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Control of the Contents of Working Memory—A Comparison of Two Paradigms and Two Age Groups

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Two experiments investigated whether young and old adults can temporarily remove information from a capacity-limited central component of working memory (WM) into another component, the activated part of long-term memory (LTM). Experiment 1 used a modified Sternberg recognition task (S. Sternberg, 1969); Experiment 2 used an arithmetic memory-updating task. In both paradigms, participants memorized 2 lists, one of which was cued as temporarily irrelevant. Removal of the irrelevant list from capacity-limited WM was indexed by the disappearance of list-length effects of that list on latencies for concurrent processing tasks. Young adults could outsource the irrelevant list within 2–3 s and retrieve it back into the central part of WM later. Old adults showed the same flexibility in the arithmetic updating task but seemed somewhat less able or inclined to temporarily move information into the activated part of LTM in the modified Sternberg task.

Keywords: working memory, capacity, list-length effect, aging

Working memory is a capacity-limited system that provides access to a small set of representations in the service of current cognitive processes. Because cognition usually proceeds quickly, it is important that the contents of working memory be updated efficiently. This involves removing contents that are no longer relevant, lest they occupy capacity that cannot be used for new, relevant information. One influential theory of age-related declines in cognitive abilities (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999) postulates that old adults have difficulties with complex tasks because they cannot efficiently inhibit contents of working memory that are no longer relevant, and thereby experience more interference with relevant material. Others have argued that children with reading difficulties (De Beni & Palladino, 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998) or arithmetic deficits (Passolunghi & Siegel, 2001) have a reduced ability to remove irrelevant items from working memory. In the work presented here, I investigated the control of working memory contents in young adults and old adults (between 65 and 80 years) using two paradigms—the modified Sternberg task and an arithmetic memory-access task—within a common experimental design.

The Modified Sternberg Paradigm

In a previous study (Oberauer, 2001), I obtained mixed support for the hypothesis that old adults have a deficit in the control of working memory contents. Young and old adults worked on a modified version of the Sternberg (1969) recognition task. In each trial they memorized two short lists of words, distinguished by their spatial position on the screen as well as their color. Each list could be one or three words long. After encoding of the list, a cue noted which of the two lists would be relevant, indicating that the other list could be forgotten and removed from working memory. After a variable cue-stimulus interval (CSI), a probe appeared that participants were to compare with the relevant list. I measured two indicators of how successfully the irrelevant list contents were removed from working memory. One was the list-length effect of the irrelevant list on reaction times (RTs). As long as the irrelevant list was maintained in working memory and absorbed limited capacity, it should slow down comparison processes, more so if the list was longer. The second indicator was the RT cost for rejecting an intrusion probe, that is, a probe from the irrelevant list, compared with the time to reject a new probe not contained in either list. Intrusion costs reflected the strength of familiarity arising from residual activation of irrelevant-list contents.

The two indicators showed markedly different behavior. The list-length effect of the irrelevant list decreased to a nonsignificant level within 1 s after the cue for both young and old adults. The intrusion costs, in contrast, remained substantial even for the longest CSI tested, which was 5 s, and they were disproportionately increased for old adults (increased intrusion costs in old adults has also been observed by Zacks, Radvansky, & Hasher, 1996, with a similar paradigm). I interpreted this pattern in the context of a model of working memory based on a proposal from Cowan (1995, 1999) in combination with a dual-process theory of recognition (Mandler, 1980; Yonelinas, 2002). According to Cowan, working memory consists of two components, the activated part of long-term memory (LTM), consisting of all representations currently activated above baseline, and the focus of attention, which has limited capacity and therefore can hold only a small subset of the activated representations—between one and

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four independent elements (Cowan, 2001). Dual-process models of recognition distinguish two sources of information affecting a recognition decision. One is a graded familiarity signal that reflects the degree to which the probe matches recently used representations. The other source is recollection, an explicit memory of having or not having experienced the probe in the relevant context (e.g., a memory of having seen the given word in the last studied list—or an explicit memory of the list confirming that it does not contain the probe).

I assume that in short-term recognition tasks such as the modified Sternberg task, familiarity arises from the activation of representations in the activated part of LTM, whereas recollection arises from a comparison of the probe with a representation of the relevant list held in the central, capacity-limited part of working memory. The data obtained with the modified Sternberg task, then, imply that both young and old adults efficiently removed the irrelevant list from the capacity-limited part of working memory (i.e., Cowan's focus of attention), thereby eliminating the effect of its list length on the speed of comparison. The irrelevant list, however, remained active in LTM, thereby generating a misleading familiarity signal that produced intrusion costs. Old adults showed increased intrusion costs either because they were less efficient than young adults in inhibiting the activation of no-longer relevant contents or because their recollection processes were slower, so that it took longer for them to overcome the tendency to accept intrusion probes. Recent findings with a broader set of recognition paradigms favor the latter interpretation (Oberauer, in press; see also Hedden & Park, 2003).

The Arithmetic Memory-Access Paradigm

Research with another experimental paradigm also suggested that people are very efficient in removing no-longer relevant contents from working memory (Oberauer, 2002, Experiment 2). Young adults were asked to memorize two lists of digits displayed in two rows of frames on the screen. Each list could consist of one or three digits. After encoding of the two lists, one of the lists was marked as the active list by turning its frames red. A sequence of nine arithmetic operations (e.g., +3) was then displayed, each in one of the red frames, and participants had to apply the operation to the content of the respective frame and type the result as fast as possible. In the meantime, the digits of the other, passive list also had to be remembered, but they were never used as input for computations. At the end of the operation sequence, both lists had to be recalled. The critical finding regarded the list-length effects on latencies of arithmetic operations. If the first operation was displayed immediately after the cue that indicated which list would be the active one, latencies depended on the length of both the active and the passive list. With increasing CSI separating the cue and the first operation, the effect of the length of the passive list gradually declined and was virtually absent at a CSI of 2.5 s or longer. The length of the active list, in contrast, affected computation latencies regardless of CSI. My interpretation of these results (Oberauer, 2002) again utilized the framework proposed by Cowan (1995, 1999): The passive list was removed from the capacity-limited component of working memory within 2–3 s, whereas the active list had to be maintained in this component and therefore continued to place a load on capacity, thereby affecting processing speed.

The application of Cowan's (1995, 1999) model to the results from the memory-access paradigm required two extensions to the model. First, I proposed to differentiate the focus of attention into two components. One component is that which I referred to as the *direct-access region*. This is the capacity-limited part of working memory, which has the function to provide immediate access to a small number of separate representational elements. Because the active list had to be accessed continuously during the processing task, it had to be maintained in the direct-access region. The other component is the *focus of attention*, which selects one element from the contents of the direct-access region as the object of the next cognitive operation. This narrow concept of a focus of attention was needed to explain that people could select one digit out of an active list of three for the arithmetic computations. The existence of a narrow focus in working memory is supported by object-switch costs: When a specific element in working memory has to be accessed for processing, RTs are longer if this is an object other than the one accessed for the previous processing operation than when the same object is accessed again (cf. Garavan, 1998; Oberauer, 2003; Voigt & Hagendorf, 2002). The observation that object-switch costs were observed for switches between digits within the active list (Oberauer, 2002) demands a distinction between the direct-access region and the focus of attention. Cowan's original model, which lacks this distinction, leads to difficulties in explaining these data: His focus of attention can either be assumed to hold the whole active list or to zoom in on the one digit selected for access but not to do both at the same time.

A second extension to Cowan's model pertained to the role of the activated part of LTM. In the experiments with the modified Sternberg task (Oberauer, 2001), the evidence for remaining memory traces of the irrelevant list could be interpreted as residual activation of individual words in LTM. In the memory-access task (Oberauer, 2002), however, the passive list has to be recalled at the end of the trial, which involves recalling which digit was in which frame (at least for three-digit lists). If the activated part of LTM is to maintain this information, it must be able to encode new links between digits and their spatial positions, or links between successive digits (i.e., forming a chunk). Therefore, I assume that new associations can be formed in the activated part of LTM within 2–3 s with sufficient strength to support recall of three digits in the correct frame with reasonable accuracy several seconds later. New associations probably can be built to encode elements of the active list as well, but the active list cannot be represented only as a chunk, because the task requires access to individual elements in that list. Therefore, individual elements of the active list must be retained in the direct-access region. Figure 1 presents an illustration of the structure of the working memory model, including the extensions discussed above.

