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Working Memory and Aging: Separating the Effects of Content and Context

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Abstract

In three experiments, we investigated the hypothesis that age-related differences in working memory might be due to the inability to bind content with context. Participants were required to find a repeating stimulus within a single series (no context memory required) or within multiple series (necessitating memory for context). Response time and accuracy were examined in two task domains: verbal and visuospatial. Binding content with context led to longer processing time and poorer accuracy in both age groups, even when working memory load was held constant. Although older adults were overall slower and less accurate than younger adults, the need for context memory did not differentially affect their performance. It is therefore unlikely that age differences in working memory are due to specific age-related problems with content-with-context binding.

Keywords

Source memory; working memory; context memory; aging; age differences

Age differences in tasks of short-term memory that require only storage and maintenance of information are relatively small. Tasks tapping true working memory, that is, tasks that require simultaneous passive storage and maintenance as well as active processing of information, show much larger age differences (see review articles such as Carpenter, Miyake, & Just, 1994; Craik & Jennings, 1992; Light, 1991; Salthouse, 1994; or meta-analyses such as Bopp & Verhaeghen, 2005; Verhaeghen, Marcoen, & Goossens, 1993; and Verhaeghen & Salthouse, 1997). Given that working memory is often used as a mechanism to explain age-related declines in higher-order cognition (Salthouse, 1991; 1994), one important question concerns the exact locus of these age-related differences in working memory performance. Working memory tasks involve a host of cognitive processes and mechanisms. One aspect that has gone largely unnoticed (with a few notable exceptions: Göthe & Oberauer, 2008; Mitchell, Johnson, Raye, & Greene, 2003; Oberauer, 2008) is that working memory measures often not only tap memory for content, but memory for context as well. That is, working memory tasks items are often presented in a context of ongoing processing, sometimes even performed on a very similar set of materials, making binding of the content with its specific context (i.e., whether the item was

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part of the set of to-be-remembered stimuli or not) necessary to achieve high performance. This requirement is less pronounced in standard short-term memory tasks such as digit span or word span.¹

It can be argued that the two of the most popular working memory tasks clearly fall into this content-with-context category. First, the so-called working memory span tasks that have become standard for measuring individual and age differences in working memory capacity (for a review, see Conway et al., 2005) all contain dual sets of materials, only one of which needs to be recalled. For example, reading span (Daneman & Carpenter, 1980) requires participants to process sets of sentences while remembering the last word of each sentence. In these tasks, then, the participant must not simply recall every stimulus presented, but only those that were targeted as the to-be-remembered stimuli. To be successful, s/he therefore must create some binding between each item and its context. In a meta-analysis, Bopp and Verhaeghen (2005) found that average span as measured by content-only tasks (viz., forward digit span, word span, letter span) is 6.2 for younger adults and 5.5 for older adults, thus yielding an age difference of 0.7 items. Content-with-context tasks (viz., computation span, listening span, reading span, and sentence span) yield a larger age difference: Younger adults have an average working memory span of 4.2 items and older adults of 3.0 items, thus yielding an age difference of 1.2 items.

A second age-sensitive task that is potentially vulnerable to context memory effects is the *N*-Back task and its many variants (e.g., Kwong-See & Ryan, 1995; Missonnier et al., 2004; Vaughan, Basak, Hartman, & Verhaeghen, 2008; Verhaeghen & Basak, 2005). In the *N*-Back task, participants are presented with a running series of stimuli (typically digits) and have to make some judgment related to the item presented *N* positions back in the series. To be able to do this, participants have to maintain a running memory of *N* items. When *N* = 1, the task can be performed without any possibility for source confusion. When *N* is larger than 1, however, the subject needs to remember not just whether the item has been presented before, but also where in the sequence of events it belongs. In previous work in our lab (Vaughan et al., 2008; Verhaeghen & Basak, 2005), we found a clear dissociation between age differences in accuracy for *N* = 1 compared to higher values of *N*. We have attributed these age differences to a specific deficit associated with the process that swaps items in and out of the focus of attention, but it is equally possible that a specific age deficit in context memory is to blame. The finding that age differences remain stable (in both accuracy and RT) when *N* increases from 2 to 5 lends further credence to this conjecture: If context binding is the culprit, one might expect an all-or-none effect operating between the condition where no binding is necessary (*N* = 1) and the conditions where it is (*N* > 1).

The content-with-context hypothesis is tempting. For one, it would connect the literature on age-related declines in working memory with the literature on age-related differences in episodic memory. In episodic memory, age differences tend to be reliably larger for tests involving memory for context in addition to memory for content (for meta-analyses, see Old & Naveh-Benjamin, 2008, and Spencer & Raz, 1995); this magnification of age differences has been ascribed to a specific age deficit in associative processing (e.g., Old & Naveh-Benjamin). If a similar deficit can be demonstrated in working memory, one more step is taken towards the unification of cognitive aging theories across cognitive systems.

The present study, which contains three experiments, was set up to explicitly investigate the context hypothesis – the hypothesis that a specific age deficit in the ability to bind content with

¹In short-term memory tasks, the subject is required to remember whether an item was presented in the context of the current trial or of a previous one, and has to bind the content to presentation order, which can be considered a form of context. Both of these requirements are also obviously present in working memory tasks, which additionally require within-trial context bindings.

context is at the root of at least some of the specific age-related effects we see in working memory tasks (as opposed to the smaller age deficit noted in tasks of short-term memory). We note here that the need for context memory is usually confounded by memory load. For example, in the *N*-back task, the true load of to-be-remembered items increases with each value of *N*. It is difficult to control memory load, especially given that it can be calculated in a number of ways, depending on what is believed to be held together as a group. This problem is no doubt beyond the scope of the current paper, but we hope to begin to disentangle, or at least make others aware of, the possible confounding effects of memory load.

