No Age Differences in Complex Memory Search: Older Adults Search as Efficiently as Younger Adults

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In 2 experiments, the authors investigated age differences in memory search under 4 conditions: forward search, backward search, random search, and fixed irregular search. Both search slopes and serial position curves were investigated. Mixing conditions led to smaller age differences than blocking conditions, suggesting that younger adults have an advantage over older adults when strategies can be applied to memory scanning. All age differences in scanning rates, however, disappeared when age differences in a magnitude-judgment control task were controlled for, showing that age differences in memory scanning tasks are not because of the scanning process per se, but because of attention, sensorimotor speed, and decision processes. In both experiments, the serial position curves of older adults echoed those of younger adults closely, demonstrating that younger and older adults use the same scanning processes.

Keywords: memory search, general slowing, short-term memory, encoding strategy, serial position effect

Working memory is the workspace of the mind, used for stimulus manipulation and temporary storage. As such, it is an essential system for cognitive processing, correlated with such diverse aspects of higher level cognition as reasoning (e.g., Kyllonen & Christal, 1990), reading comprehension (e.g., Daneman & Carpenter, 1980), and general intelligence (e.g., Conway, Kane, & Engle, 2003). There is little doubt that with advancing age, the capacity of the working memory system to hold and manipulate information declines. In a recent meta-analysis, for instance, Bopp and Verhaeghen (2007) concluded that all measures of short-term memory span show age differences favoring the young, but measures of true working memory show larger effects than those requiring mere storage and maintenance. For instance, the average age difference in forward digit span is about 0.5 items; in computation span, it is 1.5 items.

This age-related decline in working memory capacity may have implications for higher level aspects of cognition: In cross-sectional research, working memory/short-term memory span explains about 38% of the age-related variance in episodic memory, 24% of the age-related variance in spatial ability, and 34% of the age-related variance in reasoning (Verhaeghen & Salthouse, 1997). It has even been speculated that working memory capacity may be the underlying cause for age differences in selected aspects of executive control, such as task switching and dual-task control (e.g., Verhaeghen & Cerella, 2008).

In addition, there is a strong link between speed of processing and working memory. Age-related variance in working memory capacity is clearly mediated through perceptual speed (Verhaeghen & Salthouse, 1997). Salthouse (1996) has even posited a theoretical mechanism for this link: the simultaneity mechanism of cognitive slowing. According to Salthouse’s theory, some elements in working memory may fail to be available for later processing because they may have decayed by the time they are needed; the probability of this failure should be larger for slower systems, and therefore age-related slowing might explain age differences in working memory capacity. In the absence of specific age effects in speed, however, working memory deficits become much harder to explain. A corroboration of these findings might then clearly point at the very specific nature of the age-related decline in working memory capacity.

In our series of experiments, we zoom in on one subprocess of working memory performance, namely memory search. In a careful meta-analysis, Sliwinski and Hall (1998) showed that older adults are about 1.2 times slower than younger adults in performing short-term memory search (also known as memory scanning or the Sternberg task; Sternberg, 1966). But the picture is less clear when it comes to a memory scan procedure that involves working memory, for example the N-back task (Vaughan, Basak, Hartman, & Verhaeghen, in press; Verhaeghen & Basak, 2005). In the N-back task, participants are presented with a random sequence of digits; the task is to compare the digit on screen with the digit presented N positions back; both response time (RT) and accuracy are recorded. This task involves memory search processes and continuous updating of the current search set. Younger adults search through working memory with perfect efficiency for set sizes (i.e., values of N) larger than 1 (Verhaeghen & Basak, 2005; slope did not differ significantly from zero), but older adults showed a clear latency × Set Size slope (Verhaeghen & Basak, 2005; slope of 70 ms/N). In addition, this line of research revealed an interesting and unexpected dissociation between response latency and response accuracy. As expected from the working memory literature, sizable age differences in accuracy emerge for set sizes larger than 1; both age groups show a dramatic and monotonic decline in accuracy over set size. Thus, we are faced with a puzzle: If there is this strong purported link between speed (i.e.,
in the present context, RT) and accuracy, why do we find set-size slopes for both younger and older adults in accuracy in the absence of a set-size effect for the younger adults in RTs, but a pronounced slope for older adults?

May part of the explanation for the findings can be found in the nature of the search processes involved in the N-back task. These differ in at least three characteristics from those involved in the standard memory search task examined by Sliwinski and Hall (1998): (a) N-back search includes multiple probes, (b) items are probed in a predictable manner, (c) output order is correlated perfectly with the input order, and (d) this correlation is positive. Lange, Cerella, and Verhaeghen (2006) demonstrated in a simple memory search procedure with multiple probes that the probe order is crucial: When input order matches output order (positive and perfect correlation), search slopes are flat; in all other conditions, clear slopes indicate memory search processes (in the random condition, about 110 ms/N in Experiments 1, 3, and 4). Correspondingly, Oberauer (2006) showed in a modified N-back task that a clear set-size slope emerged for younger adults when the input–output order was corrupted (the slope was about 130 ms/N). Both investigations point in the same direction: Probe order is a crucial determinant of Latency × Set Size slopes. However, both investigations only concentrated on younger adults.

