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Adult Age Differences in Working Memory Capacity: Spared Central Storage but Deficits in Ability to Maximize Peripheral Storage

Nathaniel R. Greene, Moshe Naveh-Benjamin, and Nelson Cowan
University of Missouri

For the first time, we quantify capacities of working memory in young and older adults in a dual-task situation, addressing whether older adults have diminished central or peripheral capacity in working memory. Across 2 experiments, 63 young and 63 old adult participants studied visual arrays of colored squares and sequences of unfamiliar tones in quick succession and were instructed to attend to one or both modalities. Memory was assessed with a single-probe change-detection task. We used a recently developed capacity-estimate model to partition participants' overall working memory capacity into 3 components: a peripheral component dedicated to visual information regardless of attention instruction; a peripheral component similarly dedicated to auditory information; and a central component allocated to either modality, or shared between both, depending on attention instruction. Capacity estimates of the peripheral components were consistently smaller in the older adults than in the young adults, but the central component was stable across both age groups. We contend that older adults are impaired in their ability to strategically encode information in ways that younger adults use to increase peripheral storage, a kind of storage that is immune to loss through bimodal attention costs.

Keywords: aging, working memory, central and peripheral storage, dual-task, selective attention

Supplemental materials: http://dx.doi.org/10.1037/pag0000476.supp

Working memory (WM) refers to the limited amount of information held in a temporary state of heightened activity useful for performing cognitive operations. There are many competing conceptions of WM (Cowan, 2017), but most researchers agree that human WM has a limited capacity (Cowan, 1988, 2001; Logie, 2011; Oberauer, 2002). This limited capacity follows an inverted U-shaped function across the life span, rising from childhood to young adulthood and declining in older adulthood (Cowan, Naveh-Benjamin, Kilb, & Saults, 2006). Many previous studies have contended that declines in WM capacity play a central role in older adults' deficiencies in other domains of cognition, such as long-term memory (LTM; Gilchrist, Cowan, & Naveh-Benjamin, 2008; Light & Anderson, 1985; Wingfield, Stine, Lahar, & Aberdeen, 1988) and selective attention (Naveh-Benjamin et al., 2014). However, it remains undetermined whether these declines reflect a domain-general loss of capacity (i.e., shared across sensory modalities and types of stimulus coding) or a loss of storage in domain-specific components of WM (i.e., storage of information in such a way that interference from other sensory modalities or codes is reduced). In the present study, we use the terms *central* and *peripheral* components of WM, respectively, to describe components of the storage of information in WM that can be shared across modalities, versus information that is modality-specific (cf. Cowan, Saults, & Blume, 2014). Our primary interest is in measuring whether deficits in WM capacity that occur in older adulthood are characterized by declines in central or peripheral storage, or both.

Theoretical Implications of Central and Peripheral Components of WM

In everyday life, humans process the world from multiple senses, and often must attend to and remember information in different sensory modalities simultaneously. The WM system is severely limited, with a capacity of about three or four separate items or chunks of information (Cowan, 2001). Therefore, when processing sensory information from multiple modalities, one may expect some dual-task trade-offs. For example, when talking on the phone while simultaneously viewing a visual scene on a TV, some of the auditory information and some of the visual information could compete for storage in WM. Indeed, many studies using dual-task methodologies have shown that the need to retain visual items interferes with the concurrent storage of acoustic or verbal items, and vice versa (e.g., Cowan & Morey, 2007; Cowan et al., 2014; Fougnie & Marois, 2011; Morey & Cowan, 2004; Morey, Cowan, Morey, & Rouder, 2011; Uittenhove, Chaabi, Camos, & Barrouillet, 2019). Such findings imply that at least some of WM capacity must be capable of being allocated across sensory modalities, and this we term *central* (or shared) WM capacity, after Cowan, Saults, and Blume (2014).

Nathaniel R. Greene, Moshe Naveh-Benjamin, and Nelson Cowan, Department of Psychological Sciences, University of Missouri.

The data appearing in these experiments have not been disseminated previously. Data and analysis scripts are available at https://osf.io/5ja8y/.

Correspondence concerning this article should be addressed to Nathaniel R. Greene, Department of Psychological Sciences, University of Missouri, 9J McAlester Hall, Columbia, MO 65211. E-mail: ngwfm@mail.missouri.edu

In contrast to central capacity, *peripheral* (or unshared) WM capacity refers to storage of information in WM that can be allocated to only one modality (e.g., visual *or* acoustic, but not both; Cowan et al., 2014). In our TV example from above, peripheral storage refers to the acoustic information that can be held in such a way that the visual information does not interfere with it (e.g., through distraction), or to visual information that can be held in such a way that auditory information does not interfere with it. For example, one may quickly memorize verbal information from a phone call, making it more immune to interference from other input, including distraction from incoming visual information.

The mechanisms by which information can be held peripherally fall out of competing theories of WM. In the multicomponent model of WM (Baddeley, 1986; Baddeley & Hitch, 1974), a central executive process could quickly transfer information to the appropriate coding module, assigning verbal information to a phonological loop and nonverbal visual information to a visuospatial sketchpad. In contrast, in the embedded-processes model (Cowan, 1988, 1999, 2005), in which a focus of attention is embedded within an activated portion of LTM, information from one modality may first impose a load on a limited-capacity focus of attention and can be off-loaded to activated LTM, outside of attention, via a strategic process (for a recent review, see Rhodes & Cowan, 2018). Under this theory, the peripheral components could map onto currently activated LTM. Off-loading (i.e., removing the load from attention without losing the information) may be accomplished through grouping items from one modality together, as by detecting patterns in a visual array (e.g., Jiang, Chun, & Olson, 2004). When patterns are detected, these new patterns can be quickly learned, forming new multiitem chunks of information (Cowan, 2019). By quickly forming and off-loading this information to activated LTM, the focus of attention is freed up to process incoming information, for example from another sensory modality in procedures like ours. Attention may be needed to off-load information, but it results in a subsequent freeing up of attention, although there still may be intermittent activities using attention, such as refreshing of the representations in some sort of temporary memory (Barrouillet, Portrat, & Camos, 2011), which may consist of items off-loaded from the focus of attention to activated long-term memory (Rhodes & Cowan, 2018).

In sum, the more information there is that can be encoded in a manner that protects it from interference from additional stimuli from the other modality, the higher the peripheral components will be. The more information there is that is actually retained at the same time in a capacity-limited focus of attention, the higher the central component. We define the encoding that protects items from cross-modal interference as off-loading of information out of the central storage and into peripheral storage, and we propose that off-loading involves rapid memorization of the stimulus pattern, allowing storage of the information in the activated portion of LTM without further use of attention to maintain that information (cf. Rhodes & Cowan, 2018). Our definition of off-loading is not to be confused with another commonly used meaning of offloading, which refers to relying on external or environmental support to reduce the cognitive demands of a task (e.g., Risko & Gilbert, 2016).

In the following sections, we first describe a paradigm to measure central and peripheral components of WM. Then, we discuss some recent developmental findings using this paradigm, and we conclude with our predictions for how the central and peripheral components may change with normal aging.

A Paradigm to Measure Central and Peripheral Components of WM

Cowan et al. (2014) developed a simple paradigm (based on previous work by Saults & Cowan, 2007) to measure shared (central) and unshared (peripheral) capacities of WM. In their experiments, young adults were presented with visual arrays and verbal sequences of items (e.g., colored squares and spoken numbers) in either order, and were instructed to attend to only one set (unimodal conditions) or both sets (bimodal condition). This procedure equates the conditions for any unavoidable interference between sets, which was not of primary interest, and allows measurement of attention-based limits. Based on responses to subsequent probes to be judged to have been present in the attended set(s) or not present, they estimated how many items could be held in a central component of WM, capable of being allocated to either modality or shared between both, depending on task instruction, and how many items could be held in either a peripheral-visual or a peripheral-verbal component that was not influenced by concurrent attention to the other modality (see Figure 1). To do so, they modified formulas developed by Cowan, Blume, and Saults (2013) to estimate the number of items in WM that could be held in each component.