In the current set of experiments, we used a relatively new paradigm, namely the repetition detection task (Bopp, 2003; Bopp & Verhaeghen, 2007) (see Figure 1). In this paradigm, a number of (in the present study: 1 to 4) distinct series of stimuli (the present study used either digits or locations in a grid; where the different series can be marked by different colors or presented in distinct locations on the screen) are presented to the subjects, one stimulus at the time. Presentation is self-paced, and latency for each stimulus is collected. Within each of the streams, one stimulus repeats; the participant's task is to detect the repeating stimulus and identify it at the end of the trial. In a previous study (Bopp & Verhaeghen, 2007), we presented participants with either a single series of ten stimuli or two alternating color-coded series of ten items (5 red and 5 blue) with the requirement to find the repeat within each of the two series. The single-series condition requires memory for content only, while the double-series condition additionally requires memory for context. (Note that no memory for order is necessary.) The latter condition yielded a specific age deficit in latency for digits, but not for locations. Unlike *N*-back tasks where memory load increases with the number of series, Bopp and Verhaeghen held total memory load constant (at ten stimuli) for single or double-series trials.

In the first experiment reported here, we explored the role of memory load by varying the length of each series so that the total memory load either increased with the number of series or remained constant. Additionally, we added a triple-series condition to the single and double-series condition, to test whether the potential increase in age differences from the single-series to double-series condition continues in the triple-series condition, which could give some indication whether the proposed increase in age effects is monotonic with load (defined as the number of series), or is simply due to the context memory requirement. As in the Bopp and Verhaeghen (2007) study, we included both a visuospatial and verbal condition, using locations in a grid and digits as the respective stimuli. Typically, visuospatial working memory tasks yield larger age differences than verbal working memory tasks (Hale & Myerson, 1996; Jenkins, Myerson, Hale, & Fry, 1999; Jenkins, Myerson, Joerding, & Hale, 2000; Myerson, Hale, Rhee, & Jenkins, 1999; Verhaeghen, Cerella, Semenec, Leo, Bopp, & Steitz, 2002; for an exception, see Park et al., 2002). It is possible that context effects are rather general, in which case we would expect no number-of-series by domain interactions with age.

Experiment 1

In this experiment, we examined accuracy and response time for performing a repetition detection task in the verbal and the visuospatial domain within a single-series, two separate series ("double-series"), or three separate series ("triple-series") under two task versions. In the "increasing load" version, five stimuli were presented per series, yielding a total memory load (defined as the total number of stimuli presented at the end of the trial) of 5, 10, or 15 items. In the "constant load" version, total working memory load remained constant at 16 (or 15, for the triple-series condition) items -- 16 stimuli were presented for single-series trials, 8 stimuli were presented per series for double-series trials, and 5 stimuli were presented per series for triple-series trials. The primary question was whether age differences would covary with total load, with the number of series to be remembered, or both.

Method

Participants—Fifty-eight younger adults and 60 older adults participated. The younger adults received course credit in return for their participation; the older adults received \$30. Participants were randomly assigned to one of two groups, one performing the increasing load version, the other the constant load version. Twenty-one younger adults were tested on the increasing load version. One did not return for the second day of the experiment, leaving 20 in the group (13 women), with an average age of 18.90 ($SD = 1.02$). Thirty-seven younger adults were tested on the constant load version. Two did not return for the second day of testing, one was excluded due to experimenter error (assigned to incorrect group on second day), and four did not finish one of the two sessions within two hours. The final group of 30 (26 women) had an average age of 19.07 ($SD = 1.84$). Twenty-five older adults were tested on the increasing load group. Three participants did not finish one of the two sessions after two hours and two did not return for the second day of testing. The remaining 20 older adults (13 women) were 72.35 ($SD = 5.72$) years of age on average. Of the 35 older adults who participated in the constant load group, four did not return for the second day due to health-related problems or inclement weather, one completed the task incorrectly (wrote down answers), and four did not finish one of the two sessions within two hours. Twenty-six older adults (20 women) remained with an average age of 71.77 ($SD = 4.70$).

Older adults had significantly more years of education compared to younger adults, $t(94) = -5.38, p < .001, M = 15.24 (SD = 2.48), M = 13.06 (SD = 1.36)$, respectively. The older and younger adults did not perform significantly different on digit span (forward and backward combined), $t(91) = 0.64, M = 15.67 (SD = 3.90), M = 16.15 (SD = 3.31)$, respectively. Younger adults performed significantly better compared to older adults on digit symbol, $t(91) = 9.09, p < .001, M = 69.71 (SD = 11.52), M = 50.40 (SD = 8.65)$, respectively. The participants in the increasing load and constant load groups did not differ significantly on years of education, $t(94) = 0.54$, digit span, $t(91) = -0.91$, or digit symbol, $t(91) = 1.26$.

Task—The participant's task was repetition detection (see Figure 1). One to four different series of stimuli (numbers or x's in a grid, see below) were presented on a computer screen, separated by color and location, one stimulus at a time. Within each series, one of the stimuli repeated; the participant's task was to identify these repeats. The computer screen was separated into four quadrants. The single-series condition appeared in red in the top left quadrant. The double-series condition added a location in blue in the bottom left quadrant. The triple-series condition added a location in green in the top right quadrant. A quadruple-series condition, at the bottom right in black, was also presented, but was excluded from the data analysis (see below). For an example of a double-series trial, see Figure 2. Analogous verbal and visuospatial versions of the task were tested; the verbal version used numbers ranging from one to 16, and the visuospatial condition used "x"s marking locations in a four-by-four grid. Only one stimulus was presented on the screen at any given time. For the multiple series conditions, the stimuli appeared in the order of top left, bottom left, top right, bottom right and continued in that order until all stimuli were presented. To keep the task manageable and lag consistent within each series, only one or two intervening items occurred between the repeated stimulus and its first presentation. Stimuli were randomly generated for each series separately; therefore, the same stimuli were often used across series. This forced participants to find the repeat within each series rather than only search for repeated stimuli without paying attention to context.

Two versions of the task were tested between subjects: a constant load version and an increasing load version (see Table 1). In the constant load version the total number of items was kept constant at 16 stimuli per trial regardless of the number of series, with the exception of 15 total stimuli for three series (where there were 5 stimuli presented in each series). In the increasing load version the number of stimuli was held constant at five items within each series, so that

the total number of items increased with the number of series. Note that the two versions of the task are identical for the triple-series condition, that is, a total load of 15, or 5 stimuli per series.

Due to the lag constraint, in the constant load version of quadruple-series trials, in which there were only 4 stimuli per series, the first and third stimuli or the second and last stimuli repeat within each series. There was some indication that participants picked up this regularity; this inflated their scores. Therefore, this condition was excluded from analyses.