Using the same procedure as in Lange et al. (2006), the present two experiments focused on a simple memory search task, differentiating between different probe orders to unconfound several factors that might contribute to age differences in the set-size effect in general. The task was simple search: N stimuli (with N ranging from 3 to 5) were presented on the computer screen, and each of those N stimuli was probed. Probing was done in any of four orders: forward, as in the N-back task (predictable search with a perfectly positive input–output correlation); backward (predictable search with a perfectly negative input–output correlation); fixed irregular (i.e., items were probed in a predictable order but with a zero input–output correlation); and random (unpredictable search with a zero input–output correlation). In Experiment 1, the four conditions were blocked so that participants could maximize strategic differences between conditions, if any. In the second experiment, three of the four conditions were randomly intermixed, allowing us to examine age differences in strategic processing. We note that given the small values of N, we expected accuracy to be near ceiling, so that all effects would be driven into the latency domain.

We manipulated probe order to differentiate between two contributors to memory search costs: Predictability of probe order and correlation of input and output order. The literature on the Sternberg (1966) task has suggested that there should be an age effect in random probing (Sliwinski & Hall, 1998); the N-back literature likewise suggests an age effect in forward probing (Verhaeghen & Basak, 2005, but see Vaughan et al., in press). We do note, however, that the age difference must not necessarily depend on memory processes. For instance, in a replication and extension of the Sliwinski and Hall (1998) meta-analysis, Verhaeghen and Cerella (2008) found that the age effect for a diverse range of tasks including memory retrieval, with the age effect expressed as the ratio of older over younger adults’ Latency × Set Size slopes, coincided with the age-related slowing factor for sensorimotor-plus-simple-response-decisions tasks (simple and choice RTs). Verhaeghen (2006) found the same coincidence in the slowing factor for memory search and simple decision tasks. It is possible, then, that the observed age effect in memory scanning is not because of the task’s memory requirement but because of a sensorimotor component (the response component is unlikely to affect search slopes in memory scanning; it should have its impact on the intercept). To examine this possibility, we included a sensorimotor-plus-simple-response-decisions control condition in both experiments. The stimuli were digits probed in the same four orders as in the memory experiment, but the participant simply had to decide whether the digits shown denoted numbers that were larger or smaller than the number 5. This task has the same visual attention, sensorimotor, and response decision requirements as our memory task (plus an additional magnitude-judgment process, which is not expected to covary with set size), but no memory requirement.

In sum, our first question is whether memory search is differently affected by predictability or correlated input–output order between age groups. If predictability drives the interaction, we should find differences in all predictable order conditions (forward, backward, and fixed irregular) but not in the unpredictable random probe order. If correlation is the critical determinant, only the forward and backward probe conditions should result in age differences. If the direction of the correlation is important, then we would find age differences in the forward condition alone. In each of the experiments, we also examined age differences in serial position curves, to hunt for potential qualitative differences in search processes between groups. A second crucial question is whether age differences in memory search can be fully or partially explained by non–memory-related task components, such as visual attention, sensorimotor, and response decision processes.

Experiment 1

Method

Participants. The group of young adults consisted of 24 Syracuse University students, 11 men and 13 women. They received course credit for participating, and their mean age was 20. For the group of older adults, we recruited 24 participants from the Syracuse community, 9 men and 15 women. The mean age of the older adult group was 73 years (range = 64 to 78). The older adults were compensated for their participation by a small honorarium of $10 per hour.

Material and apparatus. The memory and probe list consisted of visually presented digits, randomly sampled without replacement from the digits 1 to 9. The digit 5 was excluded in the memory experiment, but the participant simply had to decide whether the digits shown denoted numbers that were larger or smaller than the number 5. This task has the same visual attention, sensorimotor, and response decision requirements as our memory task (plus an additional magnitude-judgment process, which is not expected to covary with set size), but no memory requirement.

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1 The younger adult data from these experiments are taken from a set of experiments aimed at a more theoretical investigation into search processes in working memory (Lange et al., 2006).
12 experimental blocks (4 search orders × 3 list lengths). The order of different factor levels was balanced between participants, using a Latin square design for list length and search order. The balancing consisted of 24 different orders, 1 serial order for each participant of each group.

Each trial in the recognition task was composed of a memory list of $N$ items, followed by $N$ probes; each trial in the magnitude-judgment task consisted of $N$ probes only. Each experimental block consisted of 20 trials for $N = 3$, 15 trials for $N = 4$, and 12 trials for $N = 5$, resulting in a constant number of 60 probes for each block independent of list length. In addition, 3 example trials were given in the beginning of each block.