Purpose of the New Experiments

To summarize, previous experiments with two paradigms provide converging evidence for an efficient mechanism to control the contents of working memory: Within about 2 s, people can remove a subset of elements encoded into working memory from the central, capacity-limited component of the system (i.e., the direct-access region) while maintaining it in the activated part of LTM. The two experiments differ in several regards, however. The theoretically most important difference is that in the experiments

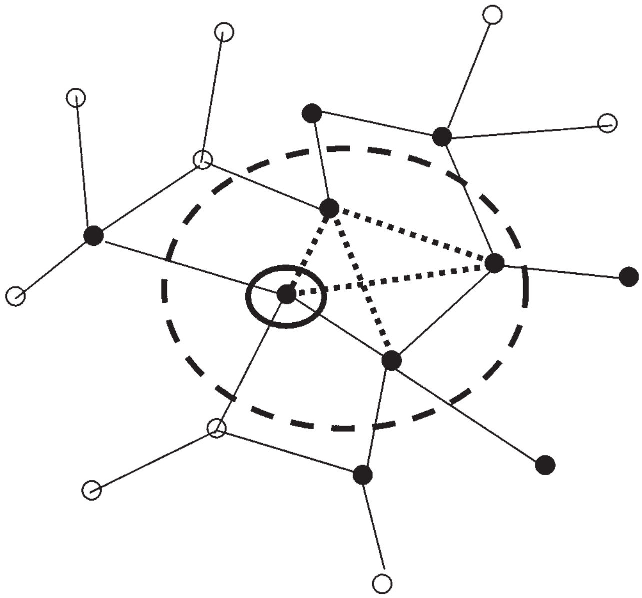


Figure 1. The embedded-component model of working memory (Oberauer, 2002). Nodes connected by continuous lines represent the associative network of LTM; the subset of black nodes stands for the activated part of LTM. The large oval in broken line delineates the direct-access region, which has a limited capacity that permits holding a small number of activated representational elements at any time. The small circle in continuous line represents the focus of attention that selects one element at a time as the object of the next cognitive operation. From "Access to Information in Working Memory: Exploring the Focus of Attention," by K. Oberauer, 2002, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28,* p. 412. Copyright 2002 by the American Psychological Association. Adapted with permission.

with the modified Sternberg task, the cue rendered one of the two lists irrelevant, so that there was no need to maintain it in the activated part of LTM, whereas in the memory-access task participants had to maintain the passive list for later recall. The purpose of the present work is to compare the two experimental paradigms directly within a common task framework. Participants encoded two lists, after which they performed two successive processing tasks, each one requiring access to one of the lists. In the modified Sternberg paradigm, the processing task involved comparing a probe with one of the lists. In the memory-access paradigm, the processing task consisted of applying an arithmetic operation to a digit from one of the lists. Preceding each processing task, a cue indicated which list would be relevant, or active, for this task. The cue for the second processing task could indicate the same list as for the first task or the other list. Therefore, during the first processing task, the list not selected was irrelevant temporarily, but not necessarily permanently, because there was a 50% chance that it would be the relevant list for the second processing task. Only during the second processing task, could participants be certain that the list then indicated as irrelevant would never become relevant again and therefore could be forgotten; in both paradigms, no final recall of the two lists was required. Figure 2 gives a schematic overview of the events in one trial of each paradigm.

With this task framework, I addressed the following questions: First, can people remove a list from the central part of working memory when it is irrelevant for a processing task temporarily but not permanently? The previous experiment with the memory-access task (Oberauer, 2002) suggests that they can, but is this true also for the modified Sternberg paradigm? Moreover, will a temporarily irrelevant list be removed from the capacity-limited part of working memory even for a much shorter period of time? It might not be worth the effort of doing so for the time it takes to complete a single operation as opposed to a sequence of nine operations. The critical data pattern showing removal of a list from the direct-access region is a decline of the list-length effect over CSI such that it vanishes at a long CSI when removal is complete.

Once a temporarily irrelevant list has been removed from the direct-access region, how efficiently can it be retrieved again from the activated part of LTM when it becomes relevant in the next step? Does the time for switching between the two lists depend on the length of the list to be retrieved back into the direct-access region, or on the length of the previously relevant, but now irrelevant, list, or both? Conway and Engle (1994) measured RTs for comparisons of probes with lists learned at the beginning of the experiment. Every probe was accompanied by a digit cue by which the appropriate list could be retrieved from LTM. When the cue preceded the probe by 1 s, participants could retrieve the list into working memory before the probe appeared. This led to shorter RTs than a condition where the cue appeared simultaneously with the probe. This gain was additive with list length, suggesting that retrieval of a list from LTM is independent of that list's length. Apparently the list was retrieved as a whole, not item by item. A natural interpretation of this finding is that a short list is encoded into LTM as a single chunk (Miller, 1956). This reasoning can be applied to the experimental paradigms used here: If the working memory system uses the activated part of LTM as a backup mechanism for temporary maintenance of information currently not needed, then later accessing this information should involve retrieval from LTM. The time for this retrieval, as reflected in list switch costs in RTs of the second processing task, should then be independent of the list that becomes relevant in the second task.

The third question regards age differences in the control of working memory contents. The previous experiment with the modified Sternberg task (Oberauer, 2001) found no evidence for age differences in the efficiency of removing an irrelevant list from the capacity-limited part of working memory. This is a null result, however, and therefore needs to be replicated before we can conclude with any confidence that old adults are indeed unimpaired in this control process. Such a replication is particularly important because recent follow-up research (Oberauer, in press) found that the decline of irrelevant list-length effects in the modified Sternberg task has insufficient reliability as an individual-difference variable, and this decreases the likelihood of detecting any correlations of this variable with other variables, including age. Moreover, it is desirable to investigate whether the finding of age invariance can be generalized (a) to a situation where the list to be removed from the direct-access region is irrelevant only temporarily, but not permanently, (b) to a different experimental paradigm, the memory-access task, and (c) to the complementary control process of retrieving a list back into the direct-access region once it has been removed from it (as reflected by list-switch costs).

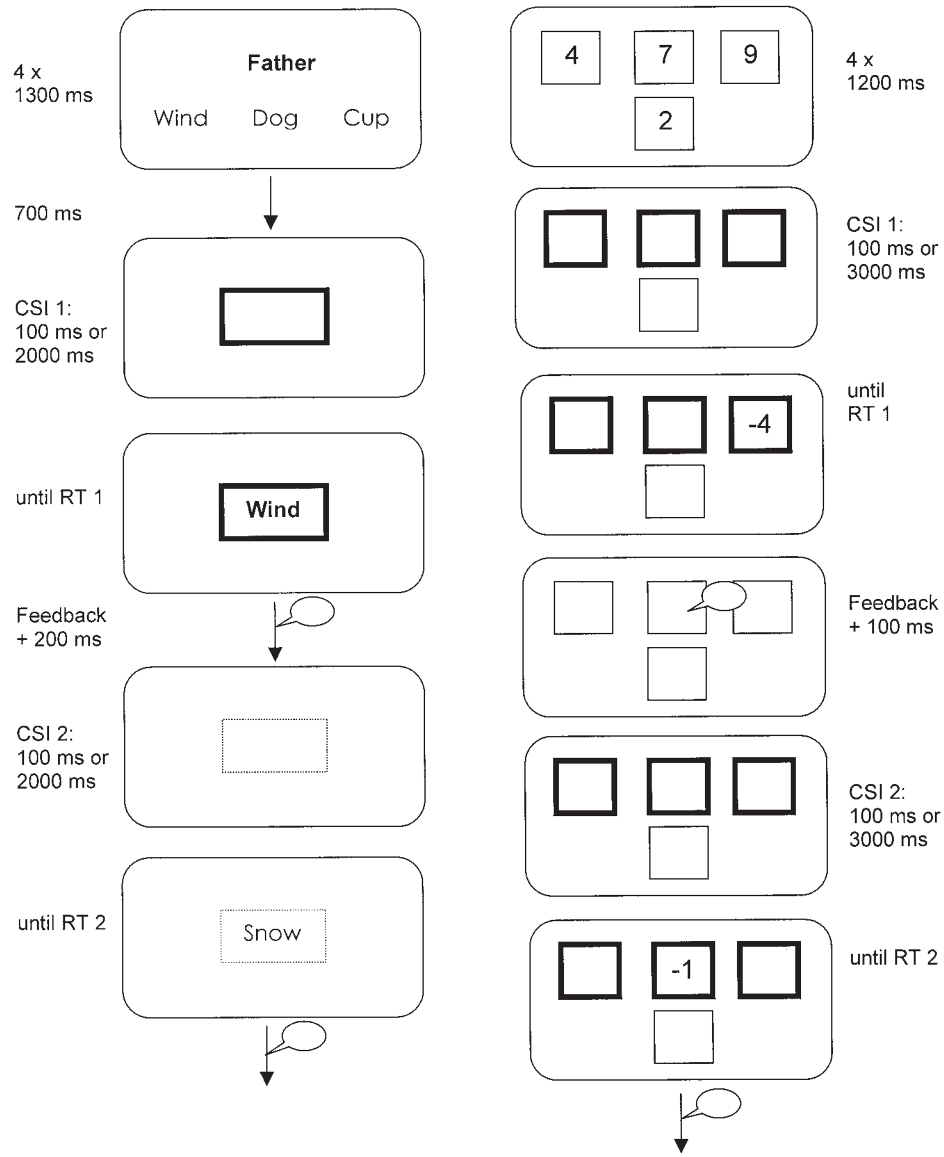


Figure 2. Sequence of events in the modified Sternberg task, as used in Experiment 1 (left side), and in the arithmetic memory-access task, as used in Experiment 2 (right side). Successive screen displays are presented from top to bottom, accompanied by their durations. Boldface font and boldface lines represent red displays, thin font and broken lines represent blue displays. The example trial for the modified Sternberg task is one involving a list switch, with a relevant-list length of one and an irrelevant-list length of three on the first probe, and the reversed combination on the second probe. The first probe is an intrusion probe, and the second probe is a new probe. The example trial for the memory-access task involves no list switch, the active-list length is three, the passive-list length is one, and there is an object switch from the first to the second operation. CSI = cue-stimulus interval; RT = reaction time.

Experiment 1

The first experiment tested young and old adults on the modified Sternberg task with two successive probes. Each probe was preceded by a cue indicating which list would be relevant for that probe. The probe followed its cue after one of two CSIs, 100 ms or 2,000 ms; CSI was varied independently for the first and the second probe. The long CSI was set to a value larger than the 1,000 ms at which young and old adults in the previous study (Oberauer, 2001) first showed near-zero list-length effects for the irrelevant list. Therefore, a CSI of 2,000 ms was considered sufficient to remove the irrelevant list from the central part of working memory.