To illustrate how Cowan et al. (2014) derived capacity estimates for the separate components in Figure 1, we first must describe a metric of capacity. Suppose that, in a studied array of N items, k of those items are held in WM. If the test probe is an old item from the array, the likelihood that the probe is present in the participant's memory is k/N. If the test probe is an old item, but not retained in the participant's memory, or if the test probe is a new item, the participant guesses whether the item was in the set. Then it can be shown that $k = N^{*}(h\text{-}f)/h$, where h denotes the probability

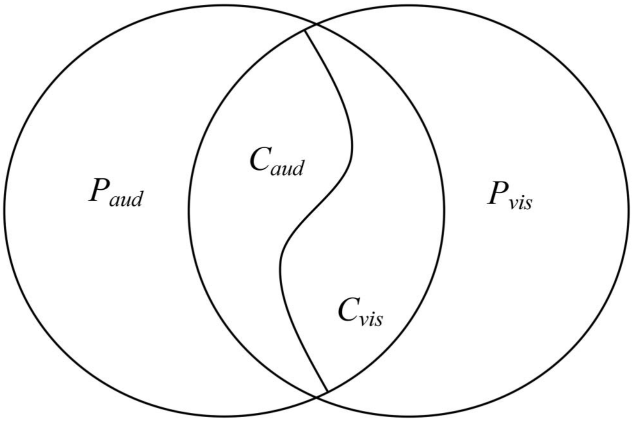

Figure 1. A theoretical model of the distribution of working memory capacity into two peripheral resources, one for auditory items (P_{aud}) and one for visual items (P_{vis}), and a shared central resource $C = C_{aud} + C_{vis}$. During bimodal attention, the central component is split, such that some resources are devoted to auditory items (C_{aud}) and others devoted to visual items (C_{vis}). The number of items retained by modality x, where x = auditory or x = visual, is $P_x + C_x$ in the bimodal condition and $P_x + C$ in the unimodal condition.

of a hit (correctly identifying the probe as new when in fact it is new), and *f* denotes the probability of a false alarm (incorrectly identifying the probe as new when in fact is old; see Cowan et al., 2013).

To derive central and peripheral components, Cowan et al. (2014) made use of four different *k* estimates for different situations: k_{au}, for the auditory-unimodal condition, in which the participant was instructed to attend only to the auditory modality; k_{ab}, for the auditory-bimodal condition, in which the participant was instructed to attend to both modalities but the test probe came from the auditory modality; k_{vu}, for the visual-unimodal condition, in which the participant was instructed to attend only to the visual modality; and k_{vb}, for the visual-bimodal condition, in which the participant was instructed to attend to both modalities but the test probe came from the visual modality. To estimate how many items could be held in the central component, *C*, Cowan et al. (2014) subtracted the sum of the bimodal estimates from the sum of the unimodal estimates:

$$C = (k_{au} + k_{vu}) - (k_{ab} + k_{vb})$$

If each unimodal memory condition is represented as a circle, then *C* reflects the overlap between the circles in the bimodal conditions (see Figure 1). Then, to estimate how many items could be held in the domain-specific peripheral components, the estimate of *C* was subtracted from the unimodal capacity estimate for each modality (P_{aud} for peripheral-auditory, and P_{vis} for peripheral-visual):

$$P_{aud} = k_{au} - C,$$

$$P_{vis} = k_{vu} - C$$

The estimate of *C* is positive any time the unimodal estimates are larger than the bimodal estimates, which is the typical pattern in dual-task situations (e.g., Cowan et al., 2014). This implies that the capacity of at least one of the modalities is larger when only that modality needs to be attended than when both modalities must be attended, suggesting that some component of WM storage is capable of being shared between modalities. In the unimodal condition, the central component could be allocated entirely to the attended modality. Then, the unimodal capacity estimate is equal to the sum of the central capacity and the peripheral capacity for that modality (e.g., $k_{au} = P_{aud} + C$). However, in the bimodal condition, the central portion of WM must make do with the same limited general resource to cover *both* modalities. Figure 1 shows how the central resource can be split between visual and acoustic objects, such that, in the bimodal condition, the capacity estimate for a given modality is equal to the sum of the peripheral component for that modality plus the proportion of the central component that is allocated to that modality (e.g., $k_{ab} = P_{aud} + C_{aud}$). The central component can be reallocated based on attentional demands (attend to one modality, or attend to both modalities), and thus would seem to require some volitional control of attention (Cowan et al., 2014; Rhodes & Cowan, 2018). The idea that attention plays a critical role in the maintenance of visual and auditory information in WM has been supported by other recent work (Souza & Oberauer, 2017; Thalmann, Souza, & Oberauer, 2019).

We do not claim that the use of attention is limited to the central component. Instead, we suggest that the use of attention strategically, to recode items in a way that allows them to be saved in peripheral components, is efficient because it reduces the subsequent need for attention, freeing it up for encoding of additional information, such as the second set to be remembered in our procedure. Also, the specific peripheral components in this method would of course not be bimodal if we drew all sets from the same modality, but that method would produce more feature-specific interference between sets, which was not our experimental aim.

A Brief Review of Findings Using the Cowan et al. (2014) Paradigm

In their experiments with young adults, Cowan et al. (2014) found that the central component consistently held about one item on average, and sometimes slightly less,[1] while the peripheral components held up to two or three items. Cowan, Li, Glass, and Saults (2018) extended the probe-recognition procedures of Cowan et al. (2014) to study developmental differences of the central and peripheral components of WM in children ranging in age from 6–14 years. Their results showed that the peripheral components of WM increased monotonically with age, while the central component did not differ in capacity across age groups, and was generally limited to the same one-item capacity as in young adults.

The results of Cowan et al. (2018) attribute, at least in part, developmental increases in WM capacity to an improved ability to maintain information from one modality in such a way to make it immune from cross-modality interference. As they argue, this could be related to the improved use of strategies among older children and adolescents, given developmental increases in knowledge, WM, and attention capabilities, which could aid with rapidly detecting and memorizing patterns in the arrays (see also Rhodes & Cowan, 2018). Extrapolating from these results and what is known about human aging (see below), we propose that the ability to maintain information in the peripheral components may decrease with adult age, possibly without changes to the central portion of WM.

Age-Related Declines in Central or Peripheral Storage?

The developmental findings of Cowan et al. (2018) are useful for framing predictions of how central and peripheral storage might change in older adulthood. (a) An early hypothesis of life span development stated that adult aging reverses the course of child development (Jackson, 1860, reprinted in Taylor, 1958). Then one might expect that the increases in peripheral capacities observed from childhood to adolescence would “reverse course” in older adulthood, following an inverted U-shaped function across the life span evident in previous studies on WM (Cowan et al., 2006). (b) One might alternatively expect a monotonic increase in peripheral storage if the growth of peripheral capacities depends

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[1] Capacity can be less than one item if there is partial loss of precision in the representation of an item due to interference or decay. The precision of items in an array diminishes as set size increases beyond three items (Anderson, Vogel, & Awh, 2011). The models used here do not explicitly model precision, but rather assume that degradation does not matter until it passes some threshold.

on increased strategies, as suggested by Cowan et al. (2018), and if these strategies in turn stem largely from developmental increases in knowledge. Older adults, who possess more knowledge than younger adults, should then be at least as capable as young adults at saving and maintaining information in the peripheral components. (c) It also could be that the *central* component declines in older adulthood, perhaps related to a diminished control of attention (e.g., Craik, 1983; Naveh-Benjamin et al., 2014). We know that overall WM capability declines with adult aging, so any increase in peripheral components would have to be compensated by decreases in a central component. (d) Combining Rationales a and c above, it could be that both peripheral and central components decline with age.

The Present Study

We used the probe-recognition procedures of Cowan et al. (2018, 2014) to provide a formal analysis of younger and older adults' WM capacity across domain-general and domain-specific components. In the procedure that has been used (Cowan et al., 2018, 2014), participants were presented with visual and acoustic items, in either order, in both unimodal and bimodal blocks. In the unimodal blocks, participants were instructed to attend to only one modality, whereas in the bimodal blocks, participants were instructed to attend to both modalities. The reason that two sets were presented even in the unimodal situation was so that any effect of interference across modalities that is not dependent on attention instructions would be constant across conditions. The central portion of performance would therefore reflect the participant's voluntary reaction to the attention instructions, whereas peripheral components indicate what portion of each modality can be retained in a stable manner regardless of the unimodal versus bimodal instructions. With regards to our TV example from earlier, the unimodal situation is like talking on the phone while ignoring visual scenes on the TV, or vice versa, while the bimodal situation is like attending to both the conversation and the visual scenes. In the present study, we kept the paradigm unchanged, so that the only major difference between conditions was the requirement to attend to one or both modalities.

Among the strengths of our approach is the use of a Bayesian estimation technique to more precisely estimate component capacities in younger and older adults than has been done in any previous report (for a recent critique of sample mean estimation, see Davis-Stober, Dana, & Rouder, 2018). Furthermore, our use of a capacity-estimate model (Cowan et al., 2014) and advanced estimation techniques address whether age-related declines in WM capacity result from diminished contributions of the central or peripheral components of WM.