In the recognition task, each block had 50% positive probes with an identity match and 50% negative probes with a mismatch. A negative probe was either a memory list item that was presented in a wrong position, so-called intrusion probes (one third of all negative probes), or it was a probe that did not occur in the memory list, so-called extralist probes (two thirds of all negative probes). In the magnitude-judgment task, 50% of the probes were larger than 5.

Before each experimental block—with either the recognition or the magnitude-judgment task—participants started with a few iterations of a location recall task (see Procedure section for details). This task served to acquaint and then remind participants of the different predictable search order conditions (forward, fixed irregular, and backward). To keep the procedure constant, this task was present in the random condition as well.

Each session started with an additional practice block of six trials for $N = 3$, five trials for $N = 4$, and four trials for $N = 5$—58 probes altogether—presented in random order, with either recognition or magnitude judgment as the task. We implemented this practice block to catch the main part of the exponential practice effect for RTs within each session. The remaining practice effect should be more or less linear, which we expected to be balanced out sufficiently by the Latin square design.

Procedure. Participants were tested individually in one of two quiet rooms. The two sessions of the experiment were no longer than 2 weeks apart. Duration of a session did not exceed 2 hr. Participants were able to select the assignment of the two response keys—the left and right error key on a standard PC keyboard—to the possible responses (“yes” or “no”; respectively, “larger 5” or “smaller 5”). This assignment was constant during a session and was announced at the beginning of each experimental block.

Participants received written instructions for the practice block; after the practice block, detailed information was provided about all aspects of the experiment, that is, the location recall task, the sequential order of the location recall task, and the main task (dependent on session; either recognition or magnitude-judgment task); the different set sizes; and search orders. Additionally, throughout the experiment, the different task manipulations were announced on the PC screen before each block. The four different search orders were explained by means of a schematic drawing on a separate sheet of paper (Figure 1). These schematics also served as onscreen cue displays for the probe orders during the experiment.

The experimental part of each session consisted of 12 blocks, 1 for each list length and search order. The block started with the location recall task, followed by the main task (either recognition or magnitude judgment). The visual display remained similar between all tasks. Figure 2 shows an example of the display sequence in the recognition task.

The location recall task started with $N$ empty frames. After 200 ms, the first memory list item occurred in one of the frames for 500 ms. Each item was masked with an X, and after a delay of 250 ms the next list item appeared. Each frame was addressed once. Memory list presentation was immediately followed by a 750-ms cue display for probe order. The cue was followed by the recall phase, starting with a display of empty frames and a mouse pointer in the middle of the screen. Participants moved the mouse pointer to the frames following the presentation order. They indicated each selected frame by pressing the left mouse button. In this task, the digits were irrelevant; just the order of addressed frames had to be recalled in serial order. Participants progressed to the next step of the experiment, the magnitude-judgment task, after recalling the order correctly in five consecutive trials.

In the magnitude-judgment task, the participants were presented with $N$ frames. A space bar press unveiled the 750-ms cue display. After the cue display, the first probe appeared and the magnitude-judgment task had to be carried out. Participants answered the question of whether each probe digit was larger or smaller than the digit 5. The answer was given by pressing one of the response keys. The probe was masked by an X that remained on the screen until the end of each trial. The next probe occurred after 200 ms. Each frame was addressed once.

An example trial of the recognition task is shown in Figure 2. The task started with $N$ empty frames. Participants initiated presentation of the first memory list item by pressing the space bar. Each memory list item occurred for 500 ms, followed by a mask (X) and an interstimulus interval of 250 ms. The presentation order was kept constant and followed the reading order left to right and up to down (forward order). The masking Xs remained on the screen until the cue display was presented for 750 ms. The cue display was followed by the probes. One probe occurred at a time, and all frames were addressed once. The task was to decide whether each probe was identical to the memory list item that was presented in the same frame before. Probes were presented until participants made their response by pressing one of the response keys, followed by masking the probe (X), and a response–probe interval of 200 ms.

![Figure 1. Schematic representation of the four probe orders for set sizes 3, 4, and 5; the display also served as the order cue before the recognition phase.](image-url)
Participants received feedback about their mean accuracy and their mean RT after each experimental block.

**Results and Discussion**

**Error rates.** Accuracy—calculated as proportion of correct answers per trial—was close to ceiling (for the younger adults, 97.41% in the magnitude-judgment task and 98.81% in the recognition task; for the older adults, 99.49% and 96.09%, respectively) and was therefore not analyzed.

**Analysis of variance (ANOVA) on response times.** We analyzed latencies regarding four factors: task type (magnitude judgment or memory search), search order (forward, backward, fixed irregular, or random), and set size (Ns = 3, 4, or 5) as the within-subject factors and age category (younger or older adult) as the between-subjects factor. Only correct responses were included, and values larger than the mean plus three times the standard deviation or smaller than 100 ms were excluded as outliers. We excluded 4% (2.2% wrong answers) of the response times of the older adults and 4.8% (2.9% wrong answers) of the younger adults. The data are presented in Figure 3. An alpha level of .05 was chosen for all statistical tests, and testing was two-tailed. The effect size is reported as partial eta-squared. If the assumption of sphericity is violated, we indicate this and report the nonadjusted degrees of freedom but the validated p values for the Fs.