Method

Participants

Participants were 40 young adults (mean age = 19.1 years, *SD* = 3.3; 30 female, 10 male) and 40 old adults (mean age = 69.3 years, *SD* = 4.5; 24

female, 16 male). Old adults had fewer years of formal education than young adults (9.8 years vs. 11.5 years), $t(66.4) = 5.66$. Nonetheless, they outperformed young adults on a vocabulary test (MWT-A [Mehrfach–Wortschatz–Test, Version A, translated as Multiple–Choice Vocabulary Test, Version A]; Lehrl, Merz, Burckhard, & Fischer, 1991), with a mean score of 32.7 ($SD = 2.4$), as compared with 30.4 ($SD = 1.6$) for the young group, $t(67.8) = -5.0$. In contrast, young adults scored higher on a standardized test of processing speed, the Digit Symbol test (young adults, $M = 62.4$, $SD = 7.7$; old adults, $M = 48.8$, $SD = 7.6$), $t(78) = 7.9$. This corresponds to the typical pattern of age-group comparisons.

Materials and Procedure

Each trial of the modified Sternberg task began with the presentation of two lists of words, one above the other, centered on the computer screen. The top list was presented in red and the bottom list, in blue on a black background. Length of the two lists was varied independently; each list consisted of one or three words. On each trial, words for the two lists were drawn at random without replacement from a pool of 400 common German nouns with one or two syllables. The lists were presented simultaneously for 1.3 s multiplied by the total number of words.

Seven hundred ms after the memory lists disappeared, a frame was displayed in the center of the screen. The color of the frame served as a cue to indicate which list is relevant for the upcoming probe; in half of the trials the frame was red and in the other half it was blue, determined at random. The probe word was displayed within the frame in the same color after a CSI of 100 or 2,000 ms, depending on the CSI condition. Participants were asked to decide whether the probe was in the relevant list as quickly and accurately as possible by pressing the right arrow key for "yes" and the left arrow key for "no." The screen was cleared immediately upon the reaction, and a feedback tone was displayed: Correct responses were followed by a 700 Hz tone for 50 ms and wrong responses, by a 300 Hz tone for 100 ms. A second cue appeared 200 ms after the end of the feedback tone. In half of the trials, the cue was a frame of the same color as that for the first probe, thus requiring no switch of the relevant list, whereas in the other half, the cue required a switch to the other, previously irrelevant list. Following an interval determined by the CSI condition, the second probe appeared in the frame, and participants were required to decide whether it was in the currently relevant list.

For both comparisons there were three kinds of probes. Half of them were positive probes, that is, words from the relevant list that were to be accepted. The other half consisted of probes that had to be rejected. The to-be-rejected probes consisted of 25% intrusion probes, that is, words from the currently irrelevant list and 25% new probes not contained in both lists. New probes were not used in any previous memory list in the whole block. Positive and intrusion probes were selected at random from the required lists. Negative words were drawn at random from the not yet used part of the word pool.

The experiment consisted of four blocks with 64 trials each. The two CSI factors were varied between blocks such that each block implemented one combination of CSI 1 (preceding the first probe: 100 vs. 2,000 ms) and CSI 2 (preceding the second probe: 100 vs. 2,000 ms); the order of blocks was counterbalanced across participants. All other factors were randomized within blocks. The 64 trials of each block were generated by crossing length of the red list (1 vs. 3), length of the blue list (1 vs. 3), switch of relevant list from first to second probe (switch vs. no switch), probe type of the first probe (positive, new, and intrusion in a 2:1:1 ratio), and color of the first relevant list (red or blue). The probe type of the second probe was determined at random, with the constraint that there were 32 positive probes and 16 each of new and intrusion probes in each block. Within each block, each participant received a new random order of the 64 trials with a new random selection of words implementing it. Each test block was preceded by a practice block with the same CSI combination, consisting of 12 trials comprising a random combination of the within-block factors.

Because of the random selection of probe types and probes, the two probes in a trial were sometimes the same word. This happened most often in trials in which both lists had length one (31% of no-switch trials and 21% of switch trials) and least often in trials with two long lists (10% regardless of switch condition). Constraining trial construction to avoid probe repetitions was not possible because that would have destroyed the independence of the two successive probes (e.g., it was not possible to have two successive positive probes in trials without list switch and relevant-list length of one). In a previous experiment, I tried to avoid the problem by using list lengths of two and four, but this led to a considerable increase of errors even in a group of young adults, and therefore I abandoned that route and decided that the best option was to tolerate potential distortions due to probe repetitions on a number of trials. All analyses reported include trials with repeated probes, but the same analyses were run with those trials excluded and led to the same conclusions except where indicated.

Results

RTs smaller than 200 ms as well as RTs exceeding an individual's mean by three within-subject standard deviations, computed separately for the first and the second probe within each block, were regarded as outliers and excluded from analysis. RTs associated with erroneous responses were also excluded. The remaining RTs were logarithmically transformed for statistical analysis to move into a proportional measurement space. This was necessary to test whether Age × Condition interactions deviate from what would be expected from proportional slowing alone. Old adults are known to be slower than young adults overall, and the general age-related slowing effect can be described by a proportional increase of old RTs relative to young RTs in the same conditions (e.g., Cerella, 1985). General proportional slowing alone implies interactions between age and condition on raw RTs, such that the age difference is larger in the slower condition. Proportional slowing, however, leads to additive effects on log-transformed RTs. Therefore, an Age × Condition interaction on log transformation serves to reject at least a very simple version of the "dull hypothesis" (Perfect & Maylor, 2000) that all age-related effects can be reduced to a general proportional slowing factor. If old adults are disproportionally impaired in one condition relative to the other, an Age × Condition interaction should be obtained with log-transformed RTs as well as on untransformed RTs.

I first report results on the list-length effect of the irrelevant list to investigate whether young and old adults removed the irrelevant list from the capacity-limited, central part of working memory. This is followed by an analysis of list-switch costs, which reflect the time to retrieve a list back into the direct-access region. Finally, I present data on age differences in intrusion costs. Effect sizes are given as partial η^2 (denoted as η_p^2), which reflects the proportion of the effect + error variance that is attributable to the effect; p values smaller than .001 are not explicitly reported.

List-Length Effects of the Irrelevant List

RTs of young and old adults, broken down by probe (first vs. second), list length, the preceding CSI, and list switch are summarized in Table 1. As can be seen in the table, list-length effects of the relevant list were substantial throughout. These effects are unsurprising and will not be analyzed in detail; of theoretical interest are the list-length effects of the irrelevant list. Figure 3 shows these effects, computed as differences in mean RT between

Table 1
Mean Reaction Times (in Milliseconds) in Experiment 1 by Probe, Preceding Cue-Stimulus Interval (CSI), List Lengths, List Switch, and Age Group

Condition	List length (relevant/irrelevant) 1/1	1/3	3/1	3/3
Young				
Probe 1, CSI 1 = 100	799 (186)	842 (171)	907 (191)	969 (189)
Probe 1, CSI 1 = 2,000	596 (144)	615 (148)	794 (180)	813 (161)
Probe 2, no switch, CSI 2 = 100	708 (127)	735 (135)	784 (143)	855 (173)
Probe 2, no switch, CSI 2 = 2,000	552 (152)	545 (159)	711 (166)	735 (165)
Probe 2, switch, CSI 2 = 100	751 (151)	899 (199)	872 (159)	1,040 (218)
Probe 2, switch, CSI 2 = 2,000	559 (151)	577 (163)	741 (156)	783 (183)
Old				
Probe 1, CSI 1 = 100	1,306 (249)	1,328 (303)	1,424 (307)	1,536 (323)
Probe 1, CSI 1 = 2,000	1,029 (240)	1,037 (261)	1,250 (267)	1,309 (271)
Probe 2, no switch, CSI 2 = 100	1,244 (242)	1,301 (356)	1,351 (352)	1,501 (415)
Probe 2, no switch, CSI 2 = 2,000	1,065 (365)	1,094 (436)	1,218 (362)	1,279 (391)
Probe 2, switch, CSI 2 = 100	1,343 (264)	1,557 (311)	1,514 (341)	1,731 (375)
Probe 2, switch, CSI 2 = 2,000	1,053 (329)	1,088 (380)	1,259 (368)	1,338 (428)

Note. CSI 1 = cue-stimulus interval preceding the first probe; CSI 2 = cue-stimulus interval preceding the second probe.
CSIs are expressed in milliseconds.
Standard deviations are presented within parentheses.

trials with long minus trials with short irrelevant lists. I computed equivalent list-length effects of the irrelevant list from log-transformed RTs as dependent variables for the statistical analyses. Irrelevant-list length effects on the first probe were submitted to an analysis of variance (ANOVA) with CSI 1 and age as factors. The main effect of age was not significant ($F = 1.32$). There was a main effect of CSI 1, $F(1, 78) = 5.62$, $\eta_p^2 = .067$, $p = .02$, but the interaction of age and CSI was not significant ($F < 1$). Separate analyses of the CSI 1 effect for the two age groups showed that the irrelevant-list-length effect declined over CSI 1 for the young, $F(1, 39) = 8.23$, $\eta_p^2 = .174$, $p = .007$, but not for the old ($F < 1$) participants.[1]

A second ANOVA investigated irrelevant-list-length effects of the second probe, including age, CSI 1, CSI 2, and switching as variables. Again, there was no main effect of age ($F < 1$). As expected, list-length effects declined with CSI 2, $F(1, 77) = 65.19$, $\eta_p^2 = .46$. This occurred with both age groups; the CSI 2 × Age interaction was not significant ($F = 1.13$). Irrelevant-list length effects were larger following a list switch than following a list repetition, $F(1, 77) = 36.30$, $\eta_p^2 = .32$. The switch effect was reduced with longer CSI 2, $F(1, 77) = 13.81$, $\eta_p^2 = .15$, but increased slightly with longer CSI 1, $F(1, 77) = 5.94$, $\eta_p^2 = .07$, $p = .02$. Table 2 shows the results from *t* tests assessing whether the irrelevant-list length effect significantly deviated from zero for the two age groups in the six conditions.