Procedure—A total of 64 trials and 16 practice trials were presented for each domain, verbal or visuospatial. The program ran four trials of each number-of-series from single to quadruple-series and then from quadruple to single-series. This sequence was completed two times. For the verbal condition, the numbers were presented within a 5.4 by 6.8 cm box, with color and location as described above. Single-digit numbers were 0.5 cm wide, double digit numbers 1.4 cm wide. For the visuospatial condition, a black-4 by-4 grid was projected inside an 11.5 by 15.3 cm box with its color and location as described above. Each “x” was 0.5 by 0.5 cm. The distance between the quadrants was 2.3 cm from top to bottom grids, and 1.8 cm from left to right grids. Participants were instructed to sit at a distance from the screen that was comfortable.

Before each trial, a computer prompt provided information regarding the number of series that would be presented, allowing the participant to prepare for the trial. The participant pressed the spacebar to begin each trial and to advance through the sequence of stimuli. Stimuli were presented in a predictable order, from top left to bottom left to top right to bottom right (with the number of locations visited depending on the number of series presented). At the end of the sequence of stimuli, a response box appeared for each quadrant (in the appropriate color). The response grid was presented in the same size as the box and grid of the visuospatial stimuli and labeled with numbers for the verbal conditions, or “x”s for the visuospatial condition. The response grids were presented one at a time for each quadrant until a response was made. The participants clicked the mouse to indicate the number or location that repeated in the series.

Testing was spread over two days and scheduled so the first and last sessions were no longer than seven days apart. Participants were randomly assigned to one of the two versions of the task. Domain was counterbalanced within each group, so that participants received either the verbal or the visuospatial condition on the first session and the other domain on the second session.

Results

Accuracy—An overall repeated-measures ANOVA was conducted: 2 domain (verbal, visuospatial) $\times$ 3 series (single, double and triple series) $\times$ 2 age (younger adults, older adults) $\times$ 2 task version (constant load, increasing load). ANOVA results are presented in Table 2; the data in Figure 3. Participants were more accurate on the verbal than the visuospatial conditions. As expected, overall accuracy declined with the number of series added. Younger adults performed significantly better than older adults. Overall, the increasing load group was more accurate than the constant load group.

In order to more closely examine the triple interaction, each group was analyzed separately (see Table 3). Age and number of series showed the same effects as in the overall analysis. A significant series by age interaction indicated that older adults' accuracy declined more rapidly over number of series and/or load than younger adults' accuracy. The domain by series interaction was also significant, with larger declines in accuracy on the visuospatial compared to the verbal domain. Pair-wise contrasts of the series were completed for each domain for the increasing load version. The decline in accuracy from single-series to double-series was significant for both the verbal, $t(39) = 8.00, p < .001$, and visuospatial domain, $t(39) = 11.64$,

$p < .001$. There was also a significant decline in accuracy from double-series to triple-series in both the verbal, $t(39) = 11.85, p < .001$, and visuospatial domains, $t(39) = 11.40, p < .001$.

Examination of the constant load version yielded significant main effects of age, domain, and number of series; the direction of these effects was the same as in the overall analysis. The domain by series interaction was significant. Follow-up pair-wise contrasts of the series for each domain showed that accuracy significantly declined from single-series to double-series for the verbal, $t(55) = 9.64, p < .001$, and visuospatial domains, $t(55) = 10.81, p < .001$. However, accuracy did not significantly decline from double-series to triple-series for the verbal domain, $t(55) = 0.60$, but it did for the visuospatial domain, $t(55) = 4.56, p < .001$.

The constant load and increasing load task versions have identical memory loads – 15 total items or 5 stimuli per series – for the triple-series trials. Therefore, a 2 domain (verbal, visuospatial) $\times$ 2 age (younger adults, older adults) $\times$ 2 task version (constant load, increasing load) repeated-measures ANOVA was conducted within the triple-series trials to ensure that the two groups of participants were similar. Accuracy was not significantly different between task versions, $F(1, 92) = 1.70$, and there were no significant interactions with age.

To examine the question of age differences in binding content with context, one type of error is of particular interest: inaccurate responses where the participant provided the repeat for another series within the same trial. Older adults committed such cross-series errors more often than younger adults, 8.6% ($SE = .004$) versus 5.2% ($SE = .004$), $F(1, 92) = 27.68, p < .001$. This finding, however, needs to be evaluated within the context of older adults producing a larger number of errors of all types than younger adults. Of all errors made by older adults, 15.4% ($SE = 1.0$) are cross-series errors; the corresponding number for younger adults is 16.7% ($SE = 1.0$) – older adults then do not make more cross-series errors than younger adults. In neither analysis were any of the interactions involving age significant.

Processing time—Processing time (PT) was calculated as the median value of latency of the spacebar key press prior to the repeated stimulus (before PT), at the repeated stimulus (target PT) and after the repeated stimulus (after PT). Our assumption is that before PT reflects memory processing (encoding and comparison). Target PT likely includes an additional marking component that commits the repeat to memory for output. Finally, after PT should be fast, as no additional information needs to be stored. This expectation was borne out in a full ANOVA: Target PT was longest ($M = 1,844, SE = 74.58$), before PT was shorter ($M = 1,753, SE = 62.35$), and after PT was shorter still ($M = 954, SE = 29.47$), $F(2, 146) = 167.70, p < .001$. Therefore, we will concentrate on before PT in the remainder of the analyses.

Before PT was examined in a 2 domain $\times$ 3 series $\times$ 2 age $\times$ 2 task version ANOVA, see Table 2. Younger adults were faster than older adults. The processing times were not significantly different between the task versions. The verbal domain was processed faster than the visuospatial domain. As expected, processing time increased with the number of series. The series by age interaction was significant, and survived a log-transformation, $F(2, 184) = 26.69, p < .001$. The series by task version interaction was significant, and so was the three-way interaction of series by age by domain, and of series by task version by domain.