In our first analysis, we investigated potential effects of predictability and correlation on age effects for search slopes. We carried out a three-factor ANOVA on latencies for performance in the recognition task, including search order (forward, backward, fixed irregular, and random), set size (Ns = 3, 4, and 5), and age group.

The main effect of search order was significant, \( F(3, 138) = 152.83, p < .001, \eta^2_p = .769 \), as was set size, \( F(2, 92) = 94.58, p < .001, \eta^2_p = .673 \), and their interaction, \( F(6, 276) = 23.45, p < .001, \eta^2_p = .338 \). The main effect of age was likewise significant, \( F(1, 46) = 48.58, p < .001, \eta^2_p = .514 \), and interacted with the two within-subject main effects of search order, \( F(3, 138) = 4.48, p < .01, \eta^2_p = .089 \), and set size, \( F(2, 92) = 4.20, p < .05, \eta^2_p = .084 \). The three-way interaction between age, search order, and set size was marginally significant, \( F(6, 276) = 2.29, p = .081 \) (Greenhouse-Geisser corrected), \( \eta^2_p = .047 \). To better understand the origin and nature of the interaction effects, we fitted our RT data into a hierarchical linear model, estimating intercepts and slopes per condition for each age group separately. The following model depicts the conditions in Experiment 1. Three search orders were designated by three dummy codes (d1, d2, and d3), assuming that one of the search orders (here, the forward order) was represented by setting all dummy codes to zero. The variables d1 to d3 capture the intercept values of the different conditions. The slope variable n captures the set-size effect (slope). Possible interactions between the slope with the search orders were captured by the products \((d1 \times n)_{ij}, (d2 \times n)_{ij}, (d3 \times n)_{ij}\). Parameters was chosen to best represent the data.

\[
rt_{ij} = \beta_{0ij} + \beta_{ij1}n_{ij} + \beta_{ij2}d_{ij1} + \beta_{ij3}d_{ij2} + \beta_{ij4}d_{ij3} + \beta_{ij5}d_{ij4} + \beta_{ij6}d_{ij5} + \beta_{ij7}d_{ij6} + \beta_{ij8}d_{ij7} + \beta_{ij9}d_{ij8} + \epsilon_{ij}
\]

\[
\beta_{0ij} = \beta_0 + u_{0ij} + e_{0ij},
\]

\[
\beta_{1ij} = \beta_1 + u_{1ij} + e_{1ij}.
\]

Data were described taking the interindividual differences into account by specifying two levels. Level 1 varied within participants (i) and Level 2 between participants (j). For Level 2, we specified as many explanatory variables as needed to describe the conditions by dummy codes (fixed effects). For Level 1, we set two parameters to capture interindividual differences (random effects) in the intercept (cons) and the slope (n), indicated by the two weights, \( \beta_{0ij} \) for the intercept and \( \beta_{1ij} \) for the slope. \( u_{0ij} \) and \( u_{1ij} \) were random departures on Level 2 (between-participant variation), and \( e_{0ij} \) and \( e_{1ij} \) were random departures on Level 1 (within-participant variation). Intercepts were fit to set-size 3. Parameters that were not significantly different from zero were excluded, and common parameters were set when the means and standard errors suggested that. Model fits were compared with a chi-square test. When model fits did not differ, the model with the fewest parameters was chosen to best represent the data.

Figure 3 shows mean latencies and superimposed regression fits. For the younger adults, slopes for the forward condition were flat as expected; all other probe orders lead to pronounced slopes, with a common slope of 105 ms/N in backward and random search and a steeper slope of 150 ms/N in the fixed irregular condition. Intercepts increased from 602 ms in the forward condition to 790 ms in the backward condition, 813 in the fixed irregular condition,
and 850 ms in the random condition. The pattern for the older adults looked very similar, with a flat slope in the forward condition (intercept = 995 ms) and steeper slopes for all other conditions (backward and random slope = 157 ms/N, fixed irregular slope = 239 ms/N, backward intercept = 1,200 ms, and random and fixed irregular intercept = 1,282 ms). When comparing conditions separately in ANOVAs with the factors set size and age, the interaction for the forward slope and age was far from significant ($F < 1$), but all other slopes were modulated by age: The common slope for the backward and random condition differed between age groups, $F(2, 92) = 5.77, p < .01, \eta^2_p = .111$, but was not differentially affected by age ($F < 1$), and the slope in the fixed irregular condition was marginally significant for age groups, $F(2, 92) = 3.37, p = .046$ (Greenhouse-Geisser corrected), $\eta^2_p = .068$. Thus, both age groups yielded a zero slope for the forward condition; the slopes for all other conditions were modulated by age.