Equivalent analyses of error data yielded largely nonsignificant results because irrelevant-list length effects on errors were small (<2% on the first probe, 3% on the second probe). One exception was the effect of list switching: Following a switch, irrelevant-list length effects on the second probe amounted to 5%, compared with 2% in trials without list switch, $F(1, 77) = 12.04$, $\eta_p^2 = .135$, $p = .001$. The two remaining significant effects were an interaction of CSI 1 with CSI 2, $F(1, 77) = 6.20$, $\eta_p^2 = .075$, $p = .02$, and an interaction of switching, CSI 1, and age, $F(1, 77) = 5.17$, $\eta_p^2 = .063$, $p = .03$. These latter two effects were small and do not have any obvious theoretical implications, so they are not discussed further.

To summarize, young adults used a preparation interval of 2 s to reduce the irrelevant-list-length effect to a low, though still significant, level for both probes. Old adults did not significantly differ from the young adults in that regard, but in separate analyses by age group their reduction of irrelevant-list length effect over CSI 1 was not reliable. The corresponding reduction over CSI 2 was reliable in both age groups.

Costs of List Switching

The second set of analyses investigates the costs of switching the relevant list between the first and the second probe. Following a switch, RTs were largely increased, $F(1, 79) = 179.97$, $\eta_p^2 = .695$. For a more detailed analysis, switch costs were computed by subtracting log-transformed RTs on the second probe following no switch from those following a switch within otherwise identical conditions. The switch costs were submitted to an ANOVA with relevant-list length, irrelevant-list length, and age as variables. Age had no significant effect on the size of switch costs ($F < 1$), nor did it enter into any interaction (all Fs < 1). This shows that the proportional increase in RTs due to list switching was statistically equivalent for both age groups, although old adults showed larger switch costs in absolute terms. Whereas relevant-list length had no effect ($F < 1$), switch costs increased with irrelevant-list length, $F(1, 78) = 25.80$, $\eta_p^2 = .249$. Switch costs were larger when the

[1] In the analysis with probe repetitions removed, the main effect of CSI was not significant in the total sample.

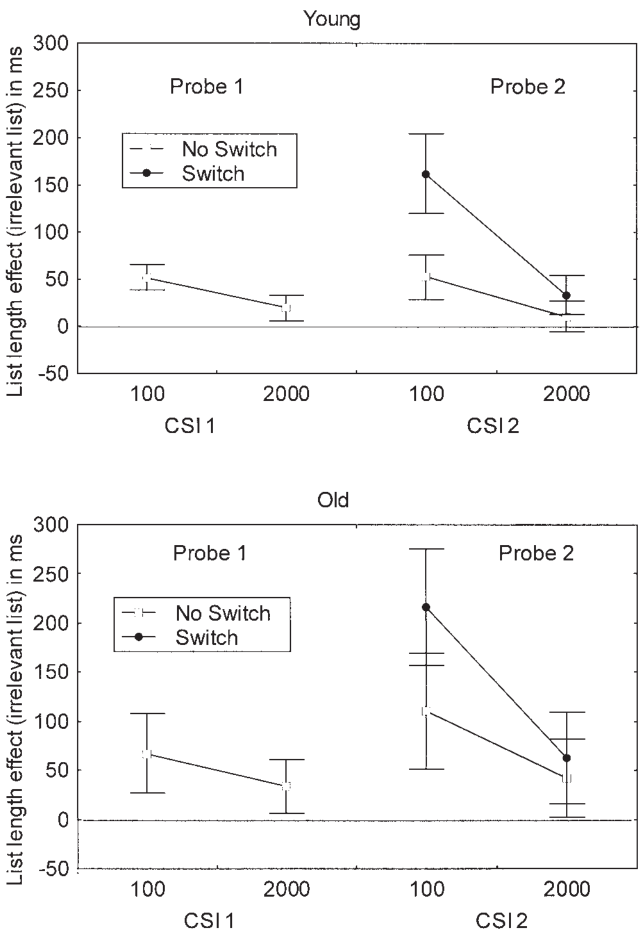


Figure 3. List-length effects of the irrelevant list (i.e., RT difference between irrelevant lists of length three minus irrelevant lists of length one) in Experiment 1 as a function of the preceding CSI and whether the second probe involved a switch of the relevant list. Top panel: young adults; bottom panel: older adults. Error bars reflect two standard errors of the mean for between-subjects comparisons; where error bars include the dotted line, the corresponding data points are not significantly different from zero (α = .05). CSI = cue-stimulus interval.

list switched away from (i.e., the currently irrelevant list) was large (costs of 110 ms) than when it was small (53 ms). The interaction of relevant- and irrelevant-list length was just significant, $F(1, 78) = 4.29$, $\eta_p^2 = .052$, $p = .04$. The list-length effects on switch costs are displayed in the top panel of Figure 4.

Switch costs were also analyzed by an ANOVA with CSI 1, CSI 2, and age as variables. Switch costs increased with a long CSI 1, $F(1, 77) = 33.13$, $\eta_p^2 = .301$, and they decreased with a long CSI 2, $F(1, 77) = 60.97$, $\eta_p^2 = .442$. The two CSI effects interacted, $F(1, 77) = 18.96$, $\eta_p^2 = .198$: Switch costs were particularly large when the first CSI was long and the second CSI was short. These effects are shown in the bottom panel of Figure 4; the relevant mean RTs are presented in Table 3.

Analogous analyses of variance based on the accuracy data confirmed most of the RT effects. List switches resulted in more errors (10% vs. 7%), $F(1, 79) = 40.74$, $\eta_p^2 = .34$. There was no effect of relevant-list length, but a significant effect of irrelevant-list length on switch costs, $F(1, 78) = 13.45$, $\eta_p^2 = .147$. In the analysis of CSI effects, only the decrease of switch costs with longer CSI 2 became significant, $F(1, 78) = 7.61$, $\eta_p^2 = .09$, $p = .007$. Again, there was no significant main effect or interaction involving age.

In sum, the cost of a switch to the other list increased with the size of the list switched away from but was independent of the size of the list switched to. Moreover, when the list switched away from had been relevant for a longer time (i.e., a long CSI 1), it took longer to leave it behind for the second probe. On the other hand, the more time there was to prepare for the new relevant list during CSI 2, the less switch costs remained after presentation of the second probe. Switch costs in reaction to the second probe were particularly pronounced when the old list was relevant for a long time, followed by little time to switch to the other list after the second cue (i.e., the combination of long CSI 1 and short CSI 2). Switch costs were larger in old adults when measured on an absolute scale, but not when measured on a proportional scale, indicating that age differences in switch costs were not larger than expected from proportional slowing.

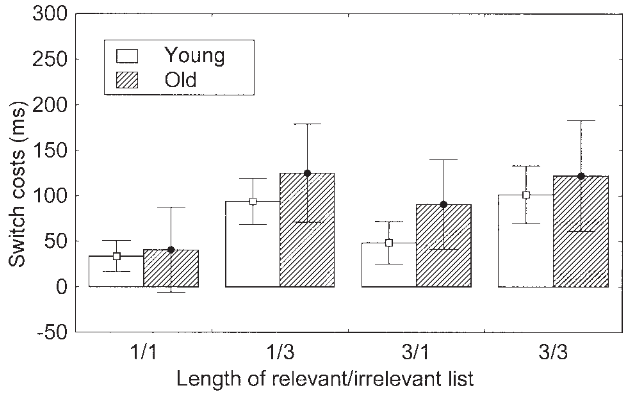
Intrusion Costs

The final analysis investigated intrusion effects in order to test whether the disproportional age differences in intrusion costs observed in previous experiments (Oberauer, 2001; Zacks et al.,

Table 2
Tests for Deviation From Zero for Irrelevant-List-Length Effects in Experiment 1

	Young			Old		
Condition	*M* (*SD*)	*t*(39)	*p*	*M* (*SD*)	*t*(39)	*p*
Probe 1, CSI 1 = 100	52 (41)	8.10	<.001	67 (127)	3.36	.002
Probe 1, CSI 1 = 2,000	19 (41)	2.97	.005	34 (87)	2.47	.018
Probe 2, CSI 2 = 100, no switch	52 (75)	4.41	<.001	111 (187)	3.74	.001
Probe 2, CSI 2 = 2,000, no switch	11 (53)	1.26	.22	42 (125)	2.14	.038
Probe 2, CSI 2 = 100, switch	162 (133)	7.72	<.001	216 (188)	7.27	<.001
Probe 2, CSI 2 = 2,000, switch	33 (66)	3.22	.003	63 (148)	2.71	.01

Note. Means are reaction time differences between long and short irrelevant lists in milliseconds. In keeping with common practice analyzing Sternberg list-length effects, and because no age comparisons were involved, reaction times were not log-transformed for the tests reported in this table. All *p* values are from two-tailed tests.