Experiment 1

The first experiment closely mirrors the procedures used in Experiment 2 of Cowan et al. (2018), which used arrays of colored squares for visual stimuli and sequences of tones for auditory stimuli. The use of tones instead of verbal stimuli (e.g., spoken digits) was intended by Cowan et al. (2018) to decrease the possibility that participants could rehearse the acoustic stimuli, without needing to impose articulatory suppression during the encoding phase (as was done in several of the experiments of Cowan et al., 2014).

Method

Participants. Thirty-three young adults and 33 older adults participated. The young adults participated in exchange for research credits toward psychology courses. The older adults were recruited over the phone and compensated with $15. All participants reported to be in good health and had normal or corrected-to-normal hearing and vision.[2] Demographic statistics are presented in Table 1. There was a significant difference in the number of years of education completed between the young and older adults, $t(64) = -5.88$, $p < .001$. However, the young adults were college students who had not yet completed their education.

Materials. The stimuli included nine auditory tones developed by Li, Cowan, and Saults (2013, Experiment 3) and nine colored squares. The auditory tones were: *trumpet section* (200 Hz), *smooth clav* (262 Hz), *classic rock organ* (343 Hz), *negril bass* (450 Hz), *tenor sax* (589 Hz), *space harpischord* (772 Hz), *grand piano* (1011 Hz), *live pop horns* (1324 Hz), and *aurora bell* (1735 Hz). The colored squares were pixels of 1,024 × 768 sampled without replacement on each trial from the following: *black, white, red, blue, green, yellow, orange, cyan,* and *magenta*. An auditory mask combining all nine tones and a visual mask consisting of patterns of multicolored squares occupying the same size and space as items in the studied array were also presented simultaneously on each trial, before the onset of the test probe, to reduce any influence of sensory memory from the last-presented modality. Tones were presented to each ear using JVC Stereo Headphones HA-RX300 adjusted to an intensity of 65–75 dB. Visual stimuli were presented on a flat-screen ASUS HDMI monitor with a resolution of 1,920 × 1,080 and a refresh rate of 60 Hz. Both auditory and visual stimuli were automated with E-Prime 2.0 software.

Procedure. All participants provided informed consent prior to participation. Participants were tested individually in a sound-attenuated room with the experimenter present. These procedures were approved by the university's Institutional Review Board.

A schematic illustration of a study trial is depicted in Figure 2. A trial began with a central fixation cross (1,000 ms), followed by a blank screen (500 ms), before the onset of the visual array or tones. The visual array and tones appeared one after the other, separated by a 500-ms blank screen, with each appearing first on half of the trials in a random order. The visual array was presented onscreen for 500 ms, with five colored squares occupying random locations. Five tones occurred in sequence for 1,250 ms, with a presentation schedule of 125 ms on, 125 ms off to prevent blending. A 250-ms delay occurred between the end of the second set and the onset of the visual and auditory masks, which were presented simultaneously (500 ms) to remove any trace of the last-presented stimulus set from sensory memory. A 500-ms blank screen separated the offset of the masks and the onset of the test probe.

A single probe (either a tone or colored square) appeared on each trial. There were an equal number of visual and auditory

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[2] For the older adults, we also collected audiometer recordings of hearing sensitivity, measures of close vision sensitivity, and ratings on a 15-item vision questionnaire. Details of these additional sensory measures are disclosed in the online supplemental materials (section Sensory Analyses).

Table 1
Demographic Statistics

	Experiment 1		Experiment 2	
Demographics	Young	Old	Young	Old
Age *M* (*SD*)	19.03 (1.55)	72.18 (3.97)	20.27 (2.85)	71.93 (3.96)
Age range	18–24	64–80	18–30	66–79
% female	75.76%	78.78%	70.00%	80.00%
YoE	12.87 (1.62)	15.75 (2.31)	13.95 (2.46)	15.93 (2.03)

Note. YoE = years of education.

probes throughout the experiment. Additionally, there were an equal number of same and different trials, randomly intermixed. Same trials featured probes that had been presented during the study phase of that trial, while different trials featured probes that were randomly sampled from the colors or tones not presented during that trial. Participants responded "S" for same and "D" for different. A smiling face appeared in the center of the screen when participants responded correctly, and a frowning face appeared when participants responded incorrectly. The face remained on screen until participants pressed the spacebar to initiate the next trial.

Participants completed five counterbalanced blocks, presented in a pseudorandom order. The first two blocks were unimodal memory blocks (20 auditory-probe trials and 20 visual-probe trials), in which participants were instructed to attend to just the colors or just the sounds. The third block was a bimodal memory block (40 auditory-probe trials randomly intermixed with 40 visual-probe trials), in which participants were not informed prior to the trial whether the test probe would be visual or auditory in nature and thus had to pay attention to both sets of stimuli. The final two blocks were additional unimodal memory blocks of 20 trials each. The presentation of the blocks was counterbalanced between-subjects in one of the following two orders: (a) auditory-unimodal, visual-unimodal, bimodal, visual-unimodal, auditory-unimodal; (b) visual-unimodal, auditory-unimodal, bimodal, auditory-unimodal, visual-unimodal.

Analysis. All analyses were conducted within the Bayesian statistical framework. Bayesian statistics confer many advantages over null hypothesis significance testing, such as the ability to quantify evidence for a null effect (e.g., Kruschke, 2011). We first analyzed performance on the task using hierarchical Bayesian logistic regression models, as logistic regression is a more appropriate method of analyzing proportion correct data than ANOVA (Dixon, 2008). This technique models the log-odds of a correct response and ensures the resulting probabilities are confined to the unit interval.

Next, we modeled the partial capacity estimates (k_{au}, k_{vu}, k_{ab}, and k_{vb}) with hierarchical Bayesian versions of the models developed by Cowan et al. (2013). We fit one model to the young adult data and one to the old adult data. These models are similar to those outlined by Morey (2011) and by Rhodes, Cowan, Hardman, and Logie (2018). Such models take into account variability by making use of all of the data to provide constraints for the estimation of each parameter. Each model has eight parameters estimated for each participant: four estimates of k and four estimates of an uninformed guessing rate when memory for the probe was absent, u (one estimate of each parameter for each attention by modality condition). Individual participant parameters were assumed to be drawn from population-level distributions with weakly informative priors that allow the data to weigh more heavily than the prior information in determining the posterior distribution. These priors followed from those used by Morey (2011) and Rhodes et al. (2018).[3]

A major advantage of the hierarchical model over the standard model is that it does not return any nonsensical negative k estimates, which can sometimes arise with the standard formula when the false alarm rate exceeds the hit rate. The hierarchical model accomplishes this by modeling k indirectly via a transformation to kappa using a mass-at-chance transformation (see Footnote 3; Morey, 2011). This transformation allows for a true, effective WM capacity of 0 and interprets below-chance performance (a negative kappa value) as due to true capacity that is small or 0 plus random measurement error. This can occur especially in the bimodal trials because a participant with WM overloaded from one modality may have little or no space left over for the other modality.

Finally, for each participant, we derived an estimate of his or her central, peripheral-visual, and peripheral-auditory capacities, based on his or her individual-level mean estimated capacities from the hierarchical model, using the formulas from Cowan et al. (2014). For each component, we submitted the estimates to a Bayesian ANOVA model to test for a main effect of age.

Results

The data and analysis code for the two experiments are available at https://osf.io/5ja8y/.

Accuracy results. We first assessed whether there were any performance differences in the task. Accuracy data are summarized as proportion correct in Table 2 and were analyzed with hierarchical Bayesian logistic regression models, estimated using the brms package for R (Bürkner, 2017; R Core Team, 2018). The models reported here included the between-subjects effect of age (coded as 0 = young, 1 = old), and all fixed and random effects of attention (0 = unimodal, 1 = bimodal) and modality (0 = auditory, 1 = visual), with the random effects nested within participants.[4] Cauchy priors with location parameters of 0 and scale parameters of 2.5 for the population-level slopes and 10 for the intercepts were specified (see Gelman, Jakulin, Pittau, & Su,

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[3] Each participant i has four k_i parameters and four u_i parameter. Hierarchical priors were placed on transformations of these parameters. For each k, we used a mass-at-chance transformation (Morey, 2011; Rouder, Morey, Speckman, & Pratte, 2007), where $k_i = \text{maximum}(\kappa_i, 0)$, and the prior is placed on the kappa (κ) values. Each κ_i was drawn from a normal distribution, with a weakly-informative Normal(3,100) prior placed on μ of this distribution, and a broad Gamma(1.01005, 0.1005012) prior placed on the σ parameter to control shrinkage. The guessing rate is constrained to fall within the unit interval [0, 1], so we applied a logit transformation to u_i, with each logit(u_i) drawn from a normal distribution with weakly informative Normal(0, 100) prior on μ and the same diffuse gamma prior on σ as described above. Models were estimated from four independent chains, with a burn-in period of 5,000 samples and a sampling period of 5,000 samples per chain, estimated using the R package R2jags (R Core Team, 2018; Su & Yajima, 2015), which interfaces with JAGS (Plummer, 2003).