Hence, we failed to replicate the Age $\times$ Set Size interaction for the forward condition that we previously obtained in the N-back task (Verhaeghen & Basak, 2005). The nonexistent forward slope for older adults had a dramatic impact on our planned orthogonal contrast between predictability and input–output correlation and its effect on age effects in memory search. Memory search orders that are predictable (all but the random condition) were not differentially affected by age in comparison to the unpredictable search order (random condition); memory search orders with input–output correlation (forward and backward) were not differentially affected by age in comparison to irregular orders (fixed irregular and random).

More specific information about search processes can be derived from serial position functions. Figure 4 shows mean RTs for serial input positions separately for search orders and age groups. The functions show pronounced effects of serial position in the four search orders. The shapes do not appear to differ between older and younger adults, suggesting that both age groups bring identical search processes to the task, with both age groups showing only minor modulation in latency as a function of position when probed in forward order (besides a pronounced slowing for the first position) and characteristic shapes for all other probe orders. To examine the age differences for serial position effects quantitatively, we conducted a linear regression analysis, regressing the mean RTs of older adults onto the corresponding mean RTs of younger adults (48 data points). The slope of the line (often identified as the age-related slowing factor; e.g., Cerella, Poon, & Williams, 1980) was 1.45, its intercept was 89.69, and the regression explained 95.96% of the variance. When excluding the data from the forward condition, the age-related slowing factor was still in the same range: 1.53 (intercept = 5.05, $R^2 = 94.44\%$), indicating that a similar slowing factor underlies the forward and all other probe orders.

The latter finding was corroborated in a replication of our initial three-factor ANOVA, now using log-transformed latencies to control for the multiplicative effects of slowing (Faust, Balota, Spieler, & Ferraro, 1999). All interactions with age disappeared: the interaction with search order, $F(3, 138) = 1.90, p = .132, \eta^2_p = .040$; the interaction with set size ($F < 1$); and the triple interaction of age with search order and set size ($F < 1$).

A second goal of our study was to test whether other processes, such as visual attention and sensorimotor or decision processes, contribute to age differences in memory search. Figure 5 presents the data from our magnitude-judgment control task. The three-factor ANOVA yielded a main effect of search order, $F(3, 138) = 33.19, p < .001, \eta^2_p = .419$, and no main effect of set size, $F(2, 92) = 1.13, p = .329, \eta^2_p = .024$, but a significant interaction, $F(6, 276) = 3.11, \eta^2_p = .063$. Although the main effect of age was significant, $F(1, 46) = 65.19, p < .001, \eta^2_p = .586$, age did not interact in any way with the other factors. The significant interaction between set size and search order did not imply differential slopes: A hierarchical linear model showed that the data were best represented by zero slopes and intercept differences. For the younger adults, the random intercept (588 ms) differed from all others (516 ms); for the older adults, the forward condition provided the lowest intercept (801 ms), followed by a common and slightly increased intercept of the fixed irregular and the backward condition (832 ms); and the random condition yielded the largest intercept (919 ms).

In sum, there is no evidence that memory search slopes are confounded with visual attention, sensorimotor, or decision processes: Those components of every memory search task showed no (linear)

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2 Means with the 95% confidence interval are based on the error term corrected for repeated measures design by Bakeman and McArthur (1996).

3 Unfortunately, a separate regression for the forward data could not be performed because the data are tightly clustered, making a reliable estimation of a linear regression line unlikely.
effect of set size. One consistent intercept increase was found for the random condition in the control and recognition tasks.

To test whether age effects—on slopes and intercepts—in the memory search task can be reduced to the age effect already present in the visual attention, sensorimotor processes, and decision components of the magnitude-judgment task, we constructed difference scores between the log-transformed memory search conditions and each corresponding log-transformed magnitude-judgment condition and submitted these to analysis of variance. The logic here is that if the same age-related slowing factor $s$ governs both types of tasks, age differences should be absent in these difference scores. This can be formalized mathematically. Under strict multiplicative slowing, we would expect latencies of older adults in the memory search task to equal those of younger adults, multiplied by a slowing factor $s_2$. By log-transforming the data, we then obtain the following equalities:

$$\log RT(\text{older, memory search}) - \log RT(\text{older, magnitude judgment}) = \log [s_1 RT(\text{younger, memory search})] - \log [s_2 RT(\text{younger, magnitude judgment})]$$

$$= \log s_1 + \log RT(\text{younger, memory search}) - \log s_2$$

$$= (\log s_1 - \log s_2) + [\log RT(\text{younger, memory search}) - \log RT(\text{younger, magnitude judgment})]$$

Figure 4. Serial input position functions for younger (above) and older (below) adults with the four probe orders forward, fixed irregular, backward, and random (from left to right) from Experiment 1. (See footnote 2.)