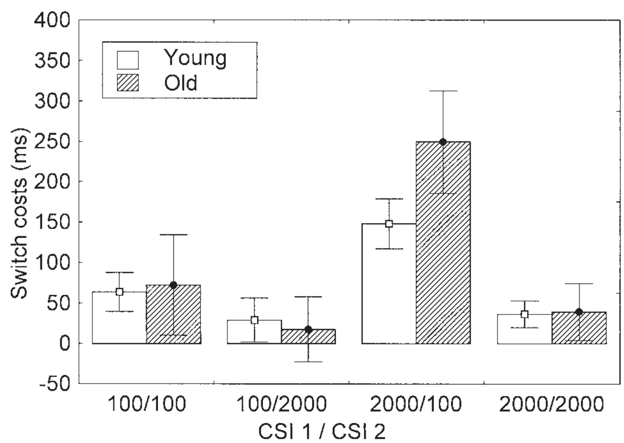


Figure 4. Switch costs (i.e., RT differences on Probe 2 between trials with a switch minus trials without a switch of the relevant list) in Experiment 1 as a function of the currently relevant list and the currently irrelevant list (top panel), and as a function of Cue-Stimulus Interval (CSI) 1 and CSI 2 (bottom panel). Error bars reflect two standard errors for between-subjects comparisons.

1996) can be replicated. This was the case: The intrusion costs (i.e., the extra time needed to reject intrusion probes compared with new probes) were larger in old than in young adults when tested with log-transformed RTs. This was confirmed by an ANOVA with probe number (first vs. second probe), probe type (new vs. intrusion), and age as variables. There was a main effect of probe type on RT, $F(1, 78) = 572.8$, $\eta_p^2 = .88$, and it interacted with age, $F(1, 78) = 33.50$, $\eta_p^2 = .294$. Young adults had mean intrusion costs of 184 ms, whereas old adults had intrusion costs of 462 ms. The effect of probe type was smaller on the second probe, as reflected by an interaction of probe type with probe number, $F(1, 78) = 32.08$, $\eta_p^2 = .291$, but the three-way interaction including age was not significant ($F = 2.46$, $p = .12$), indicating that the age-related increase in intrusion costs was equivalent on both probes.

Analyses of the accuracy data confirmed most of these effects. On the first probe, both age groups made less than 1% errors on new probes, but they differed in their error rates on intrusion probes. Young adults committed 6% errors on intrusion probes, compared with 12% for old adults. On the second probe, both age groups made 2% errors on new probes, but they differed markedly on intrusion probes (young adults, 11%, old adults, 19%). The ANOVA revealed a main effect of probe type, $F(1, 78) = 191.7$, $\eta_p^2 = .711$, which interacted with age, $F(1, 78) = 19.7$, $\eta_p^2 = .202$. The main effect of probe number was also significant, $F(1, 78) = 81.24$, $\eta_p^2 = .510$, together with its interaction with probe type, $F(1, 78) = 39.11$, $\eta_p^2 = .334$, reflecting the fact that more errors were made on intrusion probes in the second than in the first comparison. To summarize, consistent with previous findings, old adults were markedly impaired relative to young adults in overcoming intrusions on both the first and the second probe.

Discussion

This experiment yielded three important results concerning the control of working memory contents. They concern the list-length effects of irrelevant lists, the costs of switching to a previously irrelevant list, and the efficiency of rejecting intrusion probes, respectively.

First, people can temporarily remove a subset of the contents of working memory from the capacity-limited component of the system, thereby reducing its impact on the speed of processes on other working memory contents to nearly zero within 2 s or less. A temporarily irrelevant list can be removed from the direct-access region even when it is likely that it will become relevant again soon, and if necessary, it can be recovered quickly, suggesting that it is still maintained in the activated part of LTM. Apparently the working memory system is quick to outsource contents currently not needed into the activated part of LTM to free the limited capacity of the direct-access region. The relevant list, in contrast, is maintained in the direct-access region continuously, as reflected in the relevant-list length effect at both short and long CSIs.

Different from my previous results (Oberauer, 2001), irrelevant-list length effects did not vanish completely in this experiment. The present experiment differs from the previous one in that the irrelevant list for the first probe could become relevant again for the second probe. This could have made participants more hesitant about removing the irrelevant list from the direct-access region. Another difference is that the present experiment involved fewer trials, so participants received less practice on the task and therefore might not have developed perfect efficiency in outsourcing an irrelevant list.

The same factors could also explain why, in the present experiment, the reduction of the irrelevant-list-length effect on the first probe could not be secured statistically for old adults. This might provide a hint that old adults are not as efficient as young adults in removing irrelevant information from the direct-access region. The age difference in this regard was not significant but that could be due to the low reliability of the critical effect—the decline of the irrelevant-list-length effect over CSI at each probe—as an individual differences variable: The split-half correlation of this effect was nonsignificant. The reduction of the irrelevant-list-length effect over CSI, though replicable as a mean effect, seems to be ill-suited for comparisons between individuals or groups. Therefore, whether old adults are as efficient as young adults in removing irrelevant information from the direct-access region of working memory cannot be decided conclusively.

Table 3
Mean Reaction Times (in Milliseconds) of Young and Old Participants as a Function of Cue-Stimulus Intervals (CSIs) and List Switching, Experiments 1 and 2

	Young		Old	
Condition	No switch	Switch	No switch	Switch
Experiment 1				
RT 1, CSI 1 = 100	879 (179)		1,199 (278)	
RT 1, CSI 1 = 2,000	704 (153)		1,157 (246)	
RT 2, CSI = 100/100	793 (152)	863 (172)	1,371 (361)	1,461 (341)
RT 2, CSI = 100/2,000	640 (171)	662 (167)	1,191 (415)	1,214 (420)
RT 2, CSI = 2,000/100	746 (134)	918 (196)	1,324 (321)	1,608 (309)
RT 2, CSI = 2,000/2,000	630 (156)	666 (162)	1,141 (366)	1,163 (329)
Experiment 2				
RT 1, CSI 1 = 100	1,597 (405)		1,970 (316)	
RT 1, CSI 1 = 3,000	1,360 (281)		1,712 (350)	
RT 2, CSI = 100/100	1,356 (479)	1,519 (403)	2,020 (413)	2,070 (388)
RT 2, CSI = 100/3,000	1,261 (336)	1,289 (324)	1,679 (349)	1,573 (285)
RT 2, CSI = 3,000/100	1,337 (366)	1,656 (313)	2,083 (450)	2,228 (434)
RT 2, CSI = 3,000/3,000	1,254 (339)	1,298 (294)	1,690 (354)	1,652 (332)

Note. RT 1 = reaction time to first stimulus; RT 2 = reaction time to second stimulus; switch refers to switch of the list from first to second stimulus (in Experiment 2 only trials without object switch are included); CSIs (expressed in milliseconds) for RT 2 are given as CSI 1/CSI 2.

A second set of results reflects the process of bringing information back into the central part of working memory when it again becomes relevant. Switching from one relevant list to the other was associated with a time cost (and a slight increase in error rate). The switching cost was higher after a long CSI 1, as should be expected, because with a short CSI 1 there was less opportunity to remove the irrelevant list from the direct-access region in the first place, so that it need not be retrieved back into it. The switching cost was smaller after a long CSI 2, which is again to be expected because participants could use the long CSI 2 to retrieve the new relevant list from the activated part of LTM.

List switch costs depended on the length of the list switched away from but not on the length of the list switched to. The time for retrieving a new relevant list from the activated part of LTM apparently is independent of that list's length. This converges with previous observations that the time to retrieve a list from LTM in the Sternberg paradigm takes a constant amount of time regardless of list length (Conway & Engle, 1994; Wickens, Moody, & Dow, 1981). On the other hand, retrieval of the new relevant list is made more difficult if the old relevant list that still occupies the central part of working memory is long. This converges with findings suggesting that retrieval from LTM is impaired by a load on working memory (Rosen & Engle, 1997). The emerging picture is that switching from one relevant list to the other involves retrieving the new relevant list from the activated part of LTM—at least when people had sufficient time to outsource that list during the CSI 1 plus the time for processing the first probe—and the efficiency of this retrieval depends on the current load on the capacity limit of working memory but not on the amount to be retrieved. The fact that old adults showed the same pattern of switch costs as young adults suggests that they, too, had to retrieve the previously irrelevant list from LTM. This implies that they cannot have been completely unsuccessful in removing that list from the direct-access region before.

A third noteworthy finding is that intrusion costs in RTs were increased in old age and, in addition, old adults made more errors on intrusion probes. The age effect on intrusion costs was significant with log-transformed RTs, implying that it went beyond a merely proportional slowing of all processes in old age. This contrasts with other effects, for instance, list-switching costs, which were not disproportionately increased in old age. Therefore, the problem of old adults with rejecting intrusion probes can hardly be explained by general slowing. This finding replicates previous results with the modified Sternberg paradigm (Oberauer, 2001, in press; Zacks et al., 1996), confirming that intrusion costs reflect a robust, specific deficit in old adults' cognitive processes.

This deficit is either due to an impairment in inhibiting no-longer relevant information in the activated part of LTM or to less efficient recollection processes needed to overcome the misleading familiarity signal of intrusion probes. The finding that old adults had increased intrusion costs on the first probe as much as on the second speaks against the inhibition-deficit interpretation: It would not be wise to inhibit the currently irrelevant list on the first probe because this list could become relevant on the second probe. If old adults had an inhibition deficit, this should not put them at a disadvantage compared with young adults in rejecting first-probe intrusions, because even young adults probably did not inhibit the irrelevant list strongly. Strong inhibition of the irrelevant list on the first probe would lead to increased switching costs, because it takes longer to reactivate the inhibited list. If anything, however, it was the old group that showed longer times to switch between the lists. I believe it is more plausible to explain the increase of intrusion costs in old age through a deficit in recollection (cf. Hedden & Park, 2003; Oberauer, in press).

