Aging and Working Memory Inside and Outside the Focus of Attention: Dissociations of Availability and Accessibility

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ABSTRACT

Two experiments used the N-Back task to test for age differences in working memory inside and outside the focus of attention. Manipulations of the difficulty of item-context binding (Experiment 1) and of stimulus feature binding (Experiment 2) were used to create conditions that varied in their demand on working memory, with the expectation that greater demand might increase age differences in focus-switching costs and the search rate outside the focus of attention. Results showed, however, that although age differences were evident in measures of overall speed and accuracy, and the manipulations significantly affected response times and accuracy in the expected direction, the experimental manipulations had no impact on age differences. Findings instead pointed to age-related reductions in accuracy but not speed of focus-switching and search outside the focus of attention. Thus, age-related deficits appear to involve the availability of representations in working memory, but not their accessibility.

Keywords: Working memory; Focus of attention; Focus-switching; Age differences; Context memory.
INTRODUCTION

Age-related declines in working memory are well documented (Bopp & Verhaeghen, 2005; Salthouse, 1991, 1996), but because working memory is a complicated system, there are many possible sources of age-related deficits. One potentially useful approach draws on theories suggesting a hierarchical structure to working memory, with regions that differ in the accessibility of the information stored. Cowan’s (1988, 1995, 1999, 2001) model has probably been most influential in this regard. The model proposes a hierarchical two-tier structure for working memory, distinguishing a zone of immediate access, labeled the focus of attention, from a zone outside the focus, the outer store, where items are stored temporarily with the expectation that they will be soon retrieved for subsequent processing. The size of the focus of attention has been subject to debate. It appears that the focus can hold three to four items under certain circumstances (e.g., subitizing or short-term memory tasks, Cowan, 2001), but only a single item (e.g., McElree, 2001) under other circumstances (viz., demanding serial-attention tasks like an N-Back task; e.g., Verhaeghen, Cerella, & Basak, 2004).

One logical consequence of the two-tier structure of working memory is the existence of a focus-switching process (McElree, 2001; Voigt & Hagendorf, 2002). When the number of items to be retained in working memory is smaller than or equal to the capacity of the focus of attention, they will be immediately retrievable, and access times will be fast. When the number of items to be retained exceeds the capacity of the focus, however, the excess items will be stored in the outer store. In that case, items will need to be swapped in and out of the focus of attention. Focus-switching has been associated with slowed performance as well as decreased accuracy, the latter likely due to information loss during encoding, maintenance, and/or retrieval (e.g., Verhaeghen & Basak, 2005; Verhaeghen et al., 2004; Verhaeghen, Cerella, Bopp, & Basak, 2005).

The focus-switching process might be a good candidate for the locus of age differences in working memory. Standard tasks for working memory, such as operation span or reading span, which yield large age differences (e.g., Bopp & Verhaeghen, 2005), by definition require frequent switching of what is likely to be a single-item focus of attention. Nevertheless, these tasks do not permit direct measurement of focus-switching. One paradigm that is ideally suited to investigate the focus-switching process, however, is the identity-judgment N-Back task (Dobbs & Rule, 1989; McElree, 2001). In this task, the participant is presented with a sequence of digits, one at a time, and is required to press one of two keys to indicate whether the digit presented on the screen is identical or not to the digit presented N positions back in the sequence. McElree (2001) found that response speed was much faster for N = 1 than for either N = 2 or N = 3, but that response speed was identical
for $N = 2$ and $N = 3$. The interpretation is that in this task only a single element can be held in the focus of attention at any given time.

Both speed (response times) and accuracy can be used to measure focus-switching in the $N$-Back task, and previous results suggest they can be dissociated. Thus, in two experiments, Verhaeghen and Basak (2005) found no evidence for specific age-sensitivity in the speed of the focus-switching process, and this was interpreted as a measure of accessibility of information that must be retrieved from outside the focus of attention. Although older adults were generally slower in the task than younger adults, the focus-switching process was not slowed disproportionately. There was, however, age-sensitivity in accuracy for items stored outside the focus of attention. Both age groups performed near ceiling for the item held within the focus, but older adults showed greater declines in accuracy for items held outside the focus, signaling an effect of aging on the availability of items once they left the focus of attention. Thus accuracy measures the probability that an item is available for processing. Outside the focus of attention, an item is subject to decay, the effects of interfering items, or both (McElree, 2001; Verhaeghen & Basak, 2005). Monotonic declines in accuracy, such as the ones demonstrated in previous results, reflect the direct relationship between $N$, storage time, and the number of interfering items.

An examination of performance as $N$ increases for items outside the focus of attention (e.g., as $N$ increases from 2 to 4) can yield additional information about age differences in focus-switching. One previous finding was that the search process outside the focus of attention appeared to be less efficient in older adults than in younger adults. Younger adults showed a non-significant RT search slope in the outer store (a finding replicated by Verhaeghen et al., 2004); older adults showed a slope of about 70 ms/$N$. Older adults also showed greater decreases in accuracy than younger adults as $N$ increased (see also Van Gerven, Meijer, & Jolles, 2007, for a similar dissociation in response times and accuracy for middle-aged and younger adults). As additional evidence of the dissociation, Missonnier et al. (2004) and Mattay et al. (2006) both demonstrated greater age differences in accuracy at $N = 2$ than $N = 1$, but not response times. Taken together, these studies suggest a combination of decreased accessibility and availability of information once it leaves the focus of attention.