In order to more closely examine the triple interaction, each load condition was analyzed separately (see Figure 4). The age result of interest is the interaction between age and number of series, potentially indicating an age-associated deficit in source memory. This interaction was significant for the increasing-load condition, $F(2, 76) = 3.27, p = .044$, and it survived a log transformation, $F(2, 76) = 15.52, p < .001$. The triple interaction was also significant for the increasing-load condition, $F(2, 76) = 5.12, p = .008$. Pair-wise comparisons of the series were conducted for each age group. Before PT was significantly slower for double-series

compared to single-series for both younger, $t(19) = -8.88, p < .001$, and older adults, $t(19) = -5.90, p < .001$. BPT was also significantly slower from double to triple-series for younger adults, $t(19) = -2.79, p = .012$, but did not significantly change for older adults, $t(19) = 0.73$. The constant-load condition, however, showed no significant age by number interaction, $F(2, 108) = 2.62$, nor a significant triple interaction, $F(2, 108) = 1.90$.

As in the accuracy analyses, we checked whether before PTs were identical in the constant-load and increasing-load task versions of the triple series (where both conditions have identical memory loads). They were, $F(1, 92) = 0.13$; there were no significant interactions with age.

Discussion

General cognitive effects: Before we turn to an examination of the age effects, we want to briefly point out some of the more general implications of our findings for cognitive psychology. We note, first, that our data support the assertion that processing occurs essentially online, that is, participants make their decision in the course of the trial rather than storing the entire sequence and making a decision regarding the repeat at the end of the trial. This is evidenced by significantly shorter processing times after occurrence of the repeated number (954 ms averaged across both age groups), indicating that participants stop encoding new items once the repeat item has been discovered, and by longer processing times when the repeat item is displayed on the screen (1,844 ms averaged across age groups), likely due to the need to mark this item for retrieval at the end of the trial (average processing time before a repeat occurred was 1,753 ms). It is, therefore, warranted to use response time before the repeat occurred as a good proxy for processing time on accurate trials.

Second, the results from the increasing load task version show a monotonic decrease in accuracy from single to double to triple-series, and a monotonic increase in latency. It appears that even when total working memory load is held constant at 15 or 16 items, we find clear effects when moving from single-series to the double-series trials: Latency increases and accuracy drops. There is, however, no effect in accuracy for the verbal domain when moving from the double-series condition to the triple-series condition for the constant load version; whereas the visuospatial data do show a decrease in accuracy, but it is smaller than for the single-series to double-series transition. This strongly suggests that there is indeed a context memory effect: In the single-series, only memory for content needs to be engaged; in the multiple-series conditions, an additional memory for an item's context (i.e., in what series it was presented) is necessary. This added requirement for context memory has two effects. First, it decreases accuracy, presumably because a complete content-context pair needs to be retrieved for perfect performance, which makes the representation more vulnerable than a content-only representation. Second, it increases latency, either because encoding an item with its context takes longer, retrieval is slowed when an additional context representation has to be retrieved, or both.

Age effects: We replicated two main findings in cognitive aging research: across-the-board slowing (e.g., Cerella, 1990), and lower accuracy on working memory tasks (see review articles such as Bopp & Verhaeghen, 2005; Craik & Jennings, 1992; Light, 1991; Salthouse, 1994). On average older adults were 1.4 times slower than younger adults, and on average younger adults detected 68 % of the repeats, older adults 55 %. Surprisingly, we did not find larger age effects for the visuospatial domain than for the verbal domain. While previous research, including our own with a similar task (Bopp & Verhaeghen, 2007), has found support for greater age differences on visuospatial tasks compared to verbal tasks (e.g., Hale & Myerson, 1996; Jenkins, et al., 2000), there is also evidence against age differences between domains (Park et al., 2002). It is unclear why we did not replicate our previous finding of an age by domain interaction; sampling variability is one likely explanation.

Our main question concerned whether age differences would covary with the need for context memory, as operationalized by larger age differences in the multiple-series trials compared to single-series trials. The results of the increasing load task version show the expected number-of-series by age interaction, but only in the accuracy domain: Older and younger adults have statistically identical (and near-ceiling) performance for the single-series conditions, but a clear age difference emerges in the double-series and triple-series conditions. The age difference is identical for both multiple-series conditions. Taken at face value, this result suggests that older adults have a specific deficit in memory for context. However, the constant load condition provides evidence that this interpretation is wrong: No age by number-of-series interactions emerged. This leaves us with only one interpretation: There is no specific age-related deficit for memory for context in working memory. The observed age differences in working memory (at least in the current implementation of the task) are due to memory for content; memory for context adds no additional age-related penalty. Additional evidence for the position that memory for context is intact in older adults comes from the analysis of cross-series errors, signifying source confusion: For both younger and older adults, such errors comprised about 16% of the total errors committed.

We note here that the design of our experiment leads to a necessary confound. By keeping lag between repeats within a series constant, the overall lag (i.e., total number of stimuli between repeating stimuli) increases with the number of series. This confound, however, only makes the multiple-series trials more difficult, and would bias the results towards finding larger age differences with an increasing number of series. This confound then, if anything, strengthens our conclusion of age constancy in context bindings in working memory.

The data leave us with a question. In the accuracy data in the increasing load condition, we do find a number-of-series by age interaction, indicating that age differences increase with load. This interaction is, however, confounded with a ceiling effect for the single-series condition. Moreover, this interaction appears to be tied to the single-series to double-series transition: Age differences do not further increase when the total memory load is increased from 10 to 15. The question is whether the age by number-of-series interaction observed in the increasing load condition is due to increasing load per se, or whether it is an artifact of a ceiling effect in the single-series condition. Therefore, in Experiment 2 we attempted to remove ceiling effects by increasing the load to eight items per series. Additionally, given that our conclusion is relatively unexpected and certainly new, a replication of the main findings would be welcome.

Experiment 2

Method

Participants—We tested 24 younger adults and 26 older adults. The younger adults (average age 19.16, $SD = 1.03$) participated in the study for course credit. The older adults (average age 68.88, $SD = 5.79$) were recruited through newspaper advertisements and community centers. They received \$20 for their effort. The younger adults had significantly more years of education ($M = 13.25$, $SD = 1.07$) than the older adults ($M = 14.96$, $SD = 3.55$), $t(48) = -2.27$, $p = .028$. The younger adults performed significantly better on the Digit Symbol Modalities Test, $t(48) = -6.02$, $p < .001$ ($M = 65.83$, $SD = 11.67$, $M = 45.48$, $SD = 11.72$, respectively).