Experiment 2

The second experiment realized a design similar to the first, using an arithmetic memory-access task as in Oberauer (2002). This task differs in several regards from the modified Sternberg task: It uses digits instead of words as memory material and recall plus computation instead of recognition as processing task. Converging evidence across the two paradigms, therefore, provides strong evidence for the generality of the findings and supports the assumption of general processes to control the contents of working memory.

Method

Participants

Young participants were 32 high school and university students from Potsdam (mean age = 18.8 years, *SD* = 2.7). Old participants were 37 adults living in the Potsdam area (mean age = 72.0 years, *SD* = 4.0); they were selected from a pool of participants who expressed interest in taking part in experiments in response to newspaper advertisements. Fourteen of the old adults but none of the younger adults had already participated in Experiment 1 about 16 months before. As before, old adults had fewer years of formal education than the young adults (10 years vs. 11.6 years), $t(65) = 4.21$. They performed better than young adults on the MWT-A Vocabulary test, with a mean score of 32.9 (*SD* = 1.4) compared with 30.7 (*SD* = 3.1) for the young group, $t(42.7) = -3.69$. Young adults had higher scores on the Digit Symbol test (*M* = 59.2, *SD* = 10.3) than old adults (*M* = 49.8, *SD* = 9.2), $t(65) = 3.96$. Hence the samples are comparable to other samples in aging research.

Materials and Procedure

In each trial, participants saw two rows of white rectangular frames displayed on top of each other on a black background. A digit between 1 and 9 was shown in each frame. All digits were presented simultaneously for 1.2 s times the total number of digits. The number of frames in each row, and thereby the list length of each digit list, was varied independently; each list consisted of either one or three digits. The digits in both rows were selected at random with the constraint that they all differed from each other.

Immediately after the digits were deleted from the screen, the frames in one row turned red, marking this row as the active list for the first operation. This was the upper row in half of the trials and the lower row in the other half, determined at random. Following a CSI 1 of either 100 or 3,000 ms, an arithmetic operation was displayed in a frame of the active list. For three-digit lists, the frame was selected at random. The operations were additions or subtractions of single digits (e.g., +4 or −6) generated at random, with the constraint that the result be between 1 and 9. Participants applied the operation to the digit they memorized in the respective frame and typed the result as quickly as possible, using the number keys in the top row of the computer keyboard. Upon registering the reaction, the computer turned the frames of the active row white again, and a feedback tone was displayed. This was a 50-ms high tone, for correct responses, or a 100-ms low tone, for wrong responses. One hundred ms later the same or the other row was marked as the active one for the second reaction, again by turning its frames red. After a CSI 2 of 100 or 3,000 ms, the second reaction was displayed in a frame of the now active row, and participants responded in the same way as before. The value of the long CSI was larger than in Experiment 1 because the previous results with the memory-access paradigm (Oberauer, 2002, Experiment 2) suggested that 2–3 s are needed to completely eliminate the list-length effect of the passive list.

As in Experiment 1, the two CSI factors were varied orthogonally between blocks, thereby generating four kinds of blocks, one for each combination of CSI 1 with CSI 2. The other design factors—the list lengths of the two lists (1 vs. 3 digits) and the list switch (switch or no switch of the active list from the first to the second operation)—were varied within blocks in a randomized order. Participants took part in two sessions, each session consisting of four blocks, one for each CSI combination; the order of blocks was counterbalanced across participants. In the first session, each block consisted of 32 test trials preceded by 16 practice trials. In the second session, each block consisted of 48 test trials without practice trials.

Results

RTs were trimmed as in Experiment 1, but with a lower cutoff of 300 ms. Analyses were based on log-transformed RTs for correct responses. Mean raw RTs broken down by the design factors are presented in Tables 3 and 4. First, I report effects of list length of the passive list on latencies and accuracies of arithmetic computations. In the second section, I analyze effects of switching between lists. Finally, I present data on the object-switch costs, that is, costs of switching from one digit to another within the same active list.

List-Length Effect of Passive List

If participants remove the passive list from the capacity-limited part of working memory, the effect of this list's length on computation latencies should diminish with a long CSI. List-length effects were again computed by subtracting RTs on the short passive list from those on the long passive list in otherwise identical conditions. These list-length effects are displayed in Figure 5 as a function of the preceding CSI. The corresponding list-length effects computed from log-transformed RTs were used for statistical analyses.

Passive-list length effects on the first operation were submitted to an ANOVA with CSI 1 and age as variables. There was a significant main effect of CSI, $F(1, 67) = 70.28$, $\eta_p^2 = .512$, which interacted with age, $F(1, 67) = 6.88$, $\eta_p^2 = .093$, $p = .011$. The main effect of age was also reliable, $F(1, 67) = 5.78$, $\eta_p^2 = .079$, $p = .019$. The effects involving age were due to the proportionally smaller list-length effect of old adults at the short CSI. Both age groups reduced the list-length effect of the irrelevant list to zero at the long CSI.

List-length effects of the passive list on the second operation showed a similar decline over the preceding CSI but only when the active list was switched. When the list was not switched, list-length effects of the passive list never exceeded zero. This pattern was confirmed by an ANOVA with CSI 2, list switch, and age as variables. There was a main effect of CSI 2, $F(1, 67) = 21.82$, $\eta_p^2 = .246$, which did not interact with age ($F = 0$). The main effect of list switching was significant, $F(1, 67) = 25.12$, $\eta_p^2 = .273$, also without interacting with age ($F = 1.44$). In addition, there was a strong interaction between CSI 2 and switch, $F(1, 67) = 60.40$, $\eta_p^2 = .474$. The three-way interaction was marginal, $F(1, 67) = 4.01$, $\eta_p^2 = .056$, $p = .049$.

Accuracy was high, reaching 99% correct on the first operation and 95% on the second operation, with no significant age difference ($F = 1.02$). Effects of the passive list's length on errors were negligible on the first operation. Those on the second operation revealed a significant interaction of list switch with age, $F(1, 67) = 12.24$, $\eta_p^2 = .154$, $p = .001$, and an interaction of list switch with CSI 2, $F(1, 67) = 13.82$, $\eta_p^2 =$

Table 4
Mean Reaction Times (in Milliseconds) in Experiment 2 by Operation, Preceding Cue-Stimulus Interval, List Lengths, List Switch, and Age Group

Condition	List length (active/passive)			
	1/1	1/3	3/1	3/3
Young				
Operation 1, CSI 1 = 100	1,417 (360)	1,559 (401)	1,635 (422)	1,777 (471)
Operation 1, CSI 1 = 3,000	1,234 (298)	1,204 (265)	1,485 (314)	1,518 (302)
Operation 2, no switch, CSI 2 = 100	1,233 (395)	1,192 (400)	1,467 (421)	1,505 (430)
Operation 2, no switch, CSI 2 = 3,000	1,059 (272)	1,100 (293)	1,439 (379)	1,450 (379)
Operation 2, switch, CSI 2 = 100	1,323 (304)	1,536 (318)	1,659 (322)	1,831 (421)
Operation 2, switch, CSI 2 = 3,000	1,111 (270)	1,141 (274)	1,460 (351)	1,465 (336)
Old				
Operation 1, CSI 1 = 100	1,733 (335)	1,832 (315)	2,126 (359)	2,191 (334)
Operation 1, CSI 1 = 3,000	1,455 (361)	1,482 (333)	1,962 (380)	1,949 (385)
Operation 2, no switch, CSI 2 = 100	1,917 (446)	1,898 (469)	2,210 (444)	2,173 (391)
Operation 2, no switch, CSI 2 = 3,000	1,483 (323)	1,491 (361)	1,913 (382)	1,866 (357)
Operation 2, switch, CSI 2 = 100	1,920 (435)	2,058 (375)	2,254 (397)	2,383 (480)
Operation 2, switch, CSI 2 = 3,000	1,401 (305)	1,359 (295)	1,838 (328)	1,868 (370)

Note. CSI 1 = cue-stimulus interval preceding the first arithmetic operation; CSI 2 = cue-stimulus interval preceding the second arithmetic operation. CSIs are expressed in milliseconds. Standard deviations are presented within parentheses.

.171. After a switch, list-length effects declined from 2% at the short CSI to 0 at the long CSI, consistent with the RT data, whereas without a switch, they increased from −1% to 2%. Following a list switch, old adults showed a passive-list-length effect of 3%, whereas young adults' was around zero. This could be a hint that old adults were not perfectly successful in removing the irrelevant list from the capacity-limited part of working memory after a list switch.

In sum, on the first operation both young and old adults showed pronounced list-length effects of the irrelevant list after a short CSI. Following a long CSI, they reduced this list-length effect to zero. The list-length effects on the second operation differed markedly for trials following a switch and trials following no switch. After a list switch, list-length effects of the irrelevant list were substantial with a short CSI 2, but declined to zero after a long CSI 2 for both age groups. When the active list was not switched, list-length effects were zero throughout. The only indication that old adults might be less efficient in eliminating the list-length effect during a long CSI was the remaining list-length effect on errors following a list switch.

Costs of Switching Between Lists

List-switching costs were computed as the difference between RTs on the second operation following a switch of the active list and those following no switch. Figure 6 shows switch costs broken down by the list length of the currently active list and the currently passive list (which is the previously active list on switch trials) in the top panel and switch costs broken down by the two CSIs in the bottom panel.