[4] An extended model including the additional factors of presentation order of the stimuli within a trial and correct answer for the probe on each trial is presented in online supplemental materials (see section Maximal Logistic Regression Results).

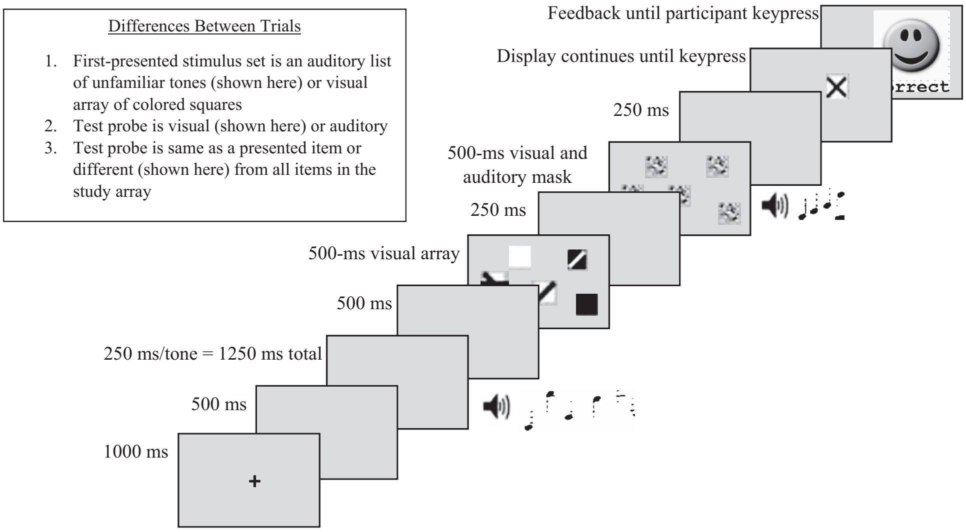

Figure 2. A detailed illustration of a trial. The insert explains the different types of trials that occurred. Patterns for the visual array objects represent colors.

2008), but we retained the program's default half *t*-distribution priors on the standard deviations of the random effects.

Results are depicted in Figure 3A, which shows the posterior mean and 95% Bayesian credible interval (CI) of the probabilities of correct responses. The Bayesian CI is a range that conveys the most probable values of the true estimate, such that values within the interval have higher credibility than values outside the interval, and should not be confused with a frequentist confidence interval, which does not provide a probability statement of the true value of an estimate (e.g., Kruschke, 2011). Those estimates whose 95% CIs do not overlap are reliably different from each other. On visual inspection alone, it is apparent that (a) older adults consistently had lower proportion correct than young adults; (b) proportion correct was, in all cases, higher in the visual than in the auditory conditions; and (c) the only apparent differences in performance between the unimodal and bimodal conditions occurred in the visual modality.

Support for these conclusions came from a series of hypothesis tests. Our primary interest was in characterizing the effect of age on response accuracy, and whether the age effect differs in unimodal and bimodal conditions and/or between auditory and visual modalities. Therefore, we first tested for a main effect of age by comparing old adults to the baseline group in the model (young adults in the auditory unimodal condition). The odds ratio (*OR*) comparing old with young adults in this condition was $OR = 0.67$, 95% CI [0.53, 0.84], demonstrating that older adults were less likely to respond correctly than the young adults. Next, we tested whether this age effect changed from the auditory unimodal to

Table 2
Proportion Correct

Probe	Attention	First presented	Answer	Experiment 1		Experiment 2	
				Young	Old	Young	Old
Auditory	Unimodal	Tones	Different	.68 (.18)	.57 (.18)	.69 (.15)	.62 (.22)
Auditory	Unimodal	Tones	Same	.73 (.17)	.63 (.22)	.80 (.16)	.70 (.13)
Auditory	Unimodal	Colors	Different	.57 (.23)	.55 (.16)	.66 (.20)	.62 (.20)
Auditory	Unimodal	Colors	Same	.80 (.17)	.65 (.19)	.88 (.12)	.80 (14)
Auditory	Bimodal	Tones	Different	.58 (.22)	.51 (.26)	.65 (.15)	.51 (.22)
Auditory	Bimodal	Tones	Same	.80 (.14)	.63 (.14)	.82 (.12)	.75 (.20)
Auditory	Bimodal	Colors	Different	.54 (.19)	.54 (.18)	.64 (.16)	.51 (.21)
Auditory	Bimodal	Colors	Same	.82 (.15)	.68 (.17)	.91 (.10)	.77 (.21)
Visual	Unimodal	Tones	Different	.88 (.13)	.76 (.20)	.90 (.08)	.77 (.18)
Visual	Unimodal	Tones	Same	.86 (.13)	.72 (.20)	.80 (.14)	.69 (.17)
Visual	Unimodal	Colors	Different	.89 (.10)	.74 (.21)	.92 (.11)	.73 (.20)
Visual	Unimodal	Colors	Same	.83 (.14)	.73 (.18)	.79 (.14)	.65 (.21)
Visual	Bimodal	Tones	Different	.87 (.11)	.72 (.21)	.89 (.13)	.68 (.24)
Visual	Bimodal	Tones	Same	.78 (.16)	.69 (.15)	.71 (.19)	.64 (.18)
Visual	Bimodal	Colors	Different	.82 (.14)	.69 (.23)	.83 (.16)	.64 (.26)
Visual	Bimodal	Colors	Same	.66 (.20)	.66 (.14)	.67 (.18)	.63 (.22)

Note. Values depict the mean (*SD*) proportion correct for each condition.

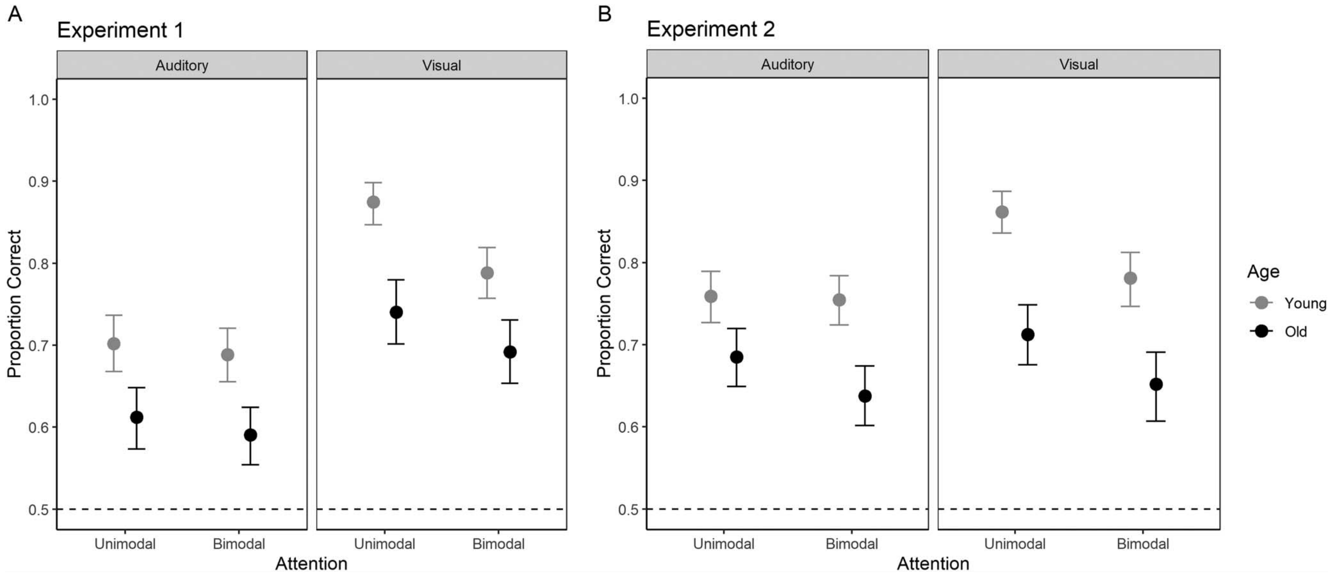

Figure 3. Mean proportion correct for each Age × Attention × Modality condition in Experiment 1 (A) and Experiment 2 (B). Values depict the Bayesian posterior mean (point) and 95% credible interval (lines). Dashed line at 0.5 corresponds to chance level accuracy.

visual unimodal conditions (i.e., an Age × Modality interaction). The resulting $OR = 4.81$, 95% CI [2.72, 8.58], shows that the odds of the age effect was much *larger* in the visual unimodal condition, confirming an Age × Modality interaction.