Task and Procedure—The task and procedure was identical to the first experiment, except that we only used single and double-series trials and the increasing load version, now with eight items per series (rather than five). A total of 64 trials were given for each domain. The participant received four trials of the following rounds: single then double-series then double then single-series trials, and completed four rounds.

Results

Accuracy—Data (see Figure 5, Table 4) were analyzed with a 2 domain (verbal, visuospatial) $\times$ 2 series (single, double) $\times$ 2 age (younger, older adult) repeated-measures ANOVA. Younger adults detected significantly more repeats than older adults. The verbal domain was significantly easier than the visuospatial domain. Accuracy decreased with the number of series. Age differences were significantly larger in visuospatial than verbal conditions.

Older adults produced cross-series errors on 8.5% of the trials ($SD = .008$), whereas younger adults only did so on 5.3% ($SD = .009$) of the trials. This difference was significant, $F(1, 48) = 7.10, p = .01$. When cross-series errors are, however, expressed as the percentage of all errors made, the age difference (13.8% for the older adults, $SE = 1.4$, 11.8% for the younger adults, $SE = 1.5$) becomes non-significant, $F(1, 48) < 1$.

Processing time—A 2 domain $\times$ 2 series $\times$ 2 age repeated-measures ANOVA was conducted on the before PT data (see Figure 5; Table 4). Older adults were significantly slower than younger adults. The single-series version was processed significantly faster than the double-series version. The verbal processing time was significantly faster than the visuospatial processing time. There was also a significant domain by age interaction, $F(1, 48) = 4.93, p = .031$. Larger age differences were found on the visuospatial compared to the verbal conditions.

Discussion—The results from Experiment 2 largely replicated those of the increasing load condition of Experiment 1. Performance decreased with load in both accuracy and processing time. Older adults were slower and less accurate than younger adults. The relative number of cross-series errors was equivalent across age groups.

Two results, however, differ between the two experiments. One difference is minor: In Experiment 2, we obtained an age by domain interaction in accuracy, with larger age differences in the visuospatial condition. We did not obtain such interaction in Experiment 1. As explained in the Discussion section of Experiment 1, the anomalous result is likely to be the one obtained in Experiment 1, not Experiment 2 – many previous studies have obtained larger age deficits in visuospatial working memory than verbal working memory (e.g., Hale & Myerson, 1996). Given that both studies used a between-subject design for the verbal-visuospatial contrast, sampling variance is a likely culprit for the discrepancy.

The other difference between experiments is more important. In the increasing-load condition of Experiment 1, we obtained a significant age by number of series interaction in accuracy, but only for the contrast between single and double-series, perhaps casting some doubt on the conclusion derived from the constant load condition and the error type analysis that older adults do not have a deficit in context binding in working memory. This effect was, however, confounded with a ceiling effect. In Experiment 2, we increased the load to eight items per series, in order to bring performance in the single-series condition down from ceiling. This manipulation also made the age by number-of-series interaction effect disappear. This, then, solved the one outstanding question from Experiment 1: Once measurement artifacts are carefully controlled, age differences in accuracy remain constant over both working memory load and the number of series to be retained.

Experiment 3

In our final experiment, we decided to probe the limits of the age constancy in context binding in working memory. It is possible that Experiments 1 and 2 showed age equivalence in content-with-context binding because participants were assisted by the architecture of the task. That is, in both previous experiments, strong environmental support is present in that the content of each series could be bound by both location (the quadrant in which stimuli were presented)

and color (each series was presented in a different color). It has been claimed (e.g., Craik, 1983; 1986) that such support decreases age-related differences in memory accuracy. In Experiment 3, we removed the support provided by location, contrasting the redundant-cue task presentation we used in our previous experiments (“separate locations presentation”) with a new presentation version in which single, double or triple-series were presented in the same location, only made distinguishable by their color (“single location presentation”).

In addition, we examined the possible effects of memory load with more precision. In both previous experiments, load was defined as the total number of stimuli presented (or number of stimuli per series). In Experiment 3, we examine load as defined by the number of stimuli presented before the repeat, and we designed the experiment explicitly around this definition, making sure enough data points were collected for each level of load to warrant analysis. For multiple-series trials, load can be calculated in two ways: memory load within each series, and total memory load, that is, combined over all series. In this experiment, we concentrated on the first aspect. To keep the duration of each session feasible, we included only one type of stimulus, namely numbers (which are less likely to lead to floor effects).

In sum, we were interested to see if we would obtain age by type of presentation interactions and age by load interactions, signifying age differences due to redundant coding of locations or due to maintenance of a high load in working memory.

Method

Participants—Forty-two younger adults participated in return for course credit, as well as 38 older adults, paid \$30. Due to computer errors seven younger adult's data were incomplete and two younger adults did not return for the second session. An outlier analysis of the overall accuracy score suggested that two additional younger adults be removed. Therefore, 31 younger adults (19 women), with an average age of 19.29 ($SD = 1.27$), remained in the analysis. Of the 38 older adults, five did not return for the second session and two experienced computer problems. The outlier analysis did not reveal that any older adults' data needed to be removed from analyses. The 31 older adults (21 women) had an average age of 72.55 ($SD = 7.27$).

Older adults had significantly more education compared to younger adults, $t(60) = -4.50, p < .001, M = 15.26 (SD = 2.23), M = 13.16 (SD = 1.32)$, respectively. The older and younger adults did not perform significantly different on digit span combined, $t(57) = 1.63, M = 14.11 (SD = 3.50), M = 15.71 (SD = 3.99)$, respectively. Younger adults performed significantly better compared to older adults on digit symbol, $t(60) = 8.39, p < .001, M = 59.16 (SD = 7.26), M = 42.03 (SD = 8.75)$, respectively. Older adults performed significantly better on Mill Hill Vocabulary test compared to younger adults, $t(60) = -2.09, p = 0.04, M = 19.68 (SD = 5.14), M = 17.45 (SD = 2.94)$, respectively.

Task and Procedure—The increasing load version of the verbal repetition detection task was used. To avoid floor effects in the triple-series condition, we used 6 items per series, leading to total maximum load of 6, 12 or 18 stimuli for single, double and triple-series trials, respectively.

Two versions of the task were compared. The “separate locations” condition was identical to Experiment 1 and 2, where each series was presented in their own color and quadrant of the computer screen. In the “single location” condition, the series were all presented in the top-left quadrant of the screen, only identified by their respective colors (red for the first series, blue for the second series, and green for the third series) (see Figure 6). Other than the location of presentation of stimuli, the task versions were identical.

