row by changing its color from white to red. After a varying CSI, a sequence of eight arithmetic operations was displayed. The operations were distributed in a random fashion among the frames of the active set (when there were three frames). Thus, for an active set of three digits, there was a one-third probability that an operation was displayed in the same frame as the previous operation (i.e., a nonswitch case), and a two-thirds probability that it was displayed in a different frame (i.e., a case of object switching). At the end of each trial, both rows had to be recalled; recall order of rows and of frames within rows was randomized for each trial.

Participants worked through six blocks; each block consisted of eight practice trials followed by 24 test trials. CSI was varied between blocks; the six CSIs were 100 ms, 300 ms, 600 ms, 1000 ms, 2.5 s, and 5 s. The order of blocks was counterbalanced over participants. Active setsize and passive setsize were varied orthogonally within blocks. The whole experiment was completed in two sessions of about 1 hr each.

Results

RTs associated with erroneous responses as well as outliers (defined as in Experiment 1, but collapsing design cells over CSI) were excluded from analysis; this eliminated between 0.5 and 2% of RTs in each design cell.[2] All RT analyses reported here were also conducted including only trials where the final recall of digits was perfect, with essentially the same results. I first report RT results on setsize effects, then those concerning object switching costs, and finally turn to the accuracy of digit recall at the end of each trial. A summary of mean RTs × Conditions can be found in Table 1.

Setsize Effects on RTs

Setsize effects were computed as the differences of RTs with setsize 3 and setsize 1, for active sets (aggregating over passive setsize) and for passive sets (aggregating over active setsize). Only nonswitch RTs were used to build these difference variables. Separate variables were formed for each serial position of the series of eight operations in each trial.

The effect of CSI is best reflected in the first reaction of each series, because this is the reaction required immediately after the CSI. Figure 5 shows the active and passive setsize effects of the first reactions over increasing CSIs. Active setsize effects were substantial regardless of CSI, whereas passive setsize effects diminished with increasing CSIs and were statistically indistinguishable from zero at CSIs of 2.5 and 5 s. Separate ANOVAs for active and passive setsize effects with CSI as factor showed no effect of CSI on the active setsize effect ($F < 1$). For passive setsize effects, the linear trend of CSI was significant, $F(1, 23) = 12.14$, $MSE = 138{,}630$. Individual t tests for each CSI level showed that the passive setsize effects were significantly different from zero for the first four CSIs, $t(23) = 4.01$, 3.63, 3.77, and 2.4, respectively, but not for CSIs of 2.5 and 5 s (ts $= 1.51$ and .42, respectively). The active setsize effects were all significantly different from zero (minimum $t = 6.33$). Thus, 2.5 s after the cue the setsizes began to show the same pattern as in Experiment 1: The size of an active set had a substantial effect on RTs, but the size of a passive set had none.

A second analysis followed the trace of setsize effects over the series of eight successive reactions in trials with CSI = 0.1 s. Figure 6 displays the results. Active and passive setsize effects were analyzed separately with ANOVAs using serial position as factor. I computed Helmert contrasts, which compare each factor level with the mean of all following levels (cf. Bock, 1975, p. 244). Thus, the first contrast compares serial position 1 with the mean of positions 2–8, the second contrast compares position 2 with the mean of positions 3–8, and so on. In both analyses, only the first contrast was significant, for active setsize effects, $F(1, 23) = 13.47$, $MSE = 191{,}052$, and for passive setsize effects, $F(1, 23) = 7.54$, $MSE = 249{,}051$. Individual t tests showed that active setsize effects were larger than zero for all serial positions, minimum $t(23) = 2.38$, whereas passive setsize effects were significant only at the first serial position ($t = 4.01$), but not at any later position (maximum $t = 1.79$). Thus, even with a minimum CSI, the same pattern as observed in Experiment 1 was obtained after the very first reaction: RTs were a function of the size of the active but not the passive set.

Object Switch Effects

Switching costs were computed by subtracting RTs without a switch from RTs following an object switch; only trials where the active set was three were included. The mean object switch cost was 231 ms ($SD = 40$ ms), which was reliably different from zero, $F(1, 23) = 33.34$, $MSE = 230{,}695$. An ANOVA with CSI and the setsize of the passive set as factors revealed no effect of CSI ($F = .65$) and no effect of setsize ($F = 2.08$). This result partially replicates Experiment 1: There were substantial object switch costs within the active set, and these switch costs did not depend on the size of the passive set. The effect of an active setsize on switch costs could not be tested in the present design; however, I also observed such an effect in two other experiments not reported here.

