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The QuadMax Task: Parametrically Manipulating Associative Memory Load across the Adult Lifespan

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ABSTRACT

Adults of all ages are worse at recognizing pairs of items that were previously seen together relative to the individual items, and this paired-associative memory deficit is exacerbated in aging. Less is known about memory for higher associative loads, which place greater demands on binding processes that link items into a cohesive memory trace, among other processes (e.g., working memory, recollection). In this study, adults across the lifespan ($n = 250$, 18–78 years) completed a novel recognition task in which they studied word pairs, triplets, and quadruplets and were tested on their memory for repeated, recombined, and novel word sets. Associative memory deficits were seen in adults of all ages as fewer correct responses to repeated sets (hits), more incorrect responses to recombined sets (recombined false alarm, FA), and larger differences between these measures (associative memory) at higher set sizes. In addition, older adults had worse associative memory performance (higher recombined FA, lower associative memory) that increased at higher set sizes. These findings indicate that associative memory deficits increase with demands on binding or other processes at higher associative loads and with aging. They further demonstrate the feasibility of manipulating and assessing associative memory load using our novel QuadMax task.

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Introduction

A critical feature of our memory for past events is that it is inherently associative (Mayes, Montaldi, & Migo, 2007; Tulving, 1983). In addition to creating memories for individual items (e.g., a mug; item memory), we form associations between items (e.g., the mug was on a table; inter-item associative memory), between items and their elements (e.g., the mug was white; intra-item associative memory), and between items and their context (e.g., the mug was in the kitchen; context or source memory). A key difference between item and associative memory is that the latter engages binding processes, which serve to link stimuli that are encountered in the same episode into a cohesive memory trace (Cohn & Moscovitch, 2007; Eichenbaum, 2006; Humphreys, 1976; Zimmer et al., 2006). Binding is thought to be mediated by medial temporal and parietal structures in the brain (Opitz, 2010; Ritchey & Cooper, 2020; Yonelinas, Ranganath, Ekstrom, & Wiltgen, 2019), although there may be differences among the various forms of associative memory (Davachi, 2006; Dimsdale-Zucker & Nicholas, 2018). Relative to the source memory

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literature (e.g., Boywitt, Kuhlmann, & Meiser, 2012; Silva et al., 2019), our current understanding of inter-item associative binding in long-term memory, and the extent to which it is impacted by aging, has been limited by a focus on associations between pairs of items.

In a typical paired-associative memory paradigm, participants study pairs of words and are later separately tested on their ability to recognize which items were presented in any studied pair (*item memory*) as well as which items were presented within the same studied pair (*associative memory*). Item memory is measured as the difference in performance to repeated and novel singletons (i.e., hits minus novel false alarms [FA]) and associative memory is measured as the difference in performance to repeated and recombined pairs (also known as intact and rearranged pairs; i.e., hits minus recombined FA). Adults of all ages perform worse on the associative compared to item memory test, and the difference in performance between these memory tests is larger in older adults (Bender, Naveh-Benjamin, & Raz, 2010; Chalfonte & Johnson, 1996; Dennis & McCormick-Huhn, 2018; Guez & Naveh-Benjamin, 2016; Hoyer & Verhaeghen, 2006; Old & Naveh-Benjamin, 2008; Wang, Dew, & Giovanello, 2010; Wang & Giovanello, 2016). It is this interaction between test type (item, associative) and age group (younger, older) that has been interpreted as evidence of an age-related impairment in the binding processes that support associative, but not item, memory (Naveh-Benjamin, 2000). Less is currently known about these associative deficits for memory beyond pairs of items.

Increasing the number of items to be associated manipulates demands on binding by increasing the amount of information that needs to be linked in memory. To date, only a handful of studies have examined memory for associations between more than two items (Clark & Shiffrin, 1987; Torres-Trejo & Cansino, 2016; Tubridy & Davachi, 2011), all of which were conducted in younger adults. After studying pairs and triplets of object images (Torres-Trejo & Cansino, 2016), one study found that younger adults made numerically more correct responses to repeated (hits) and fewer incorrect responses to recombined (recombined FA) pairs than triplets. Although statistical comparisons were not conducted between these set sizes (pairs, triplets), the results appear consistent with the notion that associative memory gets worse as associative load increases. Yet, it remains unknown whether such effects continue at higher associative loads that place even greater demands on binding (e.g., quadruplets) or whether age effects on memory performance are larger at these higher associative loads that more closely approximate the numerous and complex inter-item associations that we form every day.