However, this interaction was further qualified by an Age × Modality × Attention interaction. The age effect in the auditory condition was approximately equivalent in the bimodal and unimodal conditions, as the odds ratio overlapped with 1, $OR = 0.96$, 95% CI [0.65, 1.42], indicating that there was about a one to one odds that the age effect differed between attention conditions. In contrast, the age effect in the visual condition was *smaller* in the bimodal than the unimodal condition, $OR = 0.38$, 95% CI [0.21, 0.71]. To understand this interaction, note that young adults performed especially well in the visual unimodal condition relative to the auditory unimodal condition (the baseline), $OR = 2.94$, 95% CI [2.27, 3.86], but the magnitude of the modality difference in performance was smaller in the visual bimodal relative to the auditory bimodal condition, $OR = 0.61$, 95% CI [0.41, 0.93].

Capacity estimates. Next, we turn our attention to the partial capacity estimates (k_{au}, k_{vu}, k_{ab}, and k_{vb}). Population-level parameter estimates are given in Table 3.[5] Across age groups, the uninformed guessing rate (i.e., the bias toward responding change) was relatively consistent, and was higher in the visual than auditory modality but did not differ between unimodal and bimodal conditions. However, capacity estimates differed by age groups. The 95% highest posterior density intervals (HDI) for each attention by modality capacity estimate did not overlap between age groups, indicating a very low (near 0) probability that any of the estimates were the same for young and older adults. In all cases, the older adults had lower capacities. This is easily visualized in Figure 4A. For the auditory estimates, older adults' capacities were 1.22 [0.43, 1.98] (median and 95% HDI) and 1.53 [0.72, 2.34] items smaller than those of the young adults for the unimodal and bimodal conditions, respectively. For the visual estimates, older adults' capacities were 0.99 [0.42, 1.56] (for the unimodal condition) and 0.74 [0.06, 1.35] (for the bimodal condition) items smaller than those of the young adults.

Declines in capacity from unimodal to bimodal conditions were mostly restricted to the visual modality. For the auditory modality, in both age groups, the unimodal and bimodal estimates were quite similar to one another, and the 95% HDIs overlapped considerably. However, in the visual modality, there was some indication that the estimates were smaller in the bimodal than unimodal conditions for both young (unimodal–bimodal = 0.74 [0.21, 1.27]) and older adults (unimodal–bimodal = 0.42 [−0.23, 1.14]), though note that 0 (corresponding to no difference in capacities between unimodal and bimodal conditions) was still contained within the 95% HDI for the older adults.

Central and peripheral components. Each component was submitted to a Bayesian ANOVA model to test for a main effect of age. Models were specified using the BayesFactor package for R (Morey & Rouder, 2015; R Core Team, 2018) with the program's default priors. Each model yields a Bayes factor, B_{10}, providing evidence in favor of an age effect (conversely, the B_{01} describes the strength of evidence against an age effect). The Bayes factor quantifies how many times more likely one hypothesis is than the other, given the data. A Bayes factor between 1 and 3.2 is interpreted as weak evidence in favor of one model, a Bayes factor between 3.2 and 10 is regarded as substantial evidence, a Bayes factor between 10 and 100 is regarded as strong evidence, and a Bayes factor larger than 100 as decisive evidence (Kass & Raftery, 1995).

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[5] Results with the standard formulas are similar to those obtained with the hierarchical models reported here (see Table S3 in the online supplemental materials).

Table 3
Posterior Medians (and Highest Density Intervals) of Population-Level Mean Parameters of Capacity Estimate Model

Exp.	Age	k_{au}	k_{vu}	k_{ab}	k_{vb}	u_{au}	u_{vu}	u_{ab}	u_{vb}
1	Young	3.16 [2.81,3.48]	4.08 [3.83,4.32]	3.27 [2.91,3.60]	3.34 [3.05,3.62]	.64 [.58,.69]	.89 [.86,.92]	.56 [.50,.62]	.85 [.82,.89]
	Old	1.94 [1.50,2.38]	3.09 [2.76,3.41]	1.74 [1.26,2.19]	2.64 [2.82,3.24]	.65 [.50,.79]	.77 [.71,.82]	.53 [.46,.60]	.73 [.66,.78]
2	Young	3.04 [2.82,3.24]	3.89 [3.68,4.10]	3.12 [2.90,3.32]	3.18 [2.93,3.43]	.68 [.63,.73]	.92 [.89,.94]	.64 [.59,.70]	.87 [.84,.90]
	Old	2.31 [1.97,2.63]	2.77 [2.41,3.12]	2.12 [1.73,2.48]	2.22 [1.83,2.62]	.63 [.55,.71]	.77 [.70,.83]	.52 [.43,.60]	.68 [.60,.75]

Note. Exp. = experiment; ab = auditory bimodal; au = auditory unimodal; vb = visual bimodal; vu = visual unimodal. The k values in the headings are model estimates: see text for detail.

For both peripheral components, there was decisive evidence for an age effect, $B_{10} = 8.65 \times 10^{10}$ (for the peripheral-auditory component) and $B_{10} = 1.56 \times 10^{8}$ (for the peripheral-visual component). In both cases, young adults had higher capacities in these components than the older adults (see Figure 5A). However, there was substantial evidence *against* an age difference on the central component, $B_{10} = 0.26$ (which corresponds to a $B_{01} = 3.90$). Therefore, the age-related deficits in WM capacity reported in the current study appear to be attributable to diminished capacity of the peripheral components but not to deficiencies in the central component.

Discussion

Results from Experiment 1 suggest that, similar to the childhood deficit observed by Cowan et al. (2018), age-related deficits in WM capacity occur in the domain-specific peripheral components of WM, rather than in the domain-general central component. This result was manifest in the decrease with age in the visual and acoustic peripheral components, but not in the central component of the model shared between modalities.

There is one important, outstanding empirical limitation, which we address in Experiment 2. In the auditory condition of Experiment 1, the older adults performed close to chance level (see Figure 3A). It could be that the auditory task was especially difficult for the older adults, as indicated by their small auditory capacities, which were less than half of the set size. This may have led some older adults to give up on the auditory task, such that the estimates of their auditory capacities do not reflect how many items they may actually be able to hold from that modality in both the unimodal and bimodal conditions. We attempted to improve performance on the task by reducing the set size of the tones in Experiment 2.

Experiment 2

Experiment 2 aimed to replicate our findings from Experiment 1, with two changes. First, we reduced the set size of the tone task from five to four tones in the hopes of improving performance on the task. Of course, it is likely this would also cause an improvement in auditory performance for the younger adults, but we were primarily interested in testing whether older adults would have

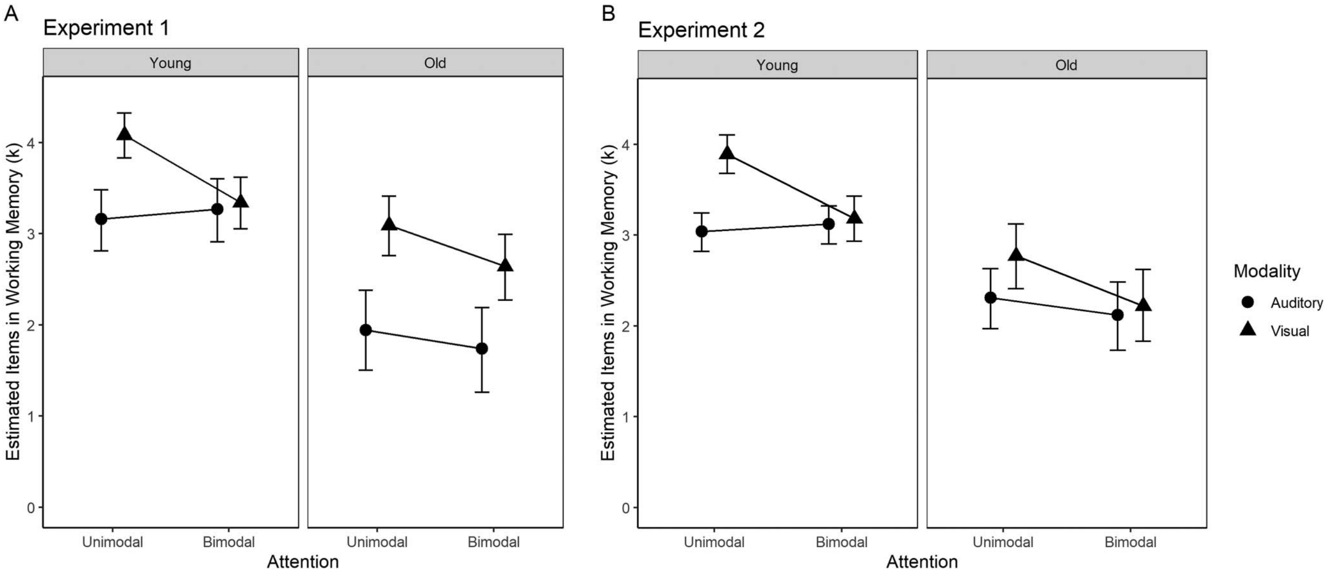

Figure 4. Capacity estimates *k* in Experiment 1 (A) and Experiment 2 (B). Points denote the population-level mean, bar corresponds to the 95% highest posterior density interval (HDI). The lines connecting points intend to show the direction of change in capacity from unimodal to bimodal attention loads.