Accuracy of Computations

Overall accuracy of the responses to arithmetic operations was 89% ($SD = 1.8$). The same set of analyses as applied to RTs was repeated with response accuracy as the dependent variable to check for speed–accuracy tradeoffs. Setsize effects on the first reaction of each series were not significant when tested for individual CSI levels, for both active and passive setsizes, with one exception (active setsize effect, CSI = 1.0, $t = 2.54$). There was a trend, however, for responses being less accurate with larger setsizes, and this trend was significant when the data were aggregated over CSI levels, $t(23) = 3.58$ for the active setsize effect and 2.37 for the passive setsize effect. These effects, however,

[2] Significantly more switching than no-switching RTs were trimmed. I reran all RT analyses with untrimmed data, with the same results, except that the passive setsize effect at serial position 2 (CSI = 100 ms) became significant, $t(23) = 2.2$, $p = .04$.

Table 1
Reaction Times in ms by Active and Passive Setsize and Switching Condition, Experiment 2

	Active setsize 1				Active setsize 3							
	Passive setsize 1		Passive setsize 3		Passive setsize 1				Passive setsize 3			
	Nonswitch		Nonswitch		Nonswitch		Switch		Nonswitch		Switch	
CSI (in s)	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
						Serial Position 1						
0.1	1,603	410	1,969	629	2,274	674			2,600	922		
0.3	1,542	355	1,781	512	2,175	671			2,481	823		
0.6	1,538	473	1,703	495	2,084	525			2,408	686		
1.0	1,341	356	1,451	373	1,896	471			2,203	742		
2.5	1,352	367	1,423	332	1,895	461			1,986	491		
5.0	1,306	252	1,388	309	2,036	783			2,003	618		
						Means over Serial Positions 2–8						
0.1	1,319	268	1,315	228	1,570	355	1,965	415	1,706	422	1,899	511
0.3	1,368	389	1,350	328	1,656	453	1,880	555	1,697	434	1,959	466
0.6	1,356	314	1,356	261	1,649	475	1,900	489	1,700	404	1,878	413
1.0	1,292	338	1,331	338	1,623	418	1,798	435	1,707	785	1,859	489
2.5	1,285	279	1,328	318	1,526	346	1,824	425	1,666	433	1,835	417
5.0	1,245	307	1,284	308	1,608	507	1,810	581	1,531	337	1,809	419

Note. Reaction times for Serial Position 1 are tabulated under "Nonswitch," although with setsizes of 3 a new digit must be selected, different from nonswitch operations later in the sequence. CSI = cue–stimulus interval.

were very small (1.4 percentage point for active and 1.0 percentage point for passive setsize). The effect of CSI was not significant for both active and passive setsize effects. When the setsize effects were analyzed over serial position for the CSI = 0.1 condition, no significant effects of position emerged. Overall, there was a significant effect of object switching, $F(1, 23) = 7.26$, $MSE = 52.4$, but it was not modulated by either CSI or passive setsize. Switching reactions were one percentage point less accurate than nonswitching responses. To sum up, the error data were less sensitive to the experimental manipulations than the RTs, but where an effect was observed, it was in line with the RT analyses.

Accuracy and Latency of Final Recall

Proportion correct scores for final recall of the digits were submitted to an ANOVA with active setsize (1 vs. 3), passive setsize (1 vs. 3), and recalled set (active vs. passive) as factors. Data were aggregated over all CSI conditions, because CSI showed no main effect or interaction with other factors. All three factors yielded significant main effects, $F(1, 23) = 12.53$, $MSE = 26.63$, for active setsize, $F(1, 23) = 8.59$, $MSE = 32.05$, for passive setsize, and $F(1, 23) = 29.6$, $MSE = 84.22$, for recalled set. Active and passive setsize interacted, $F(1, 23) = 18.71$, $MSE = 16.51$, and passive setsize interacted with the recalled set, $F(1, 23) = 6.05$, $MSE = 25.94$. The three-way interaction also