In order to avoid confounding memory load with the lag between repeated stimuli, lag was kept constant at two (i.e., one stimulus intervened between repeated items within each series). This implies that a memory load (defined as the total number of items presented within a series before the repeat occurred) of two, three, four or five was possible within any series (see Table 5).

A total of 4 practice trials and 120 trials were presented for each task version. The program ran six trials of single-series, six trials of double-series, then eight trials of triple-series, then gave participants a break and then repeated the pattern five more times. In single-series trials, there were nine trials of each of the memory loads (two to five) for a total of 36 trials. In double-series trials, there were nine trials of each of the within memory loads for each series (for a total of 36 trials). Finally, in triple-series trials, there were fourteen trials of within memory loads two and five, and ten trials of within memory loads of three and four (for total of 48 trials). The difference in number of trials was done to also control total memory load, which is not described here since it is not reported due to space constraints.

Procedure was identical to Experiment 1. Testing was spread over two sessions. Participants were randomly assigned to one of the two conditions (single location or separate locations) for the first session, and completed the other at the second session.

Results

The unique additional analyses for Experiment 3 include examination of the effect of presentation version of the task (single location versus separate locations of each series) and the effect of memory load. To anticipate, we are interested in any age by type of presentation interactions and age by load interactions; none were obtained in accuracy.

Accuracy—Figure 7 presents the data; Table 6 the ANOVA results. Accuracy decreased with the number of series. Accuracy generally decreased with an increase in memory load, except for an increase at a memory load of 5. The latter finding is an end effect: With a load of 5, the repeat is the last item of the series. As expected, accuracy for the separate locations version was significantly better than for the single location presentation version. Younger adults performed significantly better than older adults. None of the interactions (or triple interactions) with age were significant, other than the interaction of age with number-of-series. The decline in accuracy over an increasing number of series was smaller for younger adults than for older adults. This effect replicates the increasing-load findings from Experiment 1.

It is possible that accuracy on multiple-series trials could be affected by a selective attention strategy in which the participant focuses on one series and ignores the others. In order to examine the data for this pattern, two repeated-measures ANOVAs were conducted, one on double-series trials, and the other on triple-series trials. For the purposes of brevity, only main effects and interactions involving series are reported. Turning to the double-series trials first, we found a main effect of series, $F(1, 60) = 18.43, p < .001$. Overall, accuracy for the red series was significantly better than accuracy for the blue series. The series by age interaction was also significant, $F(1, 60) = 4.98, p = .029$. The difference between accuracy performance on red ($M = 0.73, SE = 0.026$) versus blue ($M = 0.70, SE = 0.030$) series was significantly smaller for younger adults compared to older adults ($M = 0.61, SE = 0.026$; $M = 0.51, SE = 0.030$, respectively). The series by presentation version interaction was not significant, $F(1, 60) = 0.75$, but the series by memory load within series was significant, $F(3, 180) = 8.98, p < .001$. The triple and four-way interactions involving series were not significant.

For the triple series, the main effect of series was significant, $F(2, 120) = 27.79, p < .001$. Overall, accuracy for the red series was significantly better than accuracy for the blue series and green series. The series by age interaction was also significant, $F(2, 120) = 10.80, p < .$

001. Younger adults performed best on the red series ($M = .57$, $SE = 0.028$), then green series ($M = .54$, $SE = 0.028$), and worst on the blue series ($M = .49$, $SE = 0.024$), whereas older adults performed best on the red series ($M = 0.50$, $SE = 0.028$), followed by the blue series ($M = .34$, $SE = 0.024$), followed by the green series ($M = .29$, $SE = 0.028$). Neither the series by presentation version interaction, $F(2, 120) = 1.00$, nor the series by memory load within series were significant, $F(6, 360) = 1.88$. The triple interaction of series by presentation version by memory load was significant, $F(6, 360) = 4.39$, $p < .001$. Red series performance compared to blue and green series was better across all memory loads for the separate locations presentation version, whereas the red series performance was only better for lower memory loads (memory load within 2 and 3) for the single location presentation version. The other three and four-way interactions involving series were not significant.

As in prior experiments, the percentage of cross-series errors (given all types of errors) were not different between younger adults ($M = .35$, $SE = .023$) and older adults ($M = .37$, $SE = .023$), $F(1, 60) = 0.36$. Nor were they different across presentation conditions, $F(1, 60) = 1.66$. No interactions were significant.

Presentation time (PT)—A repeated-measures ANOVA was conducted on before PT (see Figure 8, and Table 6)². Latency increased with the number of series and with memory load. Before PT for the separate locations version was marginally faster than for the single location presentation version. Younger adults were faster than older adults. None of the interactions involving age were significant, except the interaction between memory load and age. While before PT did not change across memory load for younger adults, older adults were faster as memory load increased (a perhaps counterintuitive result). Finally, the interaction of memory load and number of series was significant; before PT remained relatively flat across memory loads for single-series and double-series trials, but became faster as memory load increased for triple-series trials.

Discussion—Experiment 3 was designed as a control experiment, to examine the influence of redundant coding of the binding of content to context, and to examine possible differential age effects across different levels of working memory load. We reduced the redundancy by including a single-location presentation version of the task. The single location task was more difficult than the separate locations version, as evidenced by lower accuracy, but age differences were identical across the two versions. This strongly suggests that our previous findings -- older adults do not have a specific deficit for content-with-context bindings in working memory -- are not an artifact of redundant coding.

We also increased the precision of our measurement of working memory load, designing the experiment so that we could include the number of stimuli presented before the presentation of the repeat as a factor in the analysis of variance. In doing so, we kept the lag, that is, the number of items between the first and the second occurrence of the repeating stimulus, constant. Accuracy declined as memory load increased, with the exception of the heaviest load -- 5 items. The latter result is likely an end effect: If load is 5, the correct answer is the final item presented in a series. This item is less likely to be forgotten or overwritten in the interval between its presentation and the response phase; it is also possible that participants who have not spotted the repeat early in the series might strategically guess that the final item is the repeat. To control for such mnemonic and/or strategic effects, the ANOVAs were repeated with the load of 5 omitted; the pattern of results remained identical.