To address these gaps, the current study sought to probe effects of associative load and aging on inter-item associative memory in a large online sample of adults across the lifespan. We developed a novel recognition task that parametrically manipulated associative load by having participants study word pairs, triplets, and quadruplets before being tested on whether sets of each size were repeated, recombined, or novel. Extending the paired- and triplet-associative memory literatures, we predicted that adults of all ages would show associative memory deficits at higher associative loads, seen as fewer correct responses to repeated sets (hits), more incorrect responses to recombined sets (recombined FA), and larger differences between these measures (associative memory) at higher set sizes. We further predicted that older adults would have worse associative memory performance (fewer hits, more recombined FA, lower associative memory), and that these age effects would be larger at higher set sizes.

Materials and Methods

Participants

Two hundred and eighty-one adults were recruited via separate CloudResearch MTurk (Litman, Robinson, & Abberbock, 2017) Toolkit studies for each decade from 20 to 70 + years. Selection criteria included (1) being a CloudResearch Approved Participant who has passed attention and engagement measures, (2) having any Worker Level and HIT Approval Rate so as to not limit the pool of older adults, (3) having verified IP addresses in the United States, including blocking duplicate and suspicious IP addresses, and (4) having not participated in a similar online study. Participants were excluded if they did not complete the task on their first attempt ($n = 3$), did not respond on more than 20% of the trials ($n = 11$), or had poor overall set recognition performance (average hits minus novel false alarms more than two standard deviations below the sample mean; i.e., < 0.08 ; $n = 16$). The final lifespan sample consisted of 250 participants (18–78 years, 52% female; see Table 1).

All participants gave informed consent. They received \$1 for attempting any portion of the study and a \$2 bonus for completing both task phases (equivalent to US \$12/hour). Bonuses were withheld from those who made no responses. The University of California, Riverside Institutional Review Board approved all procedures.

Associative Memory Task

General procedure

Our novel associative memory task, the QuadMax task (Figure 1), was hosted on Inquisit 6 web software (<https://www.millisecond.com>). After providing informed consent, participants accessed the task using a link through the Mturk portal. The separate study and test phases were completed in a single, 15-min testing session with no delay between phases.

Stimuli

High-frequency English nouns composed of 3–7 letters were acquired from the English Lexicon Project hosted by the University of Washington in St. Louis (Balota et al., 2007). One hundred and thirty-five of these words were randomly selected and sorted into semantically unrelated sets of two (pairs), three (triplets), and four (quadruplets) words (15 sets per set sizes).

Word sets were presented in 30-point black Arial font on a white background, with one word centered on each of four lines. Filler text (five X's) was displayed in the top and/or bottom rows for pairs and triplets for perceptual matching to quadruplets.

Table 1. Demographic information by decade.

Age Group	n	Mean Age $\pm$ SD	Sex (% Female)	Mean Education $\pm$ SD
18–29	55	25.0 $\pm$ 2.8	56.4%	14.7 $\pm$ 2.2
30–39	40	34.7 $\pm$ 3.0	47.5%	15.7 $\pm$ 1.8
40–49	36	44.9 $\pm$ 3.1	47.2%	15.3 $\pm$ 2.2
50–59	38	56.6 $\pm$ 2.8	55.3%	15.7 $\pm$ 2.3
60–69	53	65.5 $\pm$ 3.2	49.1%	15.4 $\pm$ 2.2
70–79	28	73.4 $\pm$ 2.8	57.1%	14.7 $\pm$ 2.5

Note. Education is reported as total years completed. n = sample size; SD = standard deviation.