Figure 5. Latency set-size functions for younger (left) and older (right) adults in the control task without the memory component of Experiment 1. Means with superimposed regression fits are based on a hierarchical linear model analysis. (See footnote 2.)
In other words, if and only if the age-related slowing factors for magnitude judgment and memory search are identical will there be no age difference in the log-transformed difference scores between the two conditions. If there is one, the difference \( d \) between younger and older adults’ difference scores gives us a direct indicator of the size of the difference between the slowing factors for the magnitude-judgment task and the memory search task: \( d = (\log s_1 - \log s_2) = \log(s_1/s_2) \), or \( \exp(d) = s_1/s_2 \).

The three-factor ANOVA on condition, set size, and age showed neither a significant main effect of age (\( F < 1 \)) nor any significant age interaction (\( F(1, 1.1) \) for the interaction with set size or the triple interaction and a marginal effect for the interaction with condition, \( F(3, 138) = 2.72, p = .057 \) (Greenhouse-Geisser corrected)), \( \eta^2_p = .056 \). The marginal interaction suggests that the difference scores for older adults were slightly larger than those for younger adults in the forward condition (0.217 vs. 0.155), but a difference scores for older adults were slightly larger than those for the random (0.426 vs. 0.444), and the fixed irregular (0.556 vs. 0.551) conditions (all \( F < 1 \)). If anything, then, the almost significant interaction counters the commonsense hypothesis that age differences (in the present case, in the memory search process per se) should be larger for more complex tasks, but the effects are nominally small. This is also evident by calculating the slowing factors as described above. In the forward condition, the age-related slowing factor was 1.06 times larger than for memory search than for magnitude judgment; in the backward condition, it was 0.99 times larger; in the random condition, it was 0.98 times larger; and in the fixed irregular condition, it was 1.00 times larger.

In conclusion, controlling for the age effect in the magnitude-judgment task, which has no memory search component at all, makes age differences in the memory search task disappear. Hence, the age differences in memory search can be attributed to the general age effects already present in the component processes of the control task.

The main goal of this experiment was to examine age differences in the dynamics of memory search under four probing orders: forward (predictable search with a perfectly positive input–output correlation), backward (predictable search with a perfectly negative input–output correlation), fixed irregular (where items were probed in a predictable order but with a zero input–output correlation), and random (unpredictable search with a zero input–output correlation). We failed to find an age interaction for memory slopes in the forward condition: Both age groups showed a flat slope, indicating that representations were directly accessible and no time-consuming and set-size–dependent search was necessary. We also failed to find an effect of predictability and input–output correlation: The three predictable conditions of probe order did not differ systematically from the one unpredictable condition, and the correlated orders did not differ systematically from the uncorrelated orders. Our results suggest that forward search, with its zero slope, has special status and that fixed-regular search, for as-yet unknown reasons, is the most complex task. A likely explanation for the latter finding is that retrieving the sequence in the context of retrieving the items leads to an increase in search time per item. This is a paradoxical effect—it suggests that if participants had simply treated the condition as a random condition, being led where the experiment leads them, they would have been faster than when trying to anticipate.

The results with regard to aging are clear, and perhaps surprising: Older adults search as efficiently as younger adults, once we control for age-related slowing in the general task components already present in the control task. The age-related deficit in memory scanning can thus be reduced to the age-related deficit in attention, sensorimotor processing, and/or response selection already present in the magnitude-judgment task.

Perhaps even stronger evidence for this position comes from the serial position curves. Each of the four conditions shows a very particular qualitative pattern, yet the average RTs for younger adults predicted the average RTs for older adults extremely well, with 96% of the variance explained by a simple linear model. This strongly suggests that younger and older adults adopted the same search strategies or processes in approaching the task—older adults are simply slower in implementing these processes, and this slowing is very well represented by just one general factor, representing about 50% slowing.

One potential objection to this interpretation is that it relies on acceptance of the null hypothesis, that is, the hypothesis that there are no age differences over and beyond the effects of general slowing. Should we trust this null result? We would argue that we can. We note that there was no failure to detect condition effects in this experiment. This suggests that the lack of a significant Age × Search Order interaction is not the result of an unreliable measurement of condition effects, but might merely reflect that these condition effects are remarkably similar across both age groups. Experiment 2 provides us with one additional opportunity to obtain Age × Condition interactions.

**Experiment 2**

Experiment 1 showed that once the sensorimotor and simple decision requirements of the task are taken into account, age differences in memory search rates disappear. Moreover, serial position curves showed the same pattern in both age groups. One potential objection to our results could be that we blocked the search order conditions, thus allowing participants to maximally prepare for each type of search order, be it during encoding or the set up for retrieval. According to this reasoning, the lack of age differences in Experiment 1 could be a result of enhanced strategic processing in the older age group. To check on this possibility, we replicated Experiment 1, except that we now mixed all conditions. In this way, participants cannot prepare for a specific type of probing order during the encoding phase, they cannot set themselves up for the first probe before retrieval, and they remain at least somewhat uncertain about the probing order during the retrieval phase. In this experiment, we could not implement the fixed-irregular condition because it is not possible to alert participants to the occurrence of a fixed-irregular trial without destroying the purpose of the experiment, that is, to negate strategic processing. Additionally, implementing this condition without warning in the hope that participants would implicitly learn the sequence would likely have prolonged the experiment considerably.
Method

Participants. Twenty-four Syracuse University students served as participants for the group of younger adults, 8 men and 16 women. Their mean age was 20 years (range = 18 to 30). The students received course credit for participation, except for 4 who were paid the same honorarium as the older adults, $10 per hour. Twenty-four people from the Syracuse community agreed to participate in the group of older adults, 10 men and 14 women. Mean age was 74 years (range = 62 to 82).