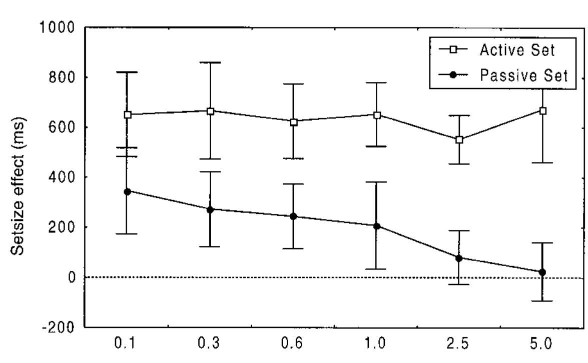

Figure 5. Experiment 2: Setsize effects (reaction time in milliseconds of setsize 3 – reaction time of setsize 1) for the first reaction after the cue for increasing cue–stimulus intervals (CSIs). Error bars represent two standard errors.

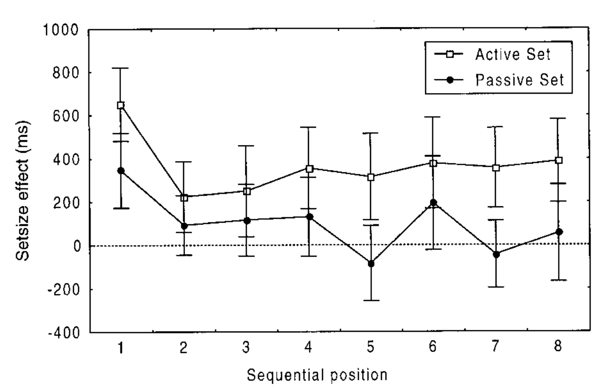

Figure 6. Experiment 2: Setsize effects (in milliseconds) for eight successive operations. Cue–stimulus interval = 0.1 s. Error bars represent two standard errors.

became significant, $F(1, 23) = 10.98$, $MSE = 12.83$. Figure 7 displays the overall picture. To summarize, digits from the active set were recalled much better than passive digits, presumably because they were continuously reused for the arithmetic tasks. Recall of the active digits was close to ceiling, leaving little room for setsize effects. Only for the passive digits were there substantial effects of both active and passive setsize, which interacted overadditively, such that recall was particularly reduced when both sets contained three items.

Latencies of final recall were also analyzed by an ANOVA with active setsize, passive setsize, and recalled set (active vs. passive) as factors (again, data were collapsed over CSI, which had no reliable effect). As in Experiment 1, recall of the passive set took longer than recall of the active set, $F(1, 23) = 10.28$, $MSE = 17{,}121$; the difference was 61 ms. In addition, there were significant effects of both setsizes, $F(1, 23) = 41.36$, $MSE = 12{,}972$, and $F(1, 23) = 21.9$, $MSE = 15{,}286$, respectively; the underadditive interaction just fell short of significance, $F(1, 23) = 3.86$, $MSE = 15{,}508$, $p = .06$.

Discussion

The present data replicate and extend the two main results from Experiment 1 with a modified task. First, RTs for arithmetic operations were a function of active but not passive setsize. This pattern of setsize effects was found to emerge only about 2 s after a cue indicated which set was the active and which the passive one. Second, object switch costs were again obtained within the active set. As in Experiment 1, these costs were independent of the size of the passive set. Object switch costs can be interpreted as the time it takes to shift the focus of attention from one item to another within the region of direct access. With the modified task used in Experiment 2, the differences between the active and the passive set can be attributed unambiguously to the fact that items from the active set must be selectively accessed for the arithmetic computations, whereas the items from the passive set could be held in the background until the final recall phase.

The manipulation of the CSI allowed me to trace how the active and the passive set are segregated and organized in working memory over time. With short CSIs, both setsizes had measurable effects on the RTs (although the passive setsize effect was noticeably smaller even with the shortest CSI). With increasing CSI, the passive setsize effect gradually dropped to zero. Because participants did not know in advance which row of digits they would have to access for the arithmetic task, they presumably encoded both rows into the region of direct access. With the appearance of the cue, they started to remove the passive set from the direct access region and kept it in the activated part of long-term memory. This process apparently took about 2 s.