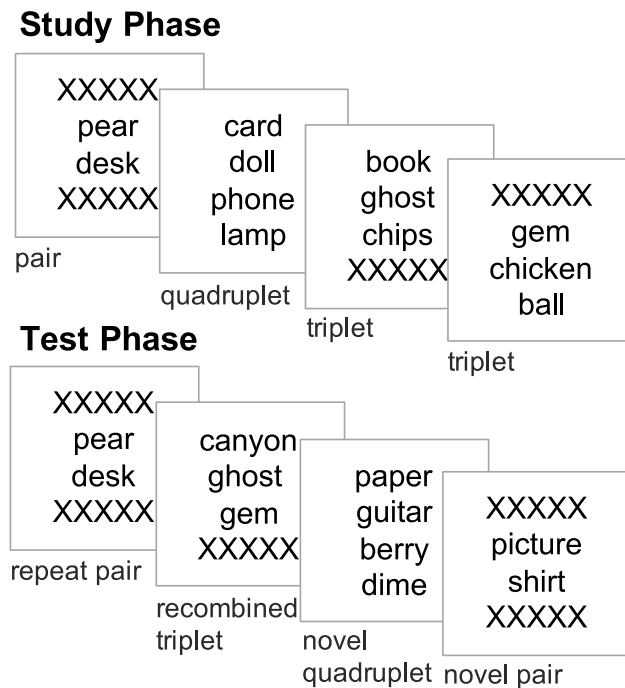


Figure 1. Representative trials from the study (top) and test (bottom) phases of the QuadMax task illustrate the manipulations of set size (pairs, triplets, quadruplets) and trial type (repeated, recombined, novel).

Task procedure

During the study phase, a total of 30 word sets (10 per set size) were displayed one at a time on the computer screen. For each set, participants were instructed to “imagine the words are doing something together” and indicate if they were (“yes”; ‘q’ key response) or were not (“no”; ‘p’ key response) successful in creating a mental image. Word sets were visible for 6,000 (pairs), 7,000 (triplets), or 8,000 (quadruplets) ms and separated by a 500 ms inter-stimulus-interval (ISI). A rest screen (black fixation cross on a white background; 30,000 ms) was displayed after 15 trials.

During the test phase, a total of 45 word sets (15 per set size) were displayed one at a time on the computer screen: 15 sets were identical to those seen during the study phase (repeated or intact; 5 per set size), 15 sets were recombinations of studied sets (recombined or rearranged; 5 per set size), and 15 sets were comprised of completely new words not seen at study (novel; 5 per set size). Recombined sets were created by recombining all words within a given set from the five studied sets per set size. For example, each recombined triplet was comprised of one word from three of the five previously studied sets that contained three words (see Figure 1). The recombined words were randomly selected and presented in any location within the recombined sets, with all participants seeing the same recombined sets. Thus, all words presented at study were later seen at test within either repeated or recombined sets.

For each set, participants were instructed to indicate whether they had (“old”; ‘q’ key response) or had not (“new”; ‘p’ key response) seen that exact set of words together at study.

Word sets were visible for 5,000 ms and separated by a 500 ms ISI, with a rest screen (see above) after each 15-trial block.

Note that although our novel paradigm was modeled after prior paired- and triplet-associative memory work (e.g., Humphreys, 1976; Naveh-Benjamin, 2000), there are at least two key differences. First, we did not include a singleton condition at test, which has been used in paired-associative memory paradigms to evaluate item memory. Rather than comparing non-associative and associative memory conditions, our interest here was in testing whether associative memory varies as associative load increases. Second, whereas prior work presented either word pairs or triplets at study, we had participants study word pairs, triplets, and quadruplets. By subsequently testing them on repeated and novel sets of each size, this allowed us to also measure recognition of the studied sets (referred to here as set recognition).

Memory measures

The proportion of correct “old” responses to repeated (hit rate), incorrect “old” responses to recombined (recombined false alarm [FA] rate), and incorrect “old” responses to novel (novel FA rate) sets were calculated separately for each set size and participant. An associative memory measure was then calculated separately for each set size as hit rate minus recombined FA rate, which is comparable to the associative memory measure used in the paired-associative memory literature. A set recognition measure was also calculated separately for each set size as hit rate minus novel FA rate, which is a traditional recognition memory comparable to item memory for singletons in the paired-associative memory literature. These memory measures are recommended when there are different numbers of target and distractor sets and multiple distractor classes (Corwin, 1994), as was the case here. Nonparametric discriminability (A') and response bias (B'') indices are also reported in the Supplemental Material.

Results

Associative Memory

Separate repeated-measures ANOVAs were conducted for associative memory and its component metrics (hits, recombined FA) using Set Size (pairs, triplets, quadruplets) as the within-subjects variable and chronological Age as a covariate of interest. Significant main effects of Set Size were followed up with post hoc pairwise comparisons between each level of the variable. Results are shown in Figure 2 and individual data points are shown in Supplemental Figure 1. The pattern of results remained unchanged when sex was included as a covariate of no interest (Supplemental Table 2).