The Verhaeghen and Basak (2005) experiments bear replicating and extending. Specifically, the finding that the focus-switch process is age-insensitive with regard to speed deserves revisiting, given findings of reduced accuracy with this task and results indicating specific age-related slowing with other tasks that seem to tap either this aspect of working memory functioning (e.g., bracketed arithmetic; Salthouse & Coon, 1994; Verhaeghen, Kliegl, & Mayr, 1997) or other aspects of inter-task coordination (e.g., Mayr & Kliegl, 1993). One possibility is that the Verhaeghen and
The Basak version of the N-Back task simply did not challenge the working memory system enough to create an age-associated reduction in speed. The stimuli used were single digits – highly over-learned and relatively simple stimuli. Additionally, Verhaeghen and Basak modified the standard version of the task to make the binding between items and their position in the sequence of events clearer. In the standard version of the task, stimuli are presented one at a time in a fixed location on the computer screen. This requires the participant to continuously keep track of the temporal position of each stimulus in the series. Verhaeghen and Basak argued that this demand might be confounded with the working memory load of the task, and that a portion of the age differences may be due to reduced memory for temporal context (Hartman & Dumas, 2003; Hartman & Warren, 2005). Therefore, they designed a ‘columnized’ version of the task, presenting the stimuli one at a time in virtual columns on the screen. Each column in this version is defined by both location and stimulus color; the number of columns is equal to $N$ (see also Hartley, Speer, Jonides, Reuter-Lorenz, & Smith, 2001). The instruction to the participant is to compare the current item to the item last presented in the same column and color; this provides external support for stimulus-to-position binding, and the context (column and color) does not need to be updated once encoded. It is possible, therefore, that the columnized version of the task is easier and places fewer demands on the processes responsible for focus-switching and thus masks age differences. It is also possible that it minimizes age differences in encoding, storing, and retrieving information from outside the focus of attention.

The present study was designed to examine age differences in focus-switching and working-memory search outside the focus of attention under conditions that are closer to the limits of the working memory system than those employed by Verhaeghen and Basak (2005). Specifically, in Experiment 1, we compared performance in the columnized version of the identity judgment N-Back task with performance in the standard version of the task, in which items are presented in a single color in a single location on the screen. This contrasts the Verhaeghen and Basak easy-binding condition with a condition where no external support for positional binding is provided and bindings likely have to be updated continuously. In Experiment 2, we compared performance in the single-digit columnized version of the task with a triple-digit version – a three-fold increase in the complexity of the to-be-remembered stimuli over Verhaeghen and Basak’s implementation of the task. One research question is whether these more extreme conditions will lead to the emergence of age sensitivity in the focus-switch cost in RT, or whether the results obtained in previous studies would stand, that is, whether focus-switching would still lead to an age deficit in accuracy only. Furthermore, we wished to determine whether increased complexity would exacerbate age differences previously observed in accuracy of focus-switching.
Additionally, we were interested in investigating whether enhanced task difficulty would increase the difficulty of search for information in the outer store across age groups, and if so whether it would exacerbate age differences in either accuracy or rate of search.

EXPERIMENT 1

Methods

Participants

The sample consisted of 54 younger adults (ages 18–27, $M = 18.7$) and 58 older adults (ages 62–91, $M = 72.2$). Younger adults were undergraduate students who participated for course credit. Older adults were community-dwelling individuals who were paid $10/h for their effort. Inclusion criteria included self-reports of good health and normal or corrected-to-normal vision. Exclusion criteria included a history of neurological disorders, serious psychiatric illness or other major illness that could affect cognitive functioning (e.g., heart attack, diabetes, lung disease, kidney disease, uncontrolled high blood pressure), current use of psychotropic medications, reported learning disabilities (younger adults), current consumption of more than four alcoholic drinks per day (older adults), or scores of less than 27 on the Mini-Mental State Exam (MMSE; Folstein, Folstein, & McHugh, 1975) (older adults). In addition, screening with the Beck Depression Inventory-II (BDI-II; Beck, Steer, & Brown, 1996) and Beck Anxiety Inventory (BAI; Beck & Steer, 1990) was used to eliminate individuals with scores above the normal-to-mild range for depression and anxiety. Last, we excluded participants who did not meet a preset accuracy criterion of 90% correct in the $N = 1$ condition, to ensure the quality of the data. Two older adults were replaced because they scored below criterion on the MMSE; eight younger and two older adults were replaced based on their scores on the depression and anxiety measures. Seven older adults were replaced because they scored below the preset accuracy criterion of 90% correct in the $N = 1$ condition. This criterion was set to ensure data quality. Because the identity judgment task at $N = 1$ is very easy (comparing a single digit currently on the screen with a single digit that was presented just before it), we assume that low accuracy indicates a lack of motivation, poor cognitive skills, or both.

The older adults completed more years of education than the younger adults ($M = 16.4$ years, range: 12–20, vs. $M = 12.9$ years, range: 12–15, respectively), $t(110) = 11.07, p < .001$, and had higher scores on the Shipley–Hartford Vocabulary Test (Shipley, 1940) ($M = 35.0$, range: 29–40, vs. $M = 30.6$, range: 20–36, respectively), $t(110) = 6.67, p < .001$. 
Tasks

In the standard version of the identity-judgment N-Back task, the participant was presented with a sequence of digits, one at a time, and required to press one of two keys to indicate whether the digit presented on the screen was identical to the digit presented \( N \) positions back in the sequence. Single digits (white; 6 mm tall) were shown one at a time in the center of a black computer screen; the first \( N \) digits were presented at a rate of 2000 ms. Beginning with the presentation of the \( (N + 1)\text{th} \) digit, participants pressed either of two keys to indicate their answer, and the presentation was self-paced. The ‘/’ key labeled ‘Yes’ indicated a match, and the ‘z’ key labeled ‘No’ indicated a non-match. With each key press, a new stimulus appeared.