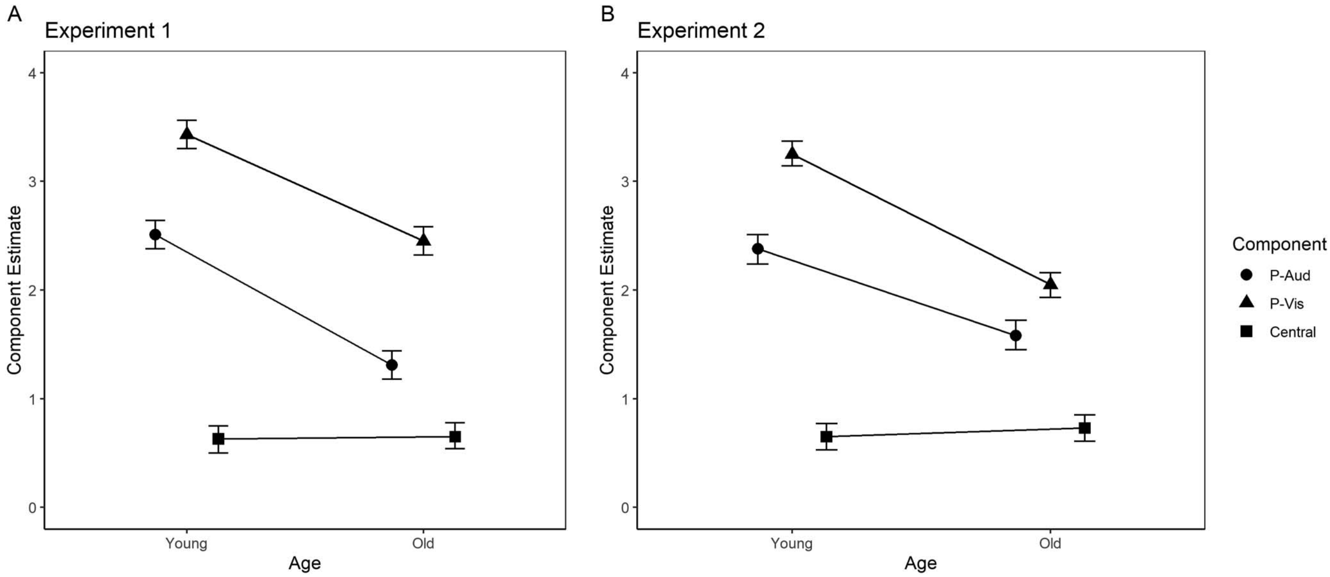

Figure 5. Estimated number of items held by each component in Experiment 1 (A) and Experiment 2 (B). Points correspond to the population-level mean, and error bars denote the 95% Bayesian credible interval. P-Aud = auditory peripheral component; P-Vis = visual peripheral component.

similar component capacities as in Experiment 1 even with improved task performance. Second, we added a simple, AX, two-stimulus change-detection task (in which a probe stimulus X is to be judged same or different from the prior stimulus A) to Experiment 2 to test whether there were age differences in the ability to detect changes in the stimuli with the smallest possible memory load. This AX task was added because it is conceivable that older adults could not adequately detect changes in the stimuli, perhaps due to diminished sensory abilities (e.g., Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994), such that performance differences on the task may be attributable to lower-level perceptual processes rather than WM capacity limitations.

Method

Participants. An additional 30 young and 30 old adults participated in Experiment 2. Demographic statistics are reported in Table 1. As in Experiment 1, the young adults, who had not yet completed their formal education, had fewer years of education than the older adults, $t(58) = -3.53$, $p = .001$.

Materials and procedure. The materials and procedure were the same as in Experiment 1, with two changes. First, the number of auditory stimuli presented in a trial was changed from five to four. Second, before the first block of trials was presented to participants, participants completed an AX probe change-detection task. This task was designed to assess whether age-related performance differences (and thus differences in capacity estimates) could be attributed to differences in the ability to detect changes in the auditory or visual stimuli. Participants completed 54 trials (27 auditory, 27 visual) of the change-detection task. On each trial, either a tone was played through the headphones or a colored square appeared onscreen, each for 125 ms. This was followed by a 125-ms delay, and then either a second tone (for tone detection trials) or second colored square (for color detection trials) was presented. The participant was instructed to respond "S" if the second stimulus was the same as the first stimulus and "D" if the second stimulus was different from the first stimulus. After completing all 54 trials, participants completed the five blocks of the experiment, in the same pseudorandom fashion described in Experiment 1. All participants provided informed consent prior to participation.

Results

AX change-detection trials results. First, we assessed whether young and older adults differed on the initial change-detection trials designed to ensure that participants could reliably detect changes in the experimental stimuli at the smallest possible memory load. There were no differences in performance between the young and old adults on either the auditory trials, $t(58) = 1.32$, $p = .191$, or the visual trials, $t(58) = -0.57$, $p = .57$. In both age groups and on both trial types, mean proportion correct was .99. Therefore, there appears to be no impairment among older adults in detecting changes in the visual or auditory stimuli at small memory loads, such that performance differences are not likely attributable to differences in stimulus change-detection.

Accuracy results. Proportion correct is summarized in Table 2, and results from the logistic regression model are plotted in Figure 3B. On visual inspection alone, these results closely mirror those of Experiment 1, but note that performance improved in the auditory condition. The main effect of age was consistent with Experiment 1. The odds ratio comparing old with young adults was $OR = 0.69$, 95% CI [0.54, 0.89], in the auditory unimodal condition (reference group in the model). There was also evidence for an Age × Modality interaction, as the magnitude of the age effect was *larger* in the visual unimodal than the auditory unimodal condition, $OR = 3.45$, 95% CI [1.97, 6.05]. There was also an Age × Modality × Attention interaction. The age effect in auditory condition held the same for both the bimodal and unimodal conditions, *OR* = 1.19, 95% CI [0.78, 1.80], but the age effect in the visual condition was smaller in the bimodal than in the unimodal condition, *OR* = 0.36, 95% CI [0.19, 0.70]. This pattern of accuracy results was the same as in Experiment 1, but the critical difference was that accuracy in the auditory conditions improved, for both age groups.

Capacity estimates. Capacity estimates from the hierarchical model are given in Table 3, along with estimates of the uninformed guessing rates. The guessing rates were nearly identical to those obtained in Experiment 1. The age-related differences in capacity estimates in Experiment 2 were strikingly similar to those in Experiment 1 (see Figure 4B). Older adults had lower capacity estimates than younger adults for each attention-by-modality condition, with no overlap in the 95% HDIs between age groups. For the auditory estimates, older adults' capacities were 0.73 [0.19, 1.27] (median and 95% HDI) and 1.00 [0.42, 1.59] items smaller than those of the young adults for the unimodal and bimodal conditions, respectively. For the visual estimates, older adults' capacities were 1.12 [0.56, 1.69] (for the unimodal condition) and 0.96 [0.31, 1.60] (for the bimodal condition) items smaller than those of the young adults.

Also consistent with Experiment 1, there was substantial overlap in the 95% HDIs for the capacity estimates in the auditory unimodal and bimodal conditions in both age groups, suggesting very little, if any, change in auditory capacity across attention condition. The evidence was less clear-cut in the visual modality. Younger adults had a higher estimated visual capacity in the unimodal than bimodal condition (unimodal–bimodal = 0.71 [0.25, 1.17]), but for the older adults, 0 was still contained within the 95% HDI (unimodal–bimodal = 0.55 [−0.21, 1.29]). Nevertheless, most of the distribution skewed away from 0, suggesting some deficit in visual capacity in the bimodal condition.