The development of the setsize effects over the course of eight successive reactions supports this interpretation. Even with the shortest CSI, passive setsize effects were observed only for the first reaction in a series. The first reaction took a mean of 2.1 s, such that the stimulus triggering the second reaction followed the cue with a mean delay of 2.3 s (taking into account the CSI of 0.1 s and a response stimulus interval of 0.1 s). The absence of a passive setsize effect for the second reaction again suggests that after about 2 s the passive set no longer drew on the limited capacity of the direct access region. Furthermore, this observation indicates that the removal of the passive set from the direct access region is not impeded by the simultaneous execution of an arithmetic operation. Thus, the passive set either drops out passively from the region of direct access, or its active removal can proceed in parallel with other cognitive processes. I think it is unlikely that elaborated chunking strategies like those reported by participants in Experiment 1 can be used simultaneously with the speeded execution of an arithmetic computation. Thus, chunking of a passive set of three items into a single mental object is not a sufficient explanation for the gradual dropout of the passive setsize effect during the first 2 s following a cue.

One unexpected finding was that the active setsize effect for the first reaction in a series was much larger than that for later reactions. The absolute RTs also were larger on the first reaction (see Table 1). I can only offer a post hoc explanation for this observation: During the first reaction, both sets are presumably still in the region of direct access, thereby competing for the same limited capacity. This could result in an overadditive effect of setsize on RTs, such that the active setsize effect becomes larger in the presence of a second set in the direct access region. A similar overadditive effect of two active sets on recall accuracy and (marginally significant) on RTs was observed in Experiment 1 (condition AA). A second factor contributing to the larger setsize effect on the first reaction could be that I compared the first reaction to the nonswitch reactions in the remaining sequence. Although the first reaction does not follow an object switch, it also is not perfectly comparable to a nonswitch operation, because for the first operation a new object must be selected into the focus of attention, in particular when the active setsize is 3.

The pattern of accuracies at final recall was more complicated in the present experiment than in the comparable condition (AP) of Experiment 1. In Experiment 2, the active set was recalled better than the passive set. Such a difference was not observed in Experiment 1, presumably because the advantage of the active set through its continuous retrieval was offset by a disadvantage through its continuous updating. Another new finding in Experiment 2 was the effect of active setsize on the recall of passive digits and its interaction with passive setsize. This indicates that the recall of items from the activated part of long-term memory is not as independent of the capacity limits of the direct access region as was suggested by Experiment 1.

At the moment it is not clear why the recall data from Experiment 1 seem to indicate a high degree of independence between

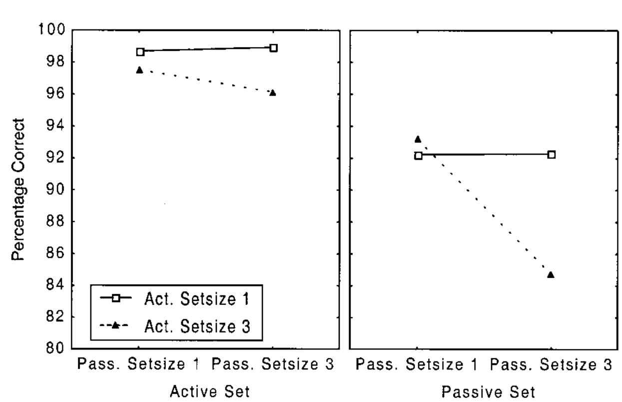

Figure 7. Experiment 2: Accuracy of the final recall of digits by recalled set (active vs. passive), active (act.) setsize, and passive (pass.) setsize.

the performance limits of the two working memory regions, whereas Experiment 2 suggests an interaction. One plausible reason for this is that in Experiment 1 participants encoded the two sets one after another, first forming retrieval structures in long-term memory for the passive set and then bringing the active set into the direct access region. In Experiment 2 they could not do this because they did not know which set would be passive and which active, so they had to encode both sets into the direct access region initially. This could generate mutual overwriting of representations (as a function of both setsizes), leading to errors when elements must be recalled later. Another reason for the interaction observed in Experiment 2 could be that participants (at least sometimes) brought the complete passive set back into the region of direct access for the final recall phase. This is supported by the fact that the difference in recall latencies between active and passive set was much smaller here (61 ms) than in Experiment 1 (376 ms), suggesting that participants had direct access to the passive set on part of the trials. The two explanations are of course compatible with each other: If the two sets were encoded together, it should be more likely that they are brought back into the direct access region together.