Each stimulus set (a ‘trial’) contained a total of 20 response items. A total of 11 trials (220 RTs total) were presented for each value of \( N \), with \( N \) varying from 1 to 4. Before the start of the first trial for each of the values of \( N \), participants were shown sample items, followed by two practice sequences. After each trial, the participant received feedback on both accuracy and mean RT. The order of trials was as follows: 6 trials of \( N = 1 \), 6 trials of \( N = 2 \), 6 trials of \( N = 3 \), 6 trials of \( N = 4 \), 5 trials of \( N = 4 \), 5 trials of \( N = 3 \), 5 trials of \( N = 2 \), and 5 trials of \( N = 1 \). For each trial, half of the stimuli were identical to the item N-Back, and the other half were not. The composition of each trial was randomized for each individual.

In the columnized version of the task, stimuli were displayed in \( N \) virtual columns on the screen. Figure 1 shows a black and white version of a sample stimulus set from one trial \( (N = 4) \), rendered as it would appear on the computer screen if all items remained visible. The digits were 6 mm tall, and the horizontal distance between the columns was 1.3 cm. Only one digit was shown at a time; the order of presentation was left-to-right and top-to-bottom. Each column was a different color; color-column assignments were constant throughout the experiment. For the first row, a new digit was presented every 2000 ms; from the second row on, participants pressed either of two keys to indicate their answer, and presentation was self-paced. With each key press, a new stimulus appeared. All other aspects of the procedure were identical to those of the standard task.

Procedure

The N-Back task was administered individually during one session that lasted approximately 90 min. All participants were screened for health problems prior to testing. At the beginning of the experiment, older adults completed the MMSE (Folstein et al., 1975). There were no other differences in procedure for younger and older adults.

Each participant took either the standard or the columnized version of the task, and the selection of task version was counterbalanced across participants.
Participants were encouraged to take short breaks half way through each task, and a longer break in the middle of the experiment. Prior to the second half of the experiment, participants took the Shipley–Hartford Vocabulary Test (Shipley, 1940). At the end of the experiment, participants completed both the BDI and BAI.

Results

Response Times

The level of significance for statistical testing was set at \( p = .05 \).

We conducted separate tests on each of the two relevant portions of the RT-by-\(N\) curve, that is, the \( N = 1 \) to \( N = 2 \) segment, associated with focus-switching, and the \( N = 2 \) to \( N = 4 \) segment, associated with working memory for items stored outside the focus of attention.

All reaction time (RT) analyses were conducted on correct responses only. For each individual, RTs above and below 2.5 \( SD \) from that individual’s mean RT were removed. Overall, 1% of younger adult RTs and 3% of older adult RTs were discarded. To examine differential age effects on RTs, a logarithmic transformation was applied to the data prior to testing for age by condition interactions (e.g., Cerella, 1994; Faust, Balota, Spieler, & Ferraro, 1999). The reason for this transformation is that one of the most pervasive effects of aging is near-multiplicative slowing, e.g., RTs of older

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adults are typically close to a ratio of RTs of younger adults (Cerella, 1990). Only age by condition interactions that survive a logarithmic transformation can be considered indicative of effects that go over and beyond the expected multiplicative effect of aging. We report full results for analyses using raw RTs, but note instances where the effects differed for log-transformed RTs. The results are presented in Figure 2.

The ANOVA for the focus-switch portion of the curve \((N = 1 \text{ and } N = 2)\) utilized a \(2 \times 2 \times 2\) \((N: 1 \text{ or } 2) \times \text{Task: standard or columnized}) design, with Age and Task as between-subjects factors and N as a within-subjects factor, and showed significant main effects of N, \(F(1, 108) = 200.49, MSE = 69,969.90, p < .001, \eta^2 = .65\); and Task, \(F(1, 108) = 17.24, MSE = 168,702.92, p < .001, \eta^2 = .14\). The interaction between the two was also significant, \(F(1, 108) = 18.31, MSE = 69,969.90, p < .001, \eta^2 = .15\). RTs were
slower at \( N = 2 \), and in the standard task. Increases in RT due to the focus switch were greater in the standard task (652 ms) than the columnized task (350 ms).

Effects of Age included a main effect, \( F(1, 108) = 72.63, MSE = 168,702.92, p < .001, \eta^2 = .40 \), as well as the two-way interaction with \( N \), \( F(1, 108) = 8.77, MSE = 69,969.90, p = .004, \eta^2 = .08 \). The Age \( \times \) \( N \) interaction did not survive logarithmic transformation, however, \( F(1, 108) = .19, MSE = .004, p = .66, \eta^2 = .002 \), indicating that the age difference in focus switching is not larger than that expected from general slowing. The Age \( \times \) Task interaction and the Age \( \times \) \( N \) \( \times \) Task interaction did not reach significance (\( F \) values <1).