Central and peripheral components. To summarize the results of Experiment 2 so far, performance in the auditory modality improved relative to Experiment 1, but the same general patterns of results on accuracy and WM capacities were observed in both experiments. The critical test was whether the change in performance in the auditory modality would reflect a change in older adults' peripheral storage capabilities in the auditory-dedicated component of WM.

Each component was estimated from each participant's individual-level mean estimated capacities from the hierarchical model using the formulas from Cowan et al. (2014), and submitted separately to a Bayesian ANOVA to test for age effects. The results are depicted in Figure 5B and closely mirror those of Experiment 1. The older adults had lower capacities in each of the unshared components, with decisive evidence for an age effect on the peripheral-auditory component, $B_{10} = 2.80 \times 10^5$, and the peripheral-visual component, $B_{10} = 5.51 \times 10^{12}$. However, there was weak evidence against an age difference for the central component, $B_{10} = 0.33$ (which corresponds to a $B_{01} = 2.99$). Therefore, even when the task is less difficult, and older adults perform better at the task, they still have deficits in peripheral storage relative to younger adults.

Comparing component capacities across experiments. We also tested whether component capacities changed across experiments by means of a separate 2 (age) × 2 (experiment) Bayesian ANOVA for each component. For the central and peripheral-auditory components, the estimated capacities were the same across experiments, with substantial evidence against an effect of Experiment (both $B_{01} = 4.64$). There was also substantial evidence against an Age × Experiment interaction for the central component ($B_{01} = 3.70$), although the evidence was more inconclusive for the Age × Experiment interaction on the peripheral-auditory component ($B_{10} = 1.96$ or $B_{01} = 0.51$, which is regarded as weak evidence not generally worth mentioning; Kass & Raftery, 1995).

However, for the peripheral-visual component, there was strong evidence for an effect of experiment ($B_{10} = 37.03$). Although the evidence for or against an Age × Experiment interaction was weak ($B_{01} = 2.11$, or $B_{10} = 0.47$), among young adults only, testing for an effect of Experiment on peripheral-visual capacity yielded weak, inconclusive evidence, $B_{10} = 1.45$. However, for the older adults, the main effect of experiment yielded substantial evidence, $B_{10} = 6.40$. Older adults had lower peripheral-visual capacities in Experiment 2 ($M = 2.05$, 95% CI [1.93, 2.16]) than in Experiment 1 ($M = 2.45$, 95% CI [2.32, 2.58]).

Discussion

As with the first experiment, in Experiment 2, older adults showed deficits in storing items in the peripheral portions of WM but were as capable as younger adults in holding information in the central, shared component of WM. Even with improved task performance, these age-related deficits still emerged. Furthermore, the capacities of the central and peripheral-auditory components were relatively unchanged even as the number of tones to-be-remembered was reduced from five to four tones. However, the capacity of the peripheral-visual component *decreased*, especially among the older adults. This result may seem counterintuitive, given that there were no changes between experiments in the set size of the visual memoranda. In our General Discussion below, we explain how these seemingly surprising results fall out of the embedded-processes model of WM and the notion of off-loading to activated LTM.

General Discussion

There have been many reports in the literature of diminished WM capacity in older adults (e.g., Cowan et al., 2006; Gilchrist et al., 2008; Light & Anderson, 1985; Naveh-Benjamin et al., 2014; Wingfield et al., 1988), but the question of whether this diminished capacity reflects a loss of storage in a domain-general resource (e.g., Kane et al., 2004) or in domain-specific components has been the subject of some debate. Reports of diminished attentional control mechanisms and a potentially smaller focus of attention in older adults (Craik, 1983; Naveh-Benjamin et al., 2014) suggest that they may have a smaller capacity central component of WM, which could be allocated across multiple modalities. There is also a dual-task cost in older adults' WM that is larger than the cost in young adults (e.g., Bopp & Verhaeghen, 2005; Rhodes et al., 2019). Although it therefore seems clear that there is an increased attention deficit with aging, the literature has not made clear whether this cost occurs because fewer items can be stored concurrently using attention, or because the ability to encode information in a way that diminishes the role of sustained attention to the information declines with age.

To date, no previous studies have provided a direct estimate of central and peripheral capacities of WM among older adults, which would provide a more conclusive answer as to whether older adults' deficits in WM capacity are attributable to domain-general or domain-specific losses. Using such a method (developed by Cowan et al., 2014), the present study provided strong support for the latter claim: Older adults had preserved central capacities, compared with younger adults, but much smaller peripheral capacities. Comparing the results here to those reported in a recent developmental study by Cowan et al. (2018), it is clear that the capacity of the central component of WM remains relatively stable across the life span, at about one item. Meanwhile, the peripheral components increase from childhood to adolescence and peak in young adulthood, then remain relatively stable into middle-age (Cowan et al., 2018). They then decline dramatically in older adulthood, as the current experiments show, such that the capacities of the peripheral components follow an inverted U-shaped function across the life span, consistent with previous research on the life span development of WM (Cowan et al., 2006).

In the following sections, we explore several possibilities for why older adults had diminished peripheral capacities. We consider how some of these possibilities can be effectively ruled out, and we present evidence suggesting that older adults in the present study may have been impaired in strategically off-loading items from the focus of attention to the peripheral components.

Compensating for Potential Sensory Loss?

One possibility is that the diminished peripheral components reflect lower-level perceptual processing differences rather than true capacity limitations. In accord with the cognitive permeation account (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Naveh-Benjamin & Kilb, 2014), older adults may attempt to hold information more centrally (i.e., with more attention) to compensate for potential sensory loss. Older adults may struggle to process information from one or both modalities, thus taxing central processing, and making off-loading to the peripheral components more difficult. We consider this possibility relatively unlikely, as the older adults in our sample had good hearing and vision, and sensory capabilities did not correlate with older adults' performance on the task (see section Sensory Analyses of the online supplemental materials for details). Moreover, in Experiment 2, we found no age differences on the simple, AX (two-stimulus) change-detection task, suggesting older adults were as capable as younger adults at detecting changes in the stimuli.

Build-Up of Proactive Interference?

A second possibility involves interference across trials. We assume that interference within a trial is all-or-none. This is because the simple stimuli in the present experiments were categorically distinct from one another (e.g., red vs. blue), such that any interference among the stimuli in a given trial is due to one stimulus replacing another (e.g., a color being replaced by another color or a tone). However, items from an earlier trial may interfere with items from the same stimulus modality if those items are held in activated LTM (i.e., the peripheral components). Hence, proactive interference from memory arrays in an earlier trial, which has been shown to affect older adults' WM performance (Bowles & Salthouse, 2003; Emery, Hale, & Myerson, 2008), may have led to lower peripheral capacities. However, we effectively ruled out this possibility by testing whether performance changed across the unimodal blocks and across trials within the bimodal block. Those results are reported in the Interference Analyses section of the online supplemental materials, and in all cases, there were no trial or block effects on memory accuracy in either the young or older adults.

Impaired Off-Loading Capabilities?

A third possibility relates to the role of attention in WM and the use of an off-loading strategy to reduce the burden on attention (e.g., Rhodes & Cowan, 2018). Off-loading refers to the process of strategically creating LTM structures out of items in a sequence or array of to-be-remembered items, to aid with their maintenance by storing them in a less attention-demanding way in peripheral components of WM, reducing the need to store them in a common mechanism that we measure as the central component (for a somewhat different conception of offloading, not to be confused with our definition here, see Risko & Gilbert, 2016).[6]

The proposal of off-loading fits within the embedded-processes model of WM (Cowan, 1988, 1999, 2005). However, off-loading is also a viable mechanism from other models of WM which propose that a dynamic relationship exists between WM and LTM (e.g., Oberauer, 2002, 2009) or which view WM and LTM as nonseparable constructs (e.g., Nairne, 2002). In the embedded-processes model, a limited capacity focus of attention resides in an activated portion of LTM. This focus of attention may be able to take on three to five items during initial encoding and is assumed to do so when items are encoded into WM (e.g., Cowan, 2001; for physiological evidence see Cowan, 2019; Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012). However, items must be quickly displaced from the focus of attention if it is to be used to carry out other tasks, such as our dual-task situation in which memoranda from two modalities must be retained in WM.

In a dual-task situation, information from one modality (e.g., visual memoranda) may first load onto the focus of attention. An individual may rapidly memorize the visual information, creating a new LTM structure by detecting a pattern in the array. This newly memorized structure could be held peripherally, in activated LTM. This process would free up the focus of attention to take in the second set (e.g., auditory memoranda), which in turn may be rapidly memorized and off-loaded to activated LTM. With both sets off-loaded, the focus of attention may be used in a more efficient way, to serially refresh both sets to prevent them from decaying (e.g., Barrouillet, Bernardin, & Camos, 2004).