For associative memory (hits – recombined FA), a significant main effect of Set Size, $F(2, 496) = 11.28$, $p < .001$, $\eta_p^2 = 0.043$, revealed worse (lower) associative memory with each increase in set size from pairs (0.57 ± 0.02) to triplets (0.32 ± 0.02) to quadruplets (0.18 ± 0.02), $ps < 0.001$. There was also a significant main effect of Age, $F(1, 248) = 7.13$, $p = .008$, $\eta_p^2 = 0.076$, with older age being associated with worse associative memory performance. The interaction between Set Size and Age was not significant, $p = .55$.

For hits, a significant main effect of Set Size, $F(2, 496) = 7.49$, $p = .001$, $\eta_p^2 = 0.029$, revealed fewer hits for triplets (0.73 ± 0.02) and quadruplets (0.75 ± 0.02) relative to pairs

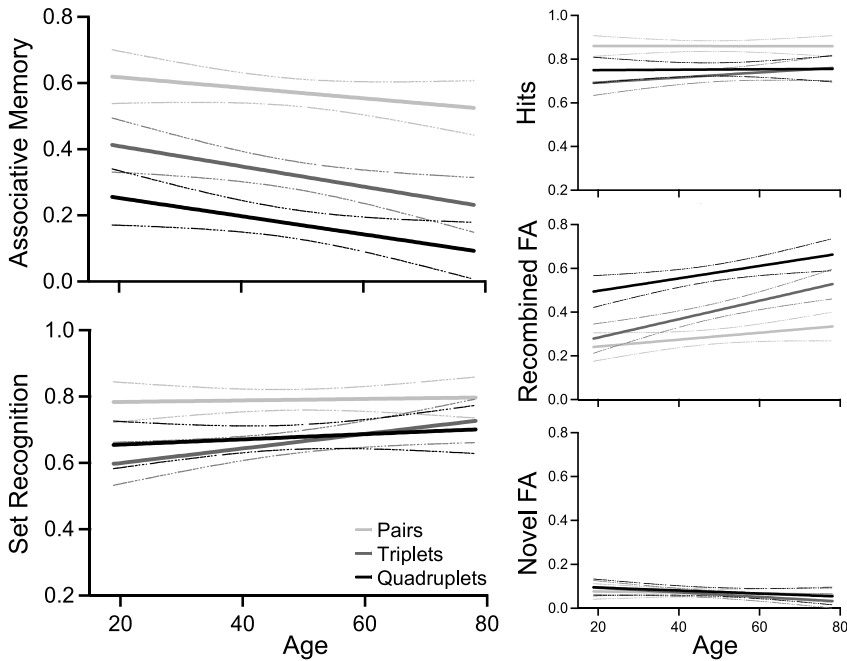


Figure 2. Regression lines show the relationship between chronological age and performance on each memory measure separately for each set size. Dashed lines = 95% confidence intervals. FA = false alarms.

(0.86 ± 0.01), $ps < 0.001$, with no difference between triplets and quadruplets, $p = .10$. The main effect of Age, $p = .49$, and interaction between Set Size and Age, $p = .41$, were not significant.

For recombined FA, a significant main effect of Set Size, $F(2, 496) = 11.43$, $p < .001$, $\eta_p^2 = 0.044$, revealed more recombined FAs with each increase in set size from pairs (0.29 ± 0.02) to triplets (0.40 ± 0.02) to quadruplets (0.58 ± 0.02), $ps < 0.001$. There was also a significant main effect of Age, $F(1, 248) = 13.44$, $p < .001$, $\eta_p^2 = 0.051$, with older age being associated with worse (higher) recombined FA performance. The interaction between Set Size and Age did not attain a significance, $p = .06$.

Extreme age groups

The non-significant trend for a Set Size $\times$ Age interaction for recombined FA may be due to having reduced power from comparisons across a lifespan sample compared to an extreme age group design (Fisher, Guha, Heller, & Miller, 2020; Preacher, Rucker, MacCallum, & Nicewander, 2005). Therefore, separate Age Group (youngest, oldest) $\times$ Set Size (pairs, triplets, quadruplets) mixed factorial ACNOVAs were conducted for each memory measure on the youngest (18–28 years, $n = 45$, 58% female) and oldest (68–78 years, $n = 44$, 61% female) decade of participants using Age Group as the between-subjects variable and Set Size as the within-subjects variable.

For associative memory, a significant main effect of Set Size, $F(2, 174) = 40.27$, $p < .001$, $\eta_p^2 = 0.316$, revealed worse (lower) associative memory with each increase in set size from pairs (0.56 ± 0.04) to triplets (0.34 ± 0.04) to quadruplets (0.19 ± 0.04), $ps <$

0.001. There was also a non-significant trend for a main effect of Age, $F(1, 87) = 3.85$, $p = .053$, $\eta_p^2 = 0.042$, with the oldest group (0.41 ± 0.04) having worse associative memory than the youngest group (0.31 ± 0.04). The interaction between Set Size and Age was not significant, $p = .77$.