Outside the focus of attention (\( N = 2 \) to \( N = 4 \)), the results of a 2(Age) \( \times \) 3 (\( N \): 2, 3, or 4) \( \times \) 2 (Task: standard or columnized) ANOVA, with Age and Task as between-subjects factors and \( N \) as a within-subjects factor, showed significant main effects of \( N \), \( F(2, 216) = 6.28, MSE = 50,720.29, p = .002, \eta^2 = .06 \); and Task, \( F(1, 108) = 16.91, MSE = 676,545.74, p < .001, \eta^2 = .14 \), but the interaction between the two was not significant, \( F(2, 216) = 1.29, MSE = 50720.29, p = .28, \eta^2 = .01 \). RTs were overall slower for higher levels of \( N \) and slower in the standard than the columnized condition.

Effects of Age included a main effect, \( F(1, 108) = 44.73, MSE = 676,545.74, p < .001, \eta^2 = .29 \). None of the two- or three-way interactions with age were significant: Age \( \times \) \( N \), Age \( \times \) Task, and Age \( \times \) \( N \) \( \times \) Task (\( F \) values < 1). Older adults thus showed overall slower RTs, but there were no differential effects of age for \( N \) or task.

**Accuracy**

The results are presented in Figure 2. Results of the ANOVA on the focus-switching portion of the curve (\( N = 1 \) and \( N = 2 \)) showed significant main effects of \( N \), \( F(1, 108) = 177.72, MSE = .002, p < .001, \eta^2 = .62 \); and Task, \( F(1, 108) = 6.85, MSE = .002, p = .01, \eta^2 = .06 \). The interaction between the two was also significant, \( F(1, 108) = 21.03, MSE = .002, p < .001, \eta^2 = .15 \). Accuracy was lower for \( N = 2 \) than \( N = 1 \), and in the standard compared to the columnized condition. Decreases in accuracy as \( N \) increased from 1 to 2 were greater in the standard task (10%) than the columnized task (5%).

Effects of Age included a main effect, \( F(1, 108) = 24.42, MSE = .002, p < .001, \eta^2 = .18 \); as well as the two-way interaction with \( N \), \( F(1, 108) = 3.03, MSE = .002, p < .001, \eta^2 = .16 \). The Age \( \times \) Task interaction and the Age \( \times \) \( N \) \( \times \) task interaction did not reach significance (\( F \) values < 1). Older adults showed overall decreased accuracy, especially at \( N = 2 \), but the type of task did not have a differential effect on their performance.

Outside the focus of attention (\( N = 2 \) to \( N = 4 \)), results of the ANOVA showed significant main effects of \( N \), \( F(2, 216) = 142.35, MSE = .002, p < .001, \eta^2 = .57 \); and Task, \( F(1, 108) = 44.44, MSE = .012, p < .001, \eta^2 = .29 \). The
interaction between the two was also significant, $F(2, 216) = 18.72, MSE = .002, p < .001, \eta^2 = .15$. Accuracy decreased with increases in $N$, and was lower in the standard than the columnized task. With accompanying increases in $N$, there were greater decreases in accuracy in the standard task (11%) than the columnized task (6%).

Effects of Age included a main effect, $F(1, 108) = 32.98, MSE = .012, p < .001, \eta^2 = .23$, and the two-way interaction with $N$, $F(2, 216) = 3.03, MSE = .002, p = .05, \eta^2 = .03$. The Age $\times$ Task and the Age $\times N \times$ Task interactions were not significant ($F$ values $< 1$). Older adults were overall less accurate, and this age difference grew with increasing $N$, but the type of task did not have a differential effect on their performance.

**Discussion**

In this experiment, we compared performance in the columnized version of the $N$-Back task with the standard version, in which items are presented in a single color in a single location on the screen. The conclusions with regard to the experimental manipulation are straightforward. First, we found evidence that our manipulation worked: The standard $N$-Back version, in which participants have to bind each item to its sequence in the time series without any environmental support, proved more difficult than the columnized version, in which clear environmental support for the binding is provided. The disadvantage of the standard condition is visible both in response times (with increases in RT of 296 ms, on average, over values of $N > 1$) and accuracy (with decreases in accuracy of 6%, on average, over values of $N > 1$). Second, we found that the manipulation influenced the focus-switching cost considerably, with greater focus-switching costs in the standard version. For RTs, the focus-switching cost was on average 350 ms in the columnized version and 653 ms in the standard version; for accuracy, the decrease associated with the focus-switching costs were 5 and 10%, respectively. Third, we found that the manipulation did not influence the speed of search processes outside the focus of attention, but that the decrease in accuracy over $N$ outside the focus of attention was larger in the standard condition than in the columnized condition. This result indicates that the accessibility (RT) and availability (accuracy) of an item stored in working memory can be reliably dissociated (see also McElree, 2001; Verhaeghen & Basak, 2005), which in turn suggests that item accessibility and item availability rely on different processes or mechanisms. The faster decrease in availability over $N$ in the standard version suggests that an increasing working memory load makes it harder to encode, maintain, or retrieve the binding between item and position when that binding is not supported by external cues, even though the search processes that bring the participant to the right ‘slot’ in working memory are equally efficient in both versions of the task. A fourth aspect of the data is more unexpected,
namely a reliable increase of RT with \( N \) outside the focus of attention (the average slope is 52 ms/\( N \)), indicating the existence of a search process. The finding is surprising because in at least three previous studies (Lange, Cerella, & Verhaeghen, 2006; Verhaeghen & Basak, 2005; Verhaeghen et al., 2004), no reliable effect of \( N \) on the RT outside the focus of attention was found. The reason of this discrepancy is unclear – likely the ‘real’ slope is shallow, and what we observe are variations around this slope that sometimes, as in the present study, become significant.