An additional result from Experiment 3 is that both younger and older adults appear to favor one series -- the red series, which is, the first series presented -- above all others, in the sense

²One older adult participant was excluded from the analyses because of zero accuracy on one of her data points

that accuracy for this series is higher. This might be a strategic adjustment to the memory demands of the task. We note that the effect does not appear to be catastrophic, that is, participants do not appear to concentrate exclusively on a single series. We also note that in the triple-series condition performance for the second and third series is roughly identical, suggesting again that our subjects do not strategically tune out one of the remaining series. We did find an age effect here, in the sense that the drop in accuracy from the red series to the others was larger in older adults, suggesting, if anything, that older adults are more likely to make the strategic choice to focus on a single series than younger adults do.

General Discussion

Our set of experiments was motivated by two observations. The first is that many working memory tests (including working memory span tasks such as operation span, reading span, and computation span, as well as the *N*-Back task) require memory not just for content of the items, but also for the context in which they were presented – whether items were part of the memory set or the intermittent bouts of processing, or what the position of the item is in a long string of stimuli. The second is that these context-plus-content working memory tasks appear to show larger age effects than tasks that tap mainly memory for an item's content alone (such as digit span tasks). Therefore, our suspicion was that age differences in working memory performance might be explained not by true age differences in working memory capacity, but by a specific age-related deficit in context memory.

We conducted three experiments with a repetition detection task designed to unconfound the effects of working memory load from those of the need for context binding (see Table 7). We found evidence for the position that binding content to context in working memory is indeed a time-consuming process that leads to less accurate performance, and this independent of working memory load.

Two age effects stand out. First, we found relatively large overall effects of age on performance: Accuracy is lower and response time longer for older adults. When we made the task difficult enough to get performance off ceiling for a single-source condition, age differences emerged even in this simple condition, suggesting a very real age-related limit on memory capacity and processing speed in this relatively simple task.

Second, and directly relevant to our main question, we found clear evidence that the need for context memory does not differentially affect older adults' performance in this working memory task. This is true even when environmental support for these bindings is kept at a minimum, as in Experiment 3. Older adults are not penalized more than younger adults by the requirement to keep different sources of information in working memory separate, at least within the boundaries explored here. We also found that older adults do not make more source confusion errors than younger adults once the total number of errors is taken into account. Both findings strongly suggest that the locus of the age difference in working memory is unlikely to be found in content-to-context binding. There is evidence that older adults, more than younger adults, might strategically prefer to focus on the first series presented, perhaps as a compensation for an age-related decline in working memory capacity for content.

We do note that this conclusion is somewhat unexpected, given the rich literature on age deficits in context binding in other aspects of memory, notably episodic memory (e.g., Old & Naveh-Benjamin, 2008). There is, fortunately, no lack of alternative mechanisms to explain the dichotomy in age effects between short-term memory tasks and working memory tasks – to name a few: a true capacity limit and/or deficient control mechanisms (e.g., Hasher & Zacks, 1988) and/or our own: age-sensitivity in switching the focus of attention (Verhaeghen, Cerella, Bopp, & Basak, 2005).

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Figure 1.

Schematic of a verbal and a visuo-spatial repetition detection task. The sequence depicts sequential screens in a single trial in which the participant attempts to determine the repeated stimulus. In the example, there is a presentation of five stimuli (participant presses the spacebar to see each one) followed by the response screen (participant uses mouse to select repeat). The correct answers in the example is the digit “3” in the verbal task and the location of the second row, second from left column of the matrix in the visuospatial task.

Figure 2.

Schematic of a trial from the repetition detection task for Experiment 1. The sequence presents an example of a verbal, double-series, increasing load version of the task. The repeated stimulus (answer) for the red, top-left series is the digit 7; the repeated stimulus in the blue, bottom-left series is the digit 3.

Figure 3. Accuracy (proportion correct) for Experiment 1, separated by age (Yng = younger adults, Older = older adults) and domain (Ver = verbal task, Vis = visuospatial task) for single, double and triple-series trials: (a) increasing load version of the task and (b) constant load version of the task. Error bars represent standard errors.

Figure 4.

Processing time (ms) before the presentation of the repeated stimulus for Experiment 1 separated by age (Yng = younger adults, Older = older adults) and domain (Ver = verbal task, Vis = visuospatial task) for single, double and triple-series trials: (a) increasing load version of the task and (b) constant load version of the task. Error bars represent standard errors.

Figure 5.

(a) Accuracy (proportion correct) and (b) processing time (ms) before the presentation of the repeated stimulus for Experiment 2 separated by age (Yng = younger adults, Older = older adults) and domain (Ver = verbal task, Vis = visuospatial task) for single, double and triple-series trials.

Figure 6.

Schematic of a trial from the repetition detection task for Experiment 3. The sequence is an example of a verbal, double-series, single location presentation version of the task. The repeated stimulus for the red series is the digit 5 (within series memory load of 2); the repeated stimulus in the blue series is the digit 2 (within series memory load of 3).

Figure 7.

Accuracy (proportion correct) for Experiment 3 by memory load within series separated by presentation version (single-loc = single location, and sep-loc = separate locations) and for single (1-series), double (2-series), and triple-series (3-series) trials for: (a) younger adults and (b) older adults. Error bars represent standard errors.

Figure 8.

Processing time (ms) before the presentation of the repeated stimulus for Experiment 3 by memory load within series separated by presentation version (single-loc = single location, and sep-loc = separate locations) and for single (1-series), double (2-series), and triple-series (3-series) trials for: (a) younger adults and (b) older adults. Error bars represent standard errors.

Table 1

Examples of a trial sequence in the verbal domain for each task version and number-of-series for Experiment 1. Each number is presented one-at-a-time in the appropriate color and quadrant of the computer screen.

	<i>Single-series trial</i>	<i>Correct responses</i>
Increasing load version:	7-2-7-4-12	7
Constant load version:	6-9-3-11-5-2-5-1-16-7-15-4-10-12-14-8	5
	<i>Double-series trial</i>	
Increasing load version:	7-4-2-11-7-3-4-9-12-3	7, 3
Constant load version:	6-9-3-11-5-9-5-1-16-7-15-4-10-12-14-8	5, 9
	<i>Triple-series trial</i>	
Increasing load version:	7-4-13-2-11-10-7-3-6-4-9-10-12-3-4	7, 3, 10
Constant load version:	6-9-3-11-5-2-5-9-16-7-15-2-5-12-14	5, 9, 2

Table 2
ANOVA table of accuracy and before presentation time (PT) data for Experiment 1 (2 domain $\times$ 3 series $\times$ 2 age $\times$ 2 task version).