Switch costs computed from log-transformed RTs were first analyzed with the length of the currently active list (2), the length of the currently passive list (2), and age (2) as variables. The length of the currently active list had no effect ($F < 1$), but switch costs increased with the length of the passive list, $F(1, 67) = 20.82$, $\eta_p^2 = .237$, $p < .001$. The only other significant effect was a main effect of age, $F(1, 67) = 25.37$, $\eta_p^2 = .275$, $p < .001$. Young adults had larger switch costs than old adults. In fact, separate analyses by age showed that the switch costs were significant only for the young adults, $F(1, 31) = 37.06$, $\eta_p^2 = .545$, but not for the old adults ($F = 1.12$).

A second analysis investigated switch costs as a function of CSI 1, CSI 2, and age. The main effect of age was again significant, $F(1, 67) = 23.78$, $\eta_p^2 = .262$. Switch costs increased with a long CSI 1, $F(1, 67) = 30.77$, $\eta_p^2 = .315$, and they decreased with a long CSI 2, $F(1, 67) = 69.52$, $\eta_p^2 = .509$. The two CSI factors interacted, $F(1, 67) = 8.35$, $\eta_p^2 = .111$, $p = .005$, reflecting the fact that switch costs were particularly large when a short CSI 2 was preceded by a long CSI 1, whereas for a long CSI 2, they were absent regardless of CSI 1.

Corresponding analyses of accuracy data revealed little of interest. Switch costs on errors were practically zero overall. There was a marginal interaction of the two list lengths on switch costs, $F(1, 67) = 4.18$, $\eta_p^2 = .059$, $p = .045$: Switch costs on error rates were 2% larger when both lists were long and when both lists were short, as compared with mixed list lengths. No interpretation is offered for this interaction. Moreover, switch costs increased with a long CSI 1, but only when CSI 2 was short, $F(1, 67) = 7.36$, $\eta_p^2 = .10$, $p = .008$, for the interaction; this mirrors the RT effects. None of the main effects or interactions involving age approached significance.

Hence, like in Experiment 1, list switch costs depended on the length of the list switched away from (i.e., the passive list), but not the length of the list switched to (i.e., the active list). Switch costs increased when the list to be abandoned had been the active list for a longer time (i.e., a long CSI 1), and they vanished completely when a long CSI 2 provided time to prepare for the new active list.

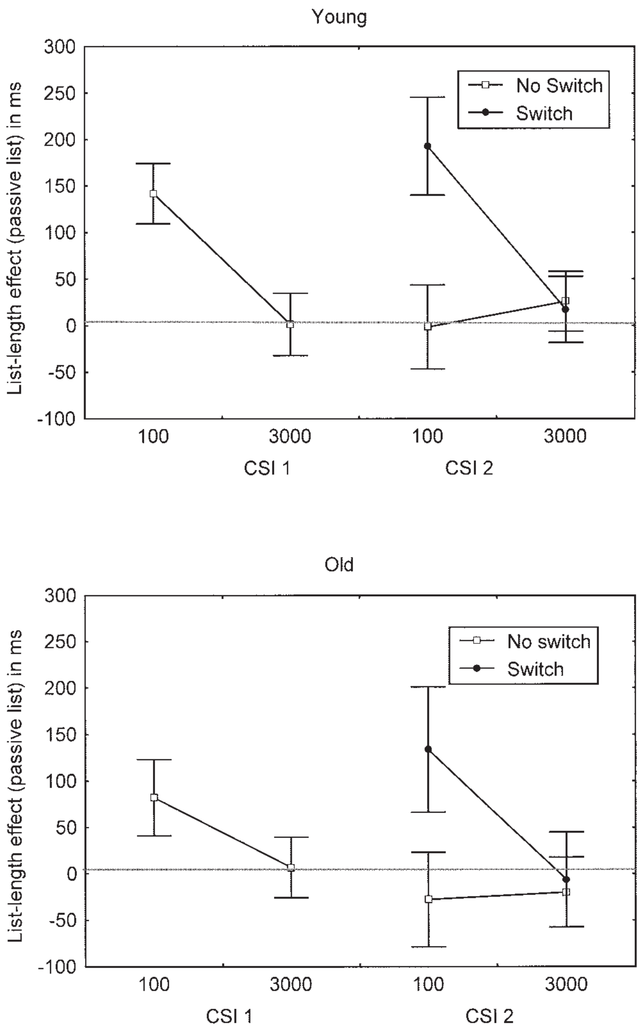


Figure 5. List-length effects of the passive list in Experiment 2 as a function of preceding cue-stimulus interval (CSI) and as a function of whether the second operation was preceded by a switch of the active list. Top panel: young adults; bottom panel: older adults. Error bars reflect two standard errors of the mean; where error bars include the dotted line, the corresponding data points are not significantly different from zero (α = .05).

Different from Experiment 1, list-switch costs were generally absent for old adults.

Object Switch Costs

One additional effect of interest in this experiment was the cost of an object switch, that is, the increase in RTs when the digit accessed within an active list changed from the first to the second operation. Object switch costs have been interpreted as reflecting the time to switch the focus of attention within working memory (Garavan, 1998; Voigt & Hagendorf, 2002). More specifically, because object switch costs have been observed for switches between objects within an active list, I have interpreted them as reflecting a switch of the focus of attention within the direct-access region (Oberauer, 2002).

In the present experiment, object switch costs can only be calculated for the subset of trials in which the active list had three elements and remained the same for both operations. In other words, the analysis was restricted to the conditions with an active-list length of three and no list switch. I computed object-switch costs from log-transformed RTs from the second operation as the difference between trials with an object switch and trials without object switch in otherwise identical conditions. Object-switch costs were analyzed by an ANOVA with length of the passive list, CSI 2, and age as variables. Object-switch costs were observed only for young adults when CSI 2 was short (M = 178 ms), whereas they were absent for long CSI 2 (−37 ms), as well as for old adults (−39 and −87 ms for the two short and long CSI conditions, respectively). This was confirmed by a main effect of CSI 2, $F(1, 67) = 22.59$, $\eta_p^2 = .252$, a main effect of age, $F(1, 67) = 13.54$, $\eta_p^2 = .168$, and an interaction of these two variables, $F(1, 67) = 8.72$, $\eta_p^2 = .115$, $p = .004$. No other effect became

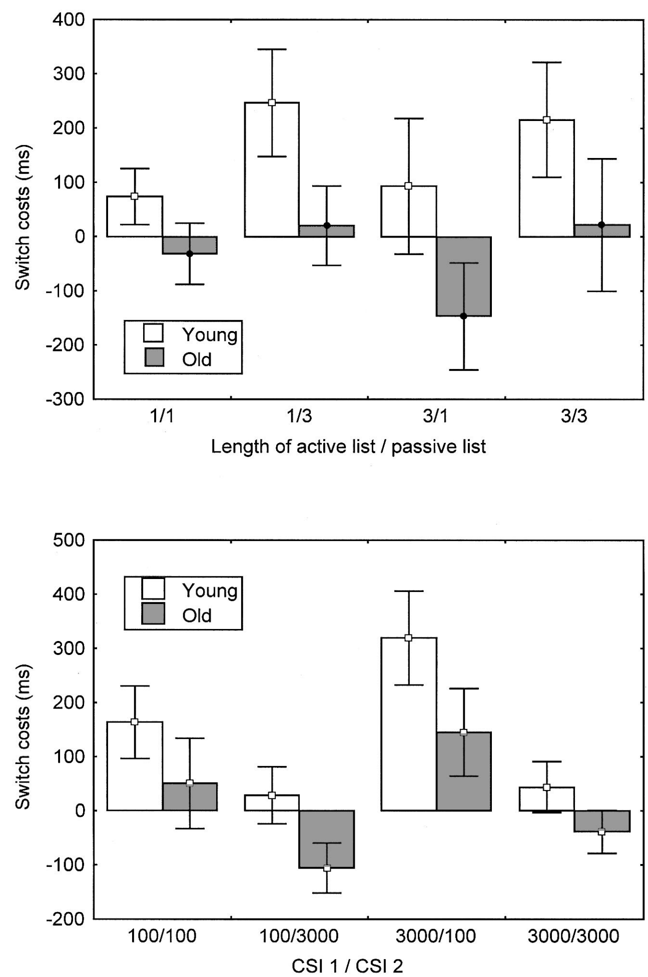


Figure 6. Switch costs (i.e., reaction time differences on second operation between trials with and without a list switch) in Experiment 2 as a function of the currently active list and the currently passive list (top panel), and as a function of Cue-Stimulus Interval (CSI) 1 and CSI 2 (bottom panel). Error bars reflect two standard errors for between-subjects comparisons.

significant. A corresponding analysis of the accuracy data yielded no significant effects.

Discussion

The main results of this experiment largely mirrored those of Experiment 1. First, on both operations the list-length effects of the passive list, which were substantial at short CSIs, vanished completely at long CSIs preceding the operation. This shows that participants were highly efficient in removing the passive list from the capacity-limited region of working memory within 3 s, even when they anticipated that this list could become the active list for the next arithmetic operation. There was hardly any difference between young and old adults in that regard, with the single possible exception that old adults showed a small, but significant passive-list length effect at the second operation following a list switch, which persisted after a long CSI 2.