Design and procedure. Material and apparatus were identical to those used in Experiment 1. The design differed in two aspects: The three different probe orders (forward, backward, and random) were quasi-randomized on a trial-by-trial basis. We increased the proportion of intrusion probes in the negative probes from one third to one half to make the task more difficult and boost possible age effects. The procedure differed in a few respects. The display was simplified by arranging colored frames in two rows. In the memory search task, the memory list items occurred in the first row and the probe items in the second row, so that identity matches were carried out between items occurring in the same column. Frames in the same column shared the same color, with the colors red, turquoise, green, hot pink, and light gray from left to right for set size 3 (with the two rightmost colors removed) to set size 5. In the magnitude-judgment task, frames of the first row were filled with an X, and probes were presented in the second row only. Timing was equivalent to Experiment 1, as was the presentation of masks. Answers were given by pressing one of two keys, as explained in the Procedure section of Experiment 1.

Results and Discussion

Error rates. Error rates were close to ceiling and were therefore not analyzed. Mean accuracy across both tasks was 97.33% for younger adults and 98.00% for older adults.

ANOVA on response times. Because of wrong answers and outlier analysis, we excluded 3.8% (2% wrong answers) of the RTs of the older adults and 4.7% (2.7% wrong answers) of the RTs of the younger adults. First, the remaining RTs for the recognition task were subjected to the three-way ANOVA (search order, set size, and age) and are shown in Figure 6. Again, there was a significant main effect of search order, $F(2, 92) = 206.31, p < .001, \eta^2_p = .818$; a main effect of set size, $F(2, 92) = 113.94, p < .001, \eta^2_p = .712$; and a significant interaction, $F(4, 184) = 37.50, p < .001, \eta^2_p = .449$. The factor age yielded a significant effect, $F(1, 46) = 22.05, p < .001, \eta^2_p = .324$, but did not interact significantly with set size or Set Size $\times$ Search Order (both $F$s < 1) and only marginally with search order, $F(2, 92) = 3.54, p = .052$ (Greenhouse-Geisser corrected), $\eta^2_p = .071$. Fitting latencies into a hierarchical linear model again revealed a flat slope in the forward condition for the younger adults (intercept = 747 ms), but a pronounced and common slope for the backward and random conditions of 113 ms/N and a common intercept of 896 ms. The latencies of the older participants fitted a flat slope in the forward condition as well (intercept = 1,080 ms), a pronounced set-size effect for backward and random order with a common slope of 126 ms/N, and slightly different intercepts (backward order = 1,221 ms; random order = 1,293 ms). The hierarchical linear model analysis on this mixed design thus differed from the analysis on the blocked design in two ways. First, the intercept difference between the backward and random conditions disappeared for the young adults but remained for the older adults. Second, the difference between the slope parameters for younger and older adults is small (only 13 ms). When testing each search order separately in a two-factor ANOVA of set size and age, none of the interactions between the two factors was significant for any of the search orders (all $F$s < 1). Hence, the ANOVA did not confirm the results from the linear regression analysis, which yielded a slightly steeper slope for the older adults than for the younger adults.

Again, another test for age differences is to examine the serial position functions; these are shown in Figure 7. Pronounced serial position effects can be seen for both younger and older adults. The shape did not appear to differ between older and younger adults, suggesting that both age groups used identical search processes for the task. This suggestion was strongly supported by a linear regression analysis that resulted in a pronounced intercept of 317 ms, but virtually no slowing factor for age, with a slope of 1.03 ($R^2 = .95$).

![Figure 6](image_url)
The results from the control task differed from those obtained in Experiment 1, as can be seen in Figure 8. The three-factor ANOVA yielded a significant main effect of search order, $F(2, 92) = 71.79, p < .001, \eta^2_g = .610$; a main effect of set size, $F(2, 92) = 5.48, p < .001, \eta^2_g = .106$; and a significant interaction, $F(4, 184) = 9.71, p < .001, \eta^2_g = .174$. The main effect of age was significant, $F(1, 46) = 50.18, p < .001, \eta^2_g = .522$, and interacted with search order, $F(2, 92) = 9.54, p < .001, \eta^2_g = .172$, and marginally with Search Order x Set Size, $F(4, 184) = 2.16, p = .087$ (Greenhouse-Geisser corrected), $\eta^2_g = .045$, but not with set size ($F < 1$). The hierarchical linear model revealed a small slope of $16 \text{ms/N}$ for the random condition for the younger adults (intercept = 613 ms) and of 29 ms/N for the older adults (intercept = 860 ms), but a flat slope for all other conditions (older adults’ intercepts: backward = 842 ms, forward = 821 ms; younger adults’ intercepts: backward = 613 ms, forward = 595 ms). Hence, we found a small effect of search order in our control task, indicating that the processes implicated in this task do contribute to the memory search slopes. Given the size of the two types of slopes, this contribution, however, seems minor.