Effect	df	err	df	Accuracy		Before PT	
				F	p	F	p
Domain	1	92	150.03	<.001	46.72	<.001	
Series	2	184	609.75	<.001	89.00	<.001	
Age	1	92	49.64	<.001	30.26	<.001	
Task Version	1	92	78.14	<.001	0.19	ns	
Domain $\times$ age	1	92	2.17	ns	0.15	ns	
Series $\times$ age	2	184	14.78	<.001	5.56	.005	
Task version $\times$ age	1	92	0.26	ns	1.98	ns	
Series $\times$ domain	2	184	32.82	<.001	3.87	.023	
Series $\times$ task version	2	184	60.27	<.001	8.31	<.001	
Domain $\times$ task version	1	92	0.91	ns	0.28	ns	
Domain $\times$ series $\times$ age	2	184	0.19	ns	6.40	.002	
Domain $\times$ task version $\times$ age	1	92	0.08	ns	0.62	ns	
Series $\times$ task version $\times$ age	2	184	10.50	<.001	1.18	ns	
Domain $\times$ series $\times$ task version	2	184	4.64	.011	6.53	.002	
Domain $\times$ series $\times$ age $\times$ task version	2	184	0.48	ns	1.05	ns	

Table 3
ANOVA table of accuracy data for Experiment 1 by task version (2 domain $\times$ 3 series $\times$ 2 age)

Effect	Increasing Load Version				Constant Load Version					
	df	err	df	F	p	df	err	df	F	p
Domain	1	38	72.89	<.001	<.001	1	54	88.76	<.001	<.001
Series	2	76	420.60	<.001	<.001	2	108	199.79	<.001	<.001
Age	1	38	20.27	<.001	<.001	1	54	32.01	<.001	<.001
Domain × age	1	38	0.81	ns	ns	1	54	1.57	ns	ns
Series × age	2	76	20.81	<.001	<.001	2	108	0.23	ns	ns
Domain × series	2	76	35.31	<.001	<.001	2	108	8.17	<.001	<.001
Domain × series × age	2	76	0.65	ns	ns	2	108	0.14	ns	ns

Table 4

ANOVA table of accuracy and before presentation time (PT) data for Experiment 2 (2 domain $\times$ 2 series $\times$ 2 age).

Effect	Accuracy			Before PT		
	df	err	F	p	F	p
Domain	1	48	51.80	<.001	21.15	<.001
Series	1	48	1184.84	<.001	30.32	<.001
Age	1	48	21.42	<.001	23.62	<.001
Domain $\times$ age	1	48	4.78	.034	4.93	.031
Series $\times$ age	1	48	1.79	ns	2.32	ns
Domain $\times$ series	1	48	50.20	<.001	10.65	.002
Domain $\times$ series $\times$ age	1	48	0.03	ns	0.48	ns

Table 5

Example sequences for single, double and triple-series trials, the correct response and the resulting memory load within each series for Experiment 3.

Memory load	Number-of-series	Correct responses
<i>Single-series trial</i>		
Memory load within = 2	7-2-7-4-12-8	7
Memory load within = 3	7-2-4-2-12-8	2
Memory load within = 4	7-2-4-12-4-8	4
Memory load within = 5	7-2-4-12-8-12	12
<i>Double-series trial</i>		
Red ML-within = 2	7-4-2-11-7-3-4-11-12-9-6-2	7, 11
Blue ML-within = 3		
<i>Triple-series trial</i>		
Red ML-within = 3	7-4-13-2-11-10-4-3-6-2-9-4-12-2-6-1-9-16	2, 9, 6
Blue ML-within = 5		
Green ML-within = 4		

Table 6ANOVA table of accuracy data for Experiment 3 (2 presentation version $\times$ 3 series $\times$ 4 memory load within series (ML) $\times$ 2 age).

Accuracy					Before PT					
Effect	df	err	df	F	p	df	err	df	F	p
Version	1	60		13.73	<.001	1	59		3.57	.06
Series	2	120		721.37	<.001	2	118		50.93	<.001
ML	3	180		56.85	<.001	3	177		6.95	<.001
Age	1	60		20.45	<.001	1	59		41.48	<.001
Version × Age	1	60		0.07	ns	1	59		1.11	ns
Version × Series	2	120		8.63	<.001	2	118		1.02	ns
Version × ML	3	180		3.41	.019	3	177		0.32	ns
Series × Age	2	120		19.91	<.001	2	118		2.25	ns
Series × ML	6	360		18.60	<.001	6	354		4.14	<.001
ML × Age	3	180		2.18	ns	3	177		2.99	.03
Version × Series × Age	2	120		0.12	ns	2	118		0.50	ns
Version × ML × Age	3	180		0.28	ns	3	177		0.51	ns
Version × Series × ML	6	360		3.82	.001	6	354		1.44	ns
Series × ML × Age	6	360		1.81	ns	6	354		1.46	ns
Version × Series × ML × Age	6	360		0.63	ns	6	354		1.37	ns

Table 7

Description of task version, number-of-series, presentation of series, and lag for Experiment 1, 2 and 3.

<u>Experiment 1</u>	
Task versions:	Increasing load (5 items per series) Constant load (16 items total)
Number-of-series:	Single-series, double-series, triple-series
Presentation of series:	By color and separate locations
Lag:	1 or 2 items between repeated stimuli within series
Domain:	Verbal and visuo-spatial
<u>Experiment 2</u>	
Task versions:	Increasing load (8 items per series)
Number-of-series:	Single-series, double-series
Presentation of series:	By color and separate locations
Lag:	1 or 2 items between repeated stimuli within series
Domain:	Verbal and visuo-spatial
<u>Experiment 3</u>	
Task versions:	Increasing load (6 items per series)
Number-of-series:	Single-series, double-series, triple-series
Presentation of series:	By color (single location presentation version) or color and location (separate location presentation version)
Lag:	1 item between repeated stimuli within series
Domain:	Verbal