Second, switching from one active list to the other was associated with an additional time cost, and this cost increased when CSI 1 was long and when CSI 2 was short. Different from Experiment 1, however, list-switch costs were observed only for young adults. Again consistent with the first experiment, list switch costs increased with the length of the list switched away from (i.e., the now passive list) but were independent of the length of the list switched to (i.e., the new active list). This pattern of results supports the same interpretation as that offered above for list switches in the modified Sternberg task: When the passive list on the first operation has been outsourced into the activated part of LTM, it must be retrieved from there upon a list switch. Apparently, a list of three digits is retrieved from LTM as a single chunk, just like a list of three words in the Sternberg task, and therefore this takes no more time than retrieving a single digit. On the other hand, the current load on working memory capacity from the previous active list (now to become passive) affects the speed of retrieval.

A further analysis focused on the object-switch costs within an active list. Object-switch costs were observed for young adults at a short CSI 2, thereby replicating the finding in the previous study (Oberauer, 2002), in which successive operations were always displayed with minimal delay, corresponding to a short CSI. This supports the contention that a focus of attention selects one digit out of a list that is held in the direct-access region simultaneously. When another digit from the same list must be selected immediately after the first operation, the time to switch the focus to the new digit is reflected in the latency of the second operation. With a long CSI 2, the focus of attention apparently disengages from the digit selected for the first operation, and no object-switch cost remains.

For old adults, however, object-switch costs were not observed at all. In a previous study using a similar experimental paradigm (Oberauer, Wendland, & Kliegl, 2003), we found that old adults had slightly smaller object-switch costs than young adults, but they were still well above zero. The experiments differed in several regards—for instance, in the Oberauer et al. (2003) study, participants performed 13 operations in an uninterrupted sequence, and they updated their working memory contents by the results of the operations. Nonetheless, the common pattern seems to be that object-switch costs in working memory are reduced in old age. One possible explanation for this is that old adults cannot focus as exclusively as young adults on one object out of a list currently held in the direct-access region, or that they disengage their focus of attention much more rapidly after, or even during, the completion of a cognitive operation on the selected object.

Possibly it is more than a superficial similarity that old adults lacked both list-switch costs and object-switch costs in this experiment. A common explanation could be that old adults adopt a more rigid control strategy than do young adults. Suppose that after the first operation old adults always release the selected digit from the focus of attention and the active list from the direct-access region, thereby essentially resetting working memory to a neutral state. When the second cue appears, they retrieve the list it indicates from the activated part of LTM, and when the second operation is displayed, they focus on the digit to be accessed. In other words, old adults do not take advantage of the repetition of an active list, and of the repetition of an object within an active list—they experience the costs of switching on all trials, including those trials where there actually is no switch. The "switch costs" observed in young adults, then, might better be understood as repetition benefits. Support for this interpretation comes from a comparison of RTs on the first operation with those on the second operation when the active list remains the same. Young adults were faster on the second operation (1,306 ms) than on the first operation (1,478 ms), but old adults were not (first operation: 1,841 ms; second operation: 1,869 ms). The interaction of operation (first vs. second) with age was significant, $F(1, 67) = 38.69$, $\eta_p^2 = .366$. Thus, young adults gained speed from the repetition of the active list on the second operation, whereas old adults did not. Following a list switch, both old and young adults were about as fast on the second operation as on the first (young adults: 1,478 ms on the first operation; 1,441 ms on the second; old adults: 1,841 ms on the first operation; 1,885 ms on the second). This is the pattern to be expected when old adults reset their working memory after every operation, whereas young adults do this only when the active list is switched.

General Discussion

The goal of this work was to investigate the control of working memory contents in young and old adults across two paradigms—the modified Sternberg recognition task and an arithmetic memory-access task. Although the two tasks differed in many regards, the results from the two experiments showed a remarkable degree of convergence. In both experiments, young participants efficiently removed a temporarily irrelevant list from the capacity-limited part of working memory. This is possible because this component, the direct-access region, needs to hold only those contents that must be accessed as input for the ongoing cognitive operations. In Experiment 2, old adults were as efficient in this control process as young adults; in Experiment 1, however, there was some indication that old adults might be less able, or less willing, to temporarily remove a subset of working memory contents from the direct-access region. This could be due to an experimental context in which lists often become temporarily, but not permanently, irrelevant so that it might be a safer strategy to keep them in the central part of working memory.

A second point of convergence is that in both experiments participants could retrieve a list from the activated part of LTM once they had removed it from the direct-access region, as is evident from the small to nonexistent effects of a list switch on error rates. Retrieving an outsourced list from the activated part of LTM took time, reflected in list-switch costs on RTs, which were consistently observed in both experiments at least in young adults. In both experiments, list-switch costs were independent of the length of the list switched to, but increased with the length of the list switched away from. This can be interpreted in the context of previous findings showing that retrieval of a short memory list from LTM is associated with a time cost that is independent of list length (Conway & Engle, 1994; Wickens et al., 1981) and that retrieval from LTM is slowed down by a load on working memory (Rosen & Engle, 1997). This pattern of findings therefore is fully consistent with the interpretation that the temporarily irrelevant list is removed from the central part of working memory and maintained in the activated part of LTM, from where it must be retrieved in order to be accessed later.

A third consistent pattern is that list-switch costs depended on the two CSI variables in a way that would be expected from my interpretation. With a short CSI 1, participants have small chances to remove the currently irrelevant list from the direct-access region; hence, often no retrieval of that list will be necessary following a switch. Furthermore, if CSI 2 is long, this time can be used to retrieve the new relevant list from the activated part of LTM before the imperative stimulus appears so that little switch costs remain in the RTs. The full time cost of retrieving a list back into the direct-access region is best reflected in the condition with long CSI 1 and short CSI 2. It is worth mentioning that in this condition, even old adults in Experiment 2, who otherwise showed little list-switch effects, were slower after a list switch than after a list repetition (see the bottom panel of Figure 6).

This set of convergent findings across two paradigms is strong evidence for a model of working memory that distinguishes a central, capacity-limited component and a supplementary backup system, together with efficient processes of moving subsets of the contents of working memory between the two components to use the system's limited capacity in the most efficient way. I proposed a model, based on the work of Cowan (1995, 1999), that incorporates such a distinction and additional assumptions about the functions of the components. The direct-access region is a capacity-limited system that can hold a small number of representational elements immediately accessible. Therefore, information that is required for ongoing processes must be held in the direct-access region. In the modified Sternberg task, the currently relevant list must be held in the direct-access region to be available for explicit comparison with the probe. In the memory-access task, the currently active list must be held in the direct-access region so that its contents can be immediately selected by the focus of attention as input for the arithmetic operations. The price for this is that because of the capacity limit, a load on the direct-access region reduces the speed of concurrent processing.

The second component, the activated part of LTM, can serve maintenance functions in working memory in two ways. First, existing representations in LTM can be activated. If the activation of content representations one wishes to maintain is sufficiently distinct, it can serve to recover the identity of these contents. Activation alone, however, is not sufficient to maintain relational information, such as which digit was seen in which spatial location on the screen. To maintain this kind of information, it must be possible to build new associations in LTM within a relatively short time. The present results with the memory-access paradigm suggest that 2–3 s is enough to encode a list of three digits into the activated part of LTM; otherwise, we could not explain how people can reduce the list-length effect of a passive list to zero on the first operation, and then, upon a list switch, recover this list for the second operation with high accuracy. One way to accomplish this is through chunking of a three-digit list, for example, by conjoining the three separate numbers into one three-digit number through mutual associations.

Other models of working memory that distinguish several components or subsystems can probably also explain the current results, although such explanations probably require a few ad hoc assumptions. The most prominent model of this kind is the one developed by Baddeley (1986, 2001). In its current version, the model has four subsystems: a central executive responsible for control of cognitive processes and actions, two slave systems (one for verbal and one for spatial contents) that can temporarily maintain representations in their dedicated content domain, and an episodic buffer that can maintain representations across domains and bind them together into objects and events. One way to map this model onto the present data is to assume that the currently relevant list is held in the episodic buffer and that the currently irrelevant list is relegated to the verbal slave system (i.e., the phonological loop). This requires the additional assumptions that the contents of the episodic buffer, but not those of the phonological loop, are accessible for processing and that the capacity limit of the episodic buffer, but not that of the slave systems, affects the speed of cognitive processes. With these assumptions, the episodic buffer would become extremely similar to my concept of the direct-access region. An additional assumption required is that contents of the phonological loop can be reloaded into the episodic buffer with a speed that is independent of the number of elements kept in the loop because the time to switch between lists was independent of the length of the list switched to. The only mechanism for retrieval from the phonological loop specified in Baddeley's model is the serial readout of list elements, as in serial recall and rehearsal. Therefore, the assumption of retrieval independent of list length is probably difficult to integrate with the model.

Finally, the data from the two experiments also speak to the issue of what is responsible for old adults' reduced working memory performance. The results with the modified Sternberg task confirm that old adults have a specific problem with rejecting intrusions, and this could be due to insufficient inhibition of information still activated in LTM or with reduced efficiency of recollection. The rejection of intrusions could be one source of difficulties old adults experience in working memory tasks when it is important to avoid proactive interference (Lustig, May, & Hasher, 2001). On the other hand, the control processes I focused on here—moving representations in and out of the capacity-limited component of working memory over short time periods—were not substantially impaired in old age. In Experiment 1, old adults were possibly less efficient in removing lists from the direct-access region, but in Experiment 2 they were remarkably efficient in this regard and hardly distinguishable from young adults. Age differences in working memory performance were observed with various tasks, among them paradigms very similar to the one used in Experiment 2 (Oberauer & Kliegl, 2001; Oberauer et al., 2003). These age differences apparently cannot be explained by age differences in the ability to control the contents of the direct-access region. On the other hand, the marked age differences in control of intrusions from the activated part of LTM might be in part responsible for old adults' problems with working memory tasks.

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