With regard to age effects, we found, as in previous research (Verhaeghen & Basak, 2005) that although older adults are slower to respond and have reduced accuracy relative to younger adults, they have no specific problems with the speed of switching their focus to items that reside outside the focus of attention, as measured by equivalent increases in RT from \( N = 1 \) to \( N = 2 \) after logarithmic transformation was applied to control for the effects of general slowing. Similarly, the search rate for items in the outer store is similar for young and old. In contrast, the relative availability of items residing outside the focus of attention is markedly lower for older adults, as measured by a much larger decrease in the probability of correct retrieval in this age group compared to younger adults when focus-switching is required or when the number of items in the outer store increases. We also note that, as in previous research, performance for both younger and older adults is nearly perfect within the focus of attention, again indicating the special, privileged status of items stored within this region of working memory.

Neither the age effects in RT or in accuracy were moderated by the experimental manipulation of task complexity. Thus, age differences in the speed of focus-switch cost did not emerge even under conditions that might be expected to be more sensitive to aging, and the results support previous findings demonstrating an age deficit in the accuracy but not speed of focus-switching. Similarly, task difficulty had no differential effect on older adults’ search rate for information in the outer store, leading us to conclude that both inside and outside the focus of attention, aging has larger effects on availability than access. All in all then, age differences in availability are present regardless of the type or difficulty of the requirements to create, maintain, and retrieve bindings between a stimulus and its place in the sequence of events. Taken together with prior evidence for reduced contextual memory in older adults across a range of tasks (Chalfonte & Johnson, 1996; Hartman & Warren, 2005; Mitchell, Johnson, Raye, Mather, & D’Esposito, 2000; Naveh-Benjamin, 1990, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003), the current findings suggest that aging has similar effects on context memory, regardless of whether the context entails temporal information or more externally-supported spatial/color context.
EXPERIMENT 2

In Experiment 1, we challenged the working memory system by increasing the difficulty of the binding-to-position process. In Experiment 2, we challenged the system in a different way, namely by increasing the complexity of the to-be-remembered items by requiring participants to bind features together in each stimulus.

Methods

Participants

The sample consisted of 42 younger adults (ages 18–22) and 41 older adults (ages 60–84). Inclusion criteria and screening procedures for younger and older adults were the same as in Experiment 1, except that the MMSE (Folstein et al., 1975) was not administered to older adults. Seven younger adults and two older adults were replaced based on their scores on the depression and anxiety measures. Two older adults were replaced because they scored below the preset accuracy criterion.

The older adults completed more years of education than the younger adults (\(M = 16.1\) years, range: 12–20, vs. \(M = 12.4\) years, range: 12.5–14.5, respectively), \(t(83) = 7.72, p < .001\), and had higher scores on the AmNart Vocabulary Test (Grober & Sliwinski, 1991) (\(M = 37.0\), range: 25–44, vs. \(M = 30.0\), range: 19–37, respectively) \(t(83) = 7.74, p < .001\).

Task

Two versions of the columnized N-Back task were used, one with single digits, the other with three-digit stimuli. The single digit version was the same as the columnized version used in Experiment 1, with the exception that each column consisted of white numbers on a black background.

In the three-digit version, stimuli were constructed using the following constraints: only the digits 1–9 were used, no two adjacent numbers were identical, and no three adjacent numbers followed a sequence (e.g., 123 or 987). Non-match stimuli varied from the target by one digit only, and this digit’s placement in the three-digit stimulus was randomized.

For both versions, each stimulus set (a ‘trial’) contained a total of 15 response items for \(N = 1\) and \(N = 3\) and 16 response items for \(N = 2\) and \(N = 4\). Before the start of the first trial for each value of \(N\), participants were shown sample items, followed by two practice sequences. After each trial, the participant received feedback on both performance accuracy and average RT. A total of 6 trials (90 RTs total for \(N = 1\) and \(N = 3\) and 96 RTs total for \(N = 2\) and \(N = 4\)) were presented for each value of \(N\). The order of trials was as follows: 3 trials of \(N = 1\), 3 trials of \(N = 2\), 3 trials of \(N = 3\), 3 trials of \(N = 4\), 3 trials of \(N = 4\), 3 trials of \(N = 3\), 3 trials of \(N = 2\), and 3 trials of \(N = 1\). For each trial, half of the stimuli were identical to the item N-Back, and the other
half were not. The composition of each trial was randomized for each individual.

**Procedure**

Using a within-subjects design, both the one-digit and the three-digit version were administered individually during a single session lasting 90 min. The order of the tasks was counterbalanced across participants. As in Experiment 1, participants were encouraged to take short breaks halfway through each task, and a longer break in the middle of the experiment. Prior to the second half of the experiment, participants took the AmNart Vocabulary Test (Grober & Sliwinski, 1991). All other screening measures were the same as in Experiment 1, and they were administered in the same order.

**Results**

**Response Times**

The level of significance for statistical testing was set at \( p = .05 \).