For hits, a significant main effect of Set Size, $F(2, 174) = 11.07$, $p < .001$, $\eta_p^2 = 0.113$, revealed fewer hits for triplets (0.72 ± 0.02) and quadruplets (0.75 ± 0.02) relative to pairs (0.85 ± 0.02), $ps < 0.001$, with no difference between triplets and quadruplets, $p = .10$. The main effect of Age, $p = .14$, and interaction between Set Size and Age, $p = .10$, were not significant.

For recombined FA, a significant main effect of Set Size, $F(2, 174) = 35.19$, $p < .001$, $\eta_p^2 = 0.288$, revealed more recombined FAs with each increase in set size from pairs (0.28 ± 0.03) to triplets (0.39 ± 0.03) to quadruplets (0.56 ± 0.03), $ps < 0.001$. There was also a significant main effect of Age, $F(1, 87) = 11.42$, $p = .001$, $\eta_p^2 = 0.116$, with the oldest group (0.48 ± 0.03) having more recombined FAs than the youngest group (0.34 ± 0.03). A significant interaction between Set Size and Age, $F(2, 174) = 3.37$, $p = .036$, $\eta_p^2 = 0.037$, revealed that this age group difference was largest for triplets (mean difference 0.22 ± 0.06 , $p = .001$) and quadruplets (mean difference 0.17 ± 0.06 , $p = .010$) relative to pairs (mean difference 0.05 ± 0.06 , $p = .37$).

Accounting for performance at study

Another source of variability in the data, particularly given the online testing format, is the extent to which participants attended to and encoded the word sets at study. To address this, separate repeated-measures ANOVAs were conducted for each memory measure using Set Size as a within-subjects variable, chronological Age as a covariate of interest, and self-reported success in creating mental images of the studied word sets as a covariate of no interest. These analyses were conducted in the full sample, excluding 13 participants who did not respond during the study phase.

For associative memory, a significant main effect of Set Size, $F(2, 468) = 5.36$, $p = .005$, $\eta_p^2 = 0.022$, revealed worse (lower) associative memory with each increase in set size from pairs (0.58 ± 0.02) to triplets (0.33 ± 0.02) to quadruplets (0.18 ± 0.02), $ps < 0.001$. There was also a significant main effect of Age, $F(1, 234) = 6.36$, $p = .012$, $\eta_p^2 = 0.026$, with older age being associated with worse associative memory performance. The interaction between Set Size and Age was not significant, $p = .45$.

For hits, a significant main effect of Set Size, $F(2, 468) = 6.87$, $p = .001$, $\eta_p^2 = 0.029$, revealed fewer hits for triplets (0.73 ± 0.02) and quadruplets (0.76 ± 0.02) relative to pairs (0.87 ± 0.01), $ps < 0.001$, with no difference between triplets and quadruplets, $p = .08$. The main effect of Age, $p = .24$, and interaction between Set Size and Age, $p = .28$, were not significant.

For recombined FA, a significant main effect of Set Size, $F(2, 468) = 9.81$, $p < .001$, $\eta_p^2 = 0.040$, revealed more recombined FAs with each increase in set size from pairs (0.28 ± 0.02) to triplets (0.41 ± 0.02) to quadruplets (0.58 ± 0.02), $ps < 0.001$. There was also a significant main effect of Age, $F(1, 234) = 14.37$, $p < .001$, $\eta_p^2 = 0.058$, with older age being associated with worse (higher) recombined FA performance. A significant interaction between Set Size and Age $F(2, 468) = 3.28$, $p = .039$, $\eta_p^2 = 0.014$, revealed that this age effect was larger for triplets ($r = 0.28$, $p < .001$) and quadruplets ($r = 0.18$, $p = .005$) relative to pairs ($r = 0.11$, $p = .11$).

Set Recognition

A repeated-measures ANOVA was conducted for set recognition (hits – novel FA) using Set Size (pairs, triplets, quadruplets) as the within-subjects variable and chronological Age as a covariate of interest. Significant main effects of Set Size were followed up with post hoc pairwise comparisons between each level of the variable. Results are shown in [Figure 2](#).