There is some neural evidence pointing to off-loading being a strategic process. Reinhart and Woodman (2014) manipulated the amount of reward that participants could receive from correctly detecting a target stimulus in a search array within a brief exposure duration. Participants were initially cued to the amount of reward that could be received on a given trial (low or

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[6] The off-loading process for a stimulus set could either occur while the stimuli are being presented, sparing the load on attention very rapidly, or during the retention interval, reducing the load on attention more gradually, but still in time to assist in the retention of two sets at once in the bimodal condition. We do not distinguish between these possibilities.

high reward). The same target stimuli were used over multiple trials in a row, but the high reward cues occurred less frequently than the low reward cues. To index storage of the templates in WM, Reinhart and Woodman (2014) measured an event-related potential component, the contralateral delay activity (CDA), which indexes the maintenance of target representations in WM (Carlisle, Arita, Pardo, & Woodman, 2011), while a P170 component was used to index the accumulation of LTM representations. The CDA decreased over multiple trial-runs, while the P170 component increased, providing evidence that activity shifted from maintaining the targets in WM to LTM. However, the declining CDA was reversible when a large reward cue was provided. This finding is in line with the proposal that items maintained in WM can be off-loaded to activated LTM, but individuals can strategically control the relative use of activated LTM in response to task demands and rewards.

There is an important finding from the Reinhart and Woodman (2014) study that bears on our suggestion that older adults have diminished off-loading capabilities. They found that WM capacity (*k*) predicted the size of the CDA. Individuals with higher *k* had smaller CDAs over repeat trial runs, indicating they relied less on WM and were thus better at off-loading information to activated LTM. There was also a negative correlation between WM capacity and the change in the P170 component over trials, indicating that with lower *k*, there is less reliance on the LTM component. This result suggests that individuals with larger WM capacities are more capable of relying on LTM, rather than WM. In the present study, older adults' WM capacities were consistently lower than the younger adults' capacities. Thus, extrapolating from the results of Reinhart and Woodman (2014), it is reasonable to conclude that older adults rely more on active maintenance in WM, and less on off-loading to LTM, than young adults. Similarly, Fukuda and Vogel (2019) have recently shown that visual WM capacity predicts how many items can be encoded into LTM. Individuals with smaller WM capacity encode less information into LTM, such that WM capacity determines the amount of LTM encoding.

Because off-loading is a strategic process of freeing up attention, it seems likely that older adults were less effective at carrying out off-loading than younger adults, or that any efforts to do so required a greater commitment of attention to maintain items in WM. In Experiment 2, we asked participants at the end of the experiment to report on any strategies they may have used. Twenty young and 17 old adults reported using some strategy, and the reported strategies were relatively similar between age groups (e.g., grouping colors, detecting a sequence in the tones). It could be that, in Experiment 1, older adults struggled with creating sequences out of five tones, and thus mostly attempted strategies only with the visual memoranda. This in turn could have led to higher peripheral-visual than peripheral-auditory capacity in the old adults in Experiment 1 (about one item more was stored in the visual modality). In Experiment 2, with more chance of success in encoding the acoustic stimuli, some attention could have been shifted from the visual stimuli to the acoustic. The acoustic peripheral component was about the same size in Experiments 1 and 2, but research with visual and verbal stimuli matches ours in showing that divided attention tends to hurt visual performance more than nonvisual (Morey & Bieler, 2013; Morey, Morey, van der Reijden, & Holweg, 2013; Vergauwe, Barrouillet, & Camos, 2010).

After off-loading, attention presumably would still be needed during the maintenance period to refresh any off-loaded representations, to prevent them from decaying (Barrouillet et al., 2004; Rhodes & Cowan, 2018). It is conceivable that any off-loading strategies older adults attempted to use required a continued, relatively high involvement of attention compared to young adults. In Experiment 2, when older adults may have attempted to off-load from *both* the auditory and visual modalities (as suggested by their reported strategy uses), there was a surprising finding that the peripheral-visual capacity declined by about half an item. This suggests that even when older adults attempt to off-load items to activated LTM, they still use more attention to maintain those items than younger adults do.

It is also theoretically possible that there is no difference between the process of refreshing and the process of off-loading and memorization of information. Consistent with that idea, Loaiza and McCabe (2013) showed that the opportunity to refresh material corresponded to the amount of long-term episodic learning of that material as shown in delayed recall. Moreover, the amount of benefit from refreshing was smaller in older adults.

The proposed use of attention for storage of information directly in our central component, versus for refreshing of information in our peripheral components, could map onto different neural structures. Off-loading may be dependent on frontal-lobe-based, executive functions that change with age (Cabeza & Dennis, 2012; West, 1996). In contrast, the central component indexes information in a way that could reflect storage in the focus of attention and could be more dependent on parietal-lobe areas, and in particular the intraparietal sulcus (Cowan et al., 2011; Majerus et al., 2016; Majerus, Péters, Bouffier, Cowan, & Phillips, 2018), and might be less affected by aging. Alternatively, rather than the direct storage of information, the central component could reflect the process of refreshing itself, and the difficulty of trying to refresh acoustic and visual materials at once; but under that hypothesis, it might be more difficult to explain why the central component did not change with age, given the aforementioned age changes in the use of refreshing (Loaiza & McCabe, 2013).

One possible reason for why older adults are less effective at off-loading items from central to peripheral storage may be related to their reduced processing speed (e.g., Salthouse, 1996), which has been shown to account for most of the age-related variance in WM performance (Fisk & Warr, 1996; Salthouse & Babcock, 1991). Accordingly, if the process of off-loading is slower, older adults may be less capable of off-loading items from one modality from the focus of attention before the second stimulus set is presented, leading to more conflict between the requirements to encode and retain two stimulus sets.

Declines in Modality-Specific Modules of Multicomponent Models?

In the previous section, we have presented the rationale for why we believe older adults are impaired in off-loading information from a limited capacity focus of attention to activated

LTM. This view falls naturally out of the embedded-processes model of WM, but many other popular models of WM exist, such as the multicomponent model (Baddeley, 1986; Baddeley & Hitch, 1974). In this model, several discrete and relatively independent coding modules store information in WM. Verbal or acoustic information is stored in a durable phonological code, referred to as the phonological loop, while visual information is coded in the visuospatial sketchpad. It is conceivable that the peripheral components of the model of Cowan et al. (2014) could map onto these modality-specific modules. Reconciling our results with the multicomponent model would imply that the visuospatial sketchpad and phonological loop decline in capacity with normal aging. This may be an appealing possibility, but it is at odds with findings suggesting similar capacities of the phonological loop between young and older adults (Nittrouer, Lowenstein, Wucinich, & Moberly, 2016) or those suggesting that most of the age-related declines in WM performance are attributable to reduced processing efficiency rather than storage capacity differences (Fisk & Warr, 1996; Salthouse & Babcock, 1991).

If the modular type of theory is correct, we believe that the most likely account of the present results from that view would involve a decline in the capabilities of central executive processes. The absence of an aging effect of the central component might map onto an absence of an effect of aging on the episodic buffer, which possibly could serve the same function here as Cowan's (1988, 2019) focus of attention (Baddeley, 2001).

Central and Peripheral Contributions to Binding

A potentially promising avenue of future research involves adapting the paradigm used here to assess age-related differences in feature binding in WM. Age differences in recognition performance are disproportionately larger for associations among items relative to individual items (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008). Some research has linked deficits in binding the basic features of objects (e.g., color, shape, and location) to the pronounced decline in visual WM capacity observed in old age (e.g., Brockmole & Logie, 2013; Cowan et al., 2006; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000; Peterson & Naveh-Benjamin, 2017). In younger adults, the contribution of the peripheral components has been shown to decrease on tasks requiring feature binding (Cowan et al., 2014, Experiments 3 and 4). As older adults already have diminished peripheral components on item-change detection tasks, as shown in the present study, it would be worthwhile to assess if their ability to assess binding-changes would place an increased burden on their central components, potentially resulting in a decline in the number of items that can be held centrally.

Conclusion

In summary, results from the present study implicate deficits in older adults' activated long-term memory or domain-specific storage, potentially from a diminished ability to effectively use strategies to off-load items from the focus of attention to this storage. In contrast, loss of domain-general storage, through which both colors and tones can be stored within a limited total capacity, does not appear to contribute to older adults' diminished WM capacities. This dissection of aging effects on WM provides an avenue for further research on how attention and executive function are involved in aging.

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