All RT analyses were conducted using correct responses only. For each individual, RTs above and below 2.5 SD from that individual’s mean RT were removed. Overall, 1% of younger adults’ and 3% of older adults’ RTs were discarded. The results are presented in Figure 3. As in Experiment 1, logarithmic transformations were applied to the data prior to testing for age by condition interactions.

A 2 (Age) × 2 (N: 1 or 2) × 2 (Digits: one and three) ANOVA on the focus-switching portion of the curve (\( N = 1 \) and \( N = 2 \)) showed significant main effects of \( N \), \( F(1, 81) = 446.22, MSE = 22538.41, p < .001, \eta^2 = .85 \), but not Digits, \( F(1, 81) = 1.72, MSE = 41,862.31, p = .193, \eta^2 = .02 \). The interaction between the two was significant, \( F(1, 81) = 5.89, MSE = 12,211.4, p = .02, \eta^2 = .07 \). RTs were overall slower for \( N = 2 \). With the increase in \( N \) from 1 to 2, the increase in RT was greater for three-digit stimuli (378 ms) than one-digit stimuli (318 ms).

Effects of Age included a main effect, \( F(1, 81) = 63.13, MSE = 184,377.67, p < .001, \eta^2 = .44 \), as well as both two-way interactions: Age × \( N \), \( F(1, 81) = 26.75, MSE = 22,538.41, p < .001, \eta^2 = .25 \), and Age × Digits, \( F(1, 81) = 4.43, MSE = 41862.31, p = .04, \eta^2 = .05 \). The Age × \( N \) × Digits interaction did not reach significance (\( F < 1 \)). The two-way interactions survived logarithmic transformation: Age × \( N \), \( F(1, 81) = 7.56, MSE = .002, p = .007, \eta^2 = .09 \), and Age × Digits, \( F(1, 81) = 6.21, MSE = .006, p = .02, \eta^2 = .07 \). Older adults showed overall slower RTs, especially as \( N \) increased. Unexpectedly, younger adults were slowed by an increase in the number of digits (76 ms), whereas older adults were in fact nominally faster for the three-digit stimuli than for the single-digit stimuli (18 ms).
Outside the focus of attention \((N = 2\) to \(N = 4\)), results of a 2 (Age) \(\times\) 3 (\(N: 2, 3,\) or 4) \(\times\) 2 (Digits: one and three) ANOVA showed significant main effects of \(N\), \(F(2, 162) = 49.18, MSE = 10,429.38, p < .001, \eta^2 = .38;\) and Digits, \(F(1, 81) = 6.17, MSE = 105,042.58, p = .02, \eta^2 = .07.\) The interaction between the two was also significant, \(F(2, 162) = 4.96, MSE = 9,386.51, p = .008, \eta^2 = .06.\) Increasing \(N\) and number of digits (three vs. one) increased RTs. RTs were somewhat more slowed across \(N = 2\) to \(N = 4\) for one-digit stimuli \((M = 117\text{ ms})\) than three-digit stimuli \((105\text{ ms})\).

The only effect involving Age was a main effect, \(F(1, 81) = 59.19, MSE = 454,064.85, p < .001, \eta^2 = .42.\) None of the two- or three-way interactions with age were significant (all \(F\) values < 1). Older adults showed overall slower RTs, but there were no differential age effects of the level of \(N\) or the number of digits.
Accuracy

The results are presented in Figure 3. Results of a 2 (Age) × 2 (N: 1 or 2) × 2 (Digits: one and three) ANOVA on the focus-switching portion of the curve, with Age as a between-subjects factors, and N and Digits as within-subjects factors, showed significant main effects of N, $F(1, 81) = 430.9$, $MSE = .001$, $p < .001$, $\eta^2 = .84$, and Digits, $F(1, 81) = 14.35$, $MSE = .001$, $p < .001$, $\eta^2 = .15$. The interaction between the two was also significant, $F(1, 81) = 16.08$, $MSE = .001$, $p < .001$, $\eta^2 = .17$. Accuracy was lower at $N = 2$, and in the three-digit condition, but the drop in accuracy from $N = 1$ to $N = 2$ was greater for three-digit stimuli (9.5%) than one-digit stimuli (7.5%).

Effects of Age on focus switching included a main effect, $F(1, 81) = 5.62$, $MSE = .002$, $p = .02$, $\eta^2 = .07$, as well as a two-way interaction with N, $F(1, 81) = 4.43$, $MSE = .001$, $p = .04$, $\eta^2 = .05$. The Age × Digit and the Age × N × Digit interactions did not reach significance ($F$ values < 1). Older adults showed overall decreased accuracy, especially as $N$ increased, but age did not differentially affect performance for three-digit stimuli.

Outside the focus of attention ($N = 2$ to $N = 4$), results of a 2 (Age) × 3 ($N$: 2, 3, or 4) × 2 (Digits: one and three) ANOVA, with Age as a between-subjects factors, and N and Digits as within-subjects factors, showed significant main effects of N, $F(2, 162) = 423.34$, $MSE = .001$, $p < .001$, $\eta^2 = .84$, and Digits, $F(1, 81) = 416.86$, $MSE = .005$, $p < .001$, $\eta^2 = .84$. The interaction between the two was also significant, $F(2, 162) = 175.67$, $MSE = .002$, $p < .001$, $\eta^2 = .68$. Overall, accuracy decreased as $N$ increased, and was lower for three-digit than one-digit stimuli. With increases in $N$, decreases in accuracy were greater for three-digit stimuli (21%) than one-digit stimuli (4%).