Because of the small contribution of attentional, sensorimotor, and decision processes to the set-size effect, an adequate test for

![Figure 7. Serial input position functions for younger (above) and older (below) adults for the four probe orders forward, fixed irregular, backward, and random (from left to right) from Experiment 2. (See footnote 2.)](image)

![Figure 8. Latency set-size functions for younger (left) and older (right) adults in the control task without memory component of Experiment 2. Means with superimposed regression fits based on a hierarchical linear model analysis. (See footnote 2.)](image)
age differences in memory search is even more important in Experiment 2 than in Experiment 1. When examining the difference scores of log-transformed latencies for the memory search conditions and the magnitude judgment conditions, the main effect of age disappeared \((F < 1)\) and so did the interaction with set size and the triple interaction; the interaction with condition, however, yielded a significant effect, \(F(2, 92) = 3.43, p = .046\) (Greenhouse-Geisser corrected), \(\eta^2_g = .069\). Again, the interaction is because of slightly larger difference scores for older adults \((M = .253)\) than for younger adults \((M = .211)\) in the forward condition, a numerical effect that was, however, not significant, \(F(1, 46) = 1.04, p = .313, \eta^2_g = .022\). Differences scores matched for older and younger adults in the random condition (both \(Ms = .434\)) and the backward condition (older \(M = .429\), younger \(M = .437\); both \(Fs < 1\)). Correspondingly, the age-related slowing factor for forward memory search was 1.04 times the slowing factor for magnitude judgment; 1.00 times for random search; and .99 for backward search. Although the interaction is statistically significant, the effects appear to be quite small in magnitude and nonsignificant in single comparisons.

### General Discussion

The results from our experiments are clear. With regard to general cognitive effects, we find a flat RT \(\times\) Set Size slope for forward probing and identical slopes for backward and random probing. Given that in Experiment 2, the conditions were mixed rather than blocked, thereby preventing participants from strategically preparing for a particular search order, this finding suggests that the flat slope for forward probing is not because of deliberate processing, but might be a natural consequence of the forward retrieval order, for instance stepwise cycling through a phonological loop (Baddeley, 1986; we explore this possibility in more detail in Lange et al., 2006). Strategies do play a role in memory search: When conditions were mixed, RTs were longer overall for the search conditions (i.e., backward and random search, where the memory set had to be accessed out of order) than when they were not. This was a constant difference rather than a slope difference, suggesting that the strategies are tied to set up rather than making the search processes themselves more efficient. The finding that the mixed versus blocked manipulation had little impact on the magnitude-judgment latencies suggests that this strategic set-up process is tied to memory processes, not to general attentional, sensorimotor, or decision processes. Further research is necessary to identify this process exactly.

Both experiments led to the conclusion that there are no specific age differences in memory search; that is, age differences in search latencies could be explained by age differences already present in the magnitude-judgment control condition, which does not contain any memory search process. When conditions were mixed, age differences were somewhat smaller than when they were blocked: Age effects in Experiment 2 were absent even before log-transformation in the three-way ANOVA and in the regression analyses on serial position latencies. This suggests that younger adults might have a slight advantage over older adults when strategies can be applied to memory scanning. More research, including a within-subject replication, is necessary before this conclusion can be drawn with some firmness.

In both experiments, the serial position curves of older adults closely echoed those of younger adults: Average RTs of younger adults predicted average RTs of older adults with high accuracy, explaining 95\% or more of the variance in a simple linear model. This is strong evidence that younger and older adults use the same scanning processes in the same sequence.

In sum, both experiments converge on the conclusions that age differences in memory scanning rates disappear once age differences in attention, sensorimotor speed, and decision processes are taken into account under a multiplicative slowing model and that younger and older adults apply an identical set of processes to the tasks. They also shed some light on the question of which processes might underlay our previous finding of a set-size slope for older but not for younger adults in the N-back task. The N-back task includes both memory encoding and memory search components, but also necessitates continuous updating of the search set. Obviously, the memory encoding and search components themselves are well preserved with age. The prominent remaining component is the updating process, as well as the processes involved in coordinating search and updating. Our working hypothesis is that this coordination requirement, imposed by the dual-task nature of the N-back task, is the driving force of the specific age deficit in this task. This assumption is obviously in need of further verification, but it is in line with a large number of findings of larger age differences under dual-tasking circumstances (for a meta-analysis, see Verhaeghen, Steitz, Sliwinski, & Cerella, 2002; see also Bopp & Verhaeghen, 2007) than single-task circumstances.

### References


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