General Discussion

The results from the two experiments reported here demonstrate a highly organized structure of information in working memory. Briefly presented contents that are not needed for ongoing processes can be retained in the background for later recall without interfering with the "working" part of working memory. This is consistent with previous evidence (Klapp et al., 1983; Oberauer et al., 2001) showing that under certain conditions the "storage" and the "processing" function of working memory are independent.

One of these conditions is that the memory contents are passive, that is, not involved in the concurrent processing task. Another condition is that participants have sufficient time to separate active from passive memory contents. Experiment 2 suggests that participants require about 2 s to organize the memory material in a way that the passive set does not interfere with a concurrent processing task. This estimate is consistent with the finding of Klapp et al. (1983), who showed that a memory load did not interfere with a choice reaction time (CRT) task when 2 s passed from the presentation of the memory set to the first CRT stimulus. The analysis of successive reaction times (see Figure 6) showed that this time need not be an unfilled delay, suggesting that the organization of memory contents is not a process that requires exclusive attention.

Results with a modified Sternberg recognition task (Oberauer, 2001, Exp. 1) suggest that the setsize effect of a no-longer relevant memory list on recognition latencies can be reduced to zero in less than 1 s. In that experiment, however, the memory list could be forgotten after it was declared irrelevant, whereas here the passive memory contents had to be remembered for the final recall. This could explain the faster time course observed in Oberauer (2001) compared to the present Experiment 2.

Working memory contents that must be held available for an ongoing processing task are kept in a functionally different state than those remembered in the background. Only the former have a substantial effect on the speed of the processing operations. This suggests that there is a capacity limit for holding items in a state of direct accessibility for cognitive operations. When more items are held in the selection set (i.e., the set of candidates for access), the selection of the required item takes more time, thus slowing the completion of the cognitive operation applied to it.

Within the selection set, the one item selected for processing at any moment has a special status. When this item is selected again for the next processing step, the operation is executed several hundred milliseconds faster than when a new item must be drawn from the selection set.

These three states of information in working memory are captured by the concentric model outlined in the introduction. The model specifies three regions in which memory contents can be held: the activated part of long-term memory, the region of direct access, and the focus of attention. I do not regard the three regions of this model as structurally (or even anatomically) separate subsystems, such that information must be transferred from one place to another when it is "moved" into another region. Rather I think of the three regions as functionally different states of representations in working memory. They differ with respect to how their contents are related to the processes executed in working memory. Memory elements in the focus of attention are already selected for whatever cognitive operation is set up in the system to be executed next. Elements in the region of direct access form the selection set; when a new item must be retrieved from working memory as input to a process, it is selected from this set. Memory contents in the activated part of long-term memory are held available in the background. They can be retrieved only indirectly through associations with items in the more central regions. Activated representations in long-term memory can influence ongoing processes indirectly. For example, when a probe in a Sternberg task matches an item held in the activated part of long-term memory, RTs are slowed (Oberauer, 2001). Presumably the activated information in long-term memory can also prime or bias the processes executed on the element in the focus.

Although the concentric model proposed here is not committed to structural distinctions, it is not incompatible with working memory models postulating separate subsystems. The best known model of this kind is the one developed by Baddeley (1986), consisting of a central executive and two content specific slave systems, the phonological loop and the visuo-spatial sketch pad. Baddeley's model could accommodate the present data by assuming that the active sets are held in the central executive, whereas the passive sets are held in the phonological loop. Baddeley and Hitch (1974) already suggested that a small number of digits can be held in the phonological loop without impairing a concurrent processing task. Their dual-task experiments supporting this idea combined a processing task with a concurrent memory load that was irrelevant for the former, thus constituting what I called a passive set. When Baddeley's model is applied to the present data in the way sketched above, this would imply that the central executive has a storage function of its own, contrary to Baddeley (1993, 2000). In addition, one would have to postulate a focus of attention within the central executive.

Although the present pattern of findings can be accommodated within alternative theoretical frameworks, it is not predicted by them. The concentric model of working memory inspired by the work of Cowan (1995, 1999), Garavan (1998), and Ericsson and Kintsch (1995), on the other hand, served to predict the main results of the experiments reported here. This model specifies more precisely than other working memory models the relationship between storage and processing. The two functions can work independently as long as the processes do not require access to the memory contents. The capacity limit of working memory thus is not a general resource that must be shared between information retention and manipulation; rather, the capacity limit arises from the problem to hold several distinct elements available for selective access.

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