Effects of Age included a main effect, $F(1, 81) = 13.19$, $MSE = .010$, $p < .001$, $\eta^2 = .14$, and a two-way interaction with $N$, $F(2, 162) = 4.23$, $MSE = .001$, $p = .02$, $\eta^2 = .05$. The Age × Digits interaction and the Age × N × Digits interaction were not significant ($F$ values < 1). Older adults were overall less accurate, especially with increasing levels of $N$, but increasing the number of digits did not have a differential effect on age.

Discussion

In this experiment, we compared performance in a single-digit columnized version of the N-Back task with performance in a three-digit columnized version. It appears that the added stimulus complexity had an impact on performance, in ways similar to the effects of the manipulation in Experiment 1: participants were slower and less accurate in the three-digit version of the task than in the one-digit version (on average 54 ms slower and 9.1% less accurate). The manipulation had a clear effect on focus-switching as well. In RTs, the focus-switching cost was on average 318 ms in the single-digit version, and 378 ms in the three-digit version; in accuracy, the decrease
associated with the focus-switching cost was on average 7.5% in the one-digit version, and 9.5% ms in the three-digit version. Furthermore, outside the focus of attention, three-digit stimuli compared to single-digit stimuli led to larger decreases in accuracy as \( N \) increased, suggesting that more complex stimuli are more difficult to store into, maintain in, or retrieve from working memory (see also Alvarez & Cavanagh, 2004). The absence of a parallel effect on RT, however, represents a dissociation between accuracy and speed, indicating as in Experiment 1 that item availability and accessibility rely on at least partially independent processes. Nevertheless, both accuracy and RT show general effects of increasing values of \( N \) outside the focus of attention, replicating the findings in Experiment 1 and best interpreted as demonstrating the presence of a search process.

In addition to overall age effects, we found that accuracy of focus-switching was sensitive to aging. Similar to Experiment 1, both younger and older adults were essentially at ceiling with respect to accuracy for items residing within the focus of attention (i.e., at \( N = 1 \)), but there was a large age difference favoring younger adults for items residing outside the focus of attention. In addition, and unlike Experiment 1 or our previous work, the focus switch cost in RT was reliably larger in older adults (433 ms) than in younger adults (263 ms), even after logarithmic transformation. For information in the outer store, although older adults were slower overall, the slowing of RTs for increasing levels of \( N \) (\( N = 2–4 \)) was similar across age groups. In addition, age differences in accuracy increased with increasing level of \( N \). This dissociation of speed and accuracy was similar to the pattern observed in Experiment 1.

The stimulus complexity manipulation failed to exacerbate age differences for RTs or accuracy. In fact, although there was an age by complexity interaction for focus-switch RTs, this interaction went counter to the hypothesis, in that only younger adults were slowed by increased stimulus complexity. Although the reasons for this finding are unclear, the results provide no support for the hypothesis that search speed outside the focus of attention is more affected by complexity in older than younger adults. Overall then Experiment 2 showed no evidence that age-related changes in working memory are affected by stimulus complexity.

**GENERAL DISCUSSION**

In previous work, Verhaeghen and Basak (2005) concluded that the process of switching items in and out of the focus of attention within working memory is age-invariant in its speed of operation, but age-sensitive in its accuracy. This suggests that once slowing in perceptual and comparison processes is taken into account, items stored in working memory are equally accessible to older and younger adults, regardless of whether focus-switching is required.
In contrast, items that have left the focus of attention are generally less available to older adults. Furthermore, despite the absence of age-related slowing in focus-switching, we previously have found parallel age effects in accessibility and availability for items in the outer store: search through items in the outer store is slowed for older adults, as indicated by greater increases in RTs for older adults as the number of items in the outer store increases, and effects of age on accuracy are larger as the number of items in the outer store increases.

The present experiments were set up to further investigate these claims. More specifically, we attempted to push the working memory system closer to its limits to test whether more extreme conditions would cause age differences to emerge in the speed of the focus-switching process, exacerbate age differences previously found in accuracy for items in the outer store, or both. In addition, we wished to determine whether the parallel effects on accessibility and availability outside the focus of attention would hold under difficult conditions. In Experiment 1, we increased the difficulty of binding items to the sequence of events by omitting cues to location and color of items; in Experiment 2, we made the stimuli more complex by requiring the participants to compare three-digit numbers rather than single digits. These manipulations increased the amount of item-to-context binding and stimulus feature binding, respectively. Before we turn to the examination of the age-related effects in the data, we report on the more general cognitive findings from our two experiments.

Implications of Our Findings for Working Memory Theories

The two experiments reaffirm the existence of the distinction between information stored inside and outside the focus of attention (e.g., Cowan, 1988). The focus of attention appears to hold only a single item available for immediate processing, as indicated by a near-step function in response times: Response times are fast when a single item is stored in working memory, but markedly longer (145 ms or more) when two or more items are stored. Additionally, accuracy is near ceiling for a single item, but drops when more than one item needs to be stored. We believe that this is a capacity-based limit that reflects the difficulty of processing temporal order information in a serial attention task. An alternative interpretation is that the limit might be strategic, that is, it might not be useful to focus on more than one item because this would impede a direct comparison between the current digit on the screen and the $N$-Back item in memory. Previous research, however (Verhaeghen et al., 2004) shows that when participants amass practice with the task, the focus expands to hold four items, as indicated by a jump in RT between $N = 4$ and $N = 5$, coupled with near-ceiling accuracy for $N < 5$, without any noticeable cost associated with this increased focus. This makes an interpretation in terms of strategy unlikely. Note that we are not claiming
that the focus of attention cannot hold more than one item of information for all tasks. For instance it appears that the focus can hold three to four items under certain circumstances (e.g., subitizing or short-term memory tasks, Cowan, 2001). In demanding serial-attention tasks like $N$-Back, the limit does appear to be 1.

In the portion of working memory outside the focus of attention (i.e., when $N > 1$), we find a linear increase of RT with $N$. The slope of this function equals about 50 ms/item. As stated above, this finding is surprising because at least three previous studies (Lange et al., 2006; Verhaeghen & Basak, 2005; Verhaeghen et al., 2004) found no reliable effect of $N$ on RT outside the focus of attention for younger adults. We have interpreted this flat slope as evidence for content-addressability of the zone of working memory outside the focus of attention, and the non-flat slope obtained in older adults (Verhaeghen & Basak, 2005) as evidence for a search process. The only difference between the current experiments and the previous ones are the samples tested. The conclusion must be that search processes do operate outside the focus, but probably at either a very fast rate or in parallel fashion such that, in certain samples, this search process is virtually undetectable. It is likely that the ‘real’ slope is shallow, and what we observe are variations around this slope that sometimes, as in the present experiments, become significant, and other times remain under the threshold of statistical significance.

Findings regarding the impact of complexity showed significant effects on working memory performance. Making contextual binding (e.g., location, color, or temporal position) more difficult and increasing stimulus complexity both resulted in slower response times and decreased accuracy, as evidenced by increased focus-switching costs for the more complex conditions and by manipulation main effects for $N > 1$. Although we removed color cues in the columnized versions of the $N$-Back task used in Experiment 2, this appeared to have negligible effects on performance. Accuracy and response times for the one-digit columnized $N$-Back task were equivalent in Experiments 1 and 2, at each level of $N$, for each age group.

**Age-Related Effects**

The results with regard to the complexity by age interactions are unequivocal. Neither of the two complexity manipulations interacted with age in the expected direction in either the RT or accuracy domain. The observed pattern suggests a general age-related deficit in the encoding, maintenance, and retrieval of items stored in the outer store, which is not impacted by the type of contextual binding requirement or the complexity of stimuli.

As in our previous work, we found that accuracy was near perfect for both age groups for the item stored within the focus. The necessity to switch
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The focus of attention lowers accuracy in both age groups, but much more so in older adults than in younger adults, and with increasing $N$, the gap widens further. With respect to speed, the results from Experiment 1 were similar to results from our previous studies (Verhaeghen & Basak, 2005; Verhaeghen & Hoyer, 2007), in that there was no evidence for an age effect on the speed of execution of the focus-switching process once age differences in perceptual and comparison processes were taken into account. In Experiment 2, however, focus-switching was executed reliably more slowly by older than younger adults. The reason for this discrepancy is unclear; at present, it seems to us that the only difference between the baseline conditions reported here and those in the other studies cited above is the sample tested.

Nevertheless, we can state clearly that focus-switching reduces accuracy more in older than in younger adults. Our previous interpretations of the imperviousness of the focus-switching speed to aging may now be in doubt, and further experimentation is necessary to pinpoint the reason for the discrepancy: The result in Experiment 2 could be truly aberrant, or specific characteristics of the sample or the task context may have triggered age-differential focus-switching costs in RT.

For items stored outside the focus of attention, testing for age differences in the search rate found that older and younger adults search working memory with equal efficiency, at a rate of about 50 ms/$N$, averaged over all conditions, regardless of binding or stimulus complexity. The search rate of older adults was similar to that found in previous studies (Verhaeghen & Basak, 2005; Verhaeghen et al., 2004), although as noted above, finding a non-zero search rate in younger adults was not expected. With respect to accuracy, however, results were as expected, with rather large age differences for items stored outside the focus of attention, and increasing differences between younger and older adults as $N$ increased.

The current finding of an age-related difference in the accuracy of retrieving items from the outer store in the absence of consistent concurrent age-related differences in access speed is consistent with earlier studies (Leonards, Ibanez, & Giannakopoulos, 2002; Mattay et al., 2006; Missonnier et al., 2004; Van Gerven et al., 2007; Van Gerven et al., in press; Verhaeghen & Basak, 2005; Verhaeghen & Hoyer, 2007), and important because it suggests an alternative account of age differences in working memory. One influential theory posits that age differences in working memory performance might be tied to a slowing down of basic processes (Salthouse, 1996), and that basic speed mediates some of the age-related variance in span tasks (Verhaeghen & Salthouse, 1997). It appears unlikely that this theory can predict the present result. We found that older adults retrieve items stored outside the focus of attention with lower accuracy, but not slower speed. This strongly suggests that a specific mechanism, over and beyond the effects of general slowing, is necessary to explain why item representations
outside the focus of attention seem to be differentially vulnerable to aging. There might be problems with encoding, maintenance, or retrieval of stimuli and their context, or combinations thereof. These in turn might be tied to problems with binding information (item to context or features) (e.g., Chalfonte & Johnson, 1996; Naveh-Benjamin et al., 2003), to difficulties with coordinating storage and processing demands in working memory (e.g., Mayr & Kliegl, 1993), or to real capacity limits in item or context memory (Basak & Verhaeghen, 2003).

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