A significant main effect of Set Size, $F(2, 496) = 8.17$, $p < .001$, $\eta_p^2 = 0.032$, revealed significantly worse set recognition for triplets (0.66 ± 0.02) and quadruplets (0.68 ± 0.02) relative to pairs (0.79 ± 0.02), $ps < 0.001$, with no difference between triplets and quadruplets, $p = .40$. The main effect of Age, $p = .16$, and interaction between Set Size and Age, $p = .18$, were not significant. Note that this pattern of results is comparable to what was seen for hits, whereas there were no significant effects for novel FA, $ps > 0.12$.

Discussion

This study examined the effects of associative load and age group on memory performance in adults across the lifespan using a novel recognition task in which participants studied word pairs, triplets, and quadruplets and were subsequently tested on their memory for repeated, recombined, and novel word sets. Results revealed that, at higher associative loads, adults of all ages were significantly worse at recognizing previously studied word sets (set recognition) as well as sets where all of the words were seen at study but not together (associative memory). Older adults also had worse associative memory than younger adults (associative memory, recombined FA), and these age effects increased as a function of associative load. These findings are consistent with an associative memory deficit that increases with demands on binding processes at higher associative loads and with aging.

Adults of all ages had worse associative memory (hits minus recombined FA) at higher associative loads, driven by significantly fewer correct “old” responses to repeated sets (hits) and more incorrect “old” responses to recombined sets (recombined FA) as a function of set size. These findings extend the well-documented paired-associative (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008) and emerging triplet-associative memory (Clark & Shiffrin, 1987; Torres-Trejo & Cansino, 2016) literatures by demonstrating associative memory deficits at higher associative loads than previously studied. Specifically, whereas the paired-associative literature has demonstrated significant differences between non-associative and associative memory for pairs of items, our findings show that associative load effects follow a monotonic trajectory in which associative memory get worse with each increase in set size. Because our paradigm manipulated the number of items to be associated across three set sizes, we interpret these results as support for the notion that associative memory is modulated by demands on binding processes that link words within a set at study into a cohesive memory trace and support retrieval of this bound set at test (Naveh-Benjamin, 2000; Zimmer et al., 2006).

Older age was associated with worse associative memory performance, driven by significantly more incorrect “old” responses to recombined sets (recombined FA) as a function of age. Moreover, we found that these age effects increased as a function of associative load, with a non-significant trend in the full lifespan sample, but significant interactions between age and set size in the extreme age group comparison and after accounting for performance at study. This finding is consistent with predictions of the associative deficit hypothesis

(Naveh-Benjamin, 2000) in that increasing demands on associative binding processes by having participants remember triplets and quadruplets of word sets should lead to even worse associative memory performance in older adults if they have a specific deficit in associative binding.

Although we interpret the effects of associative load and age on associative memory as evidence of a binding deficit, as in prior work (Naveh-Benjamin, 2000), there are alternative interpretations to consider. For example, working memory processes have been shown to contribute to associative memory performance and decline with age (Castel & Craik, 2003; Wang & Giovanello, 2016; c.f., Naveh-Benjamin, Guez, & Shulman, 2004). In the study phase of the QuadMax task, participants likely rely on working memory to hold the words within a set in mind while imagining them doing something together, and these demands on working memory would increase at higher associative loads, and may be more difficult for older adults with reduced working memory capacity. We note that while this may have contributed to the set size effects seen across almost all memory measures and adults of all ages, it is less likely to explain the age effects as they were selectively seen for the associative memory measures (associative memory, recombined FA), but not for set recognition. An important future direction will be to acquire functional neuroimaging during QuadMax task performance to assess whether and in which task phases there is hippocampal-dependent binding or prefrontal-dependent working memory activity that varies systematically with associative load and age.

Associative load effects may also reflect demands on recollection processes during the test phase. Higher fidelity recollection is needed to distinguish between repeated and recombined sets because all words within both of these sets were seen in the study and would therefore have similar familiarity signals (Gardiner, 1988; Hockley & Consoli, 1999; Tulving, 1985; Yonelinas, 2002). Whereas these recollection processes would be involved for all set sizes examined here, it is possible that demands on recollection are lower when retrieving the bound memory trace linking two items (pairs) relative to the memory trace linking three (triplets) or four (quadruplets) items. Future studies that acquire confidence or remember/know judgments (Tulving, 1985; Wixted, 2009), or that separately assess associative memory and set recognition using paradigms with only repeated and recombined or repeated and novel trials at test, respectively, will be needed to test for differences in recollection (and familiarity) at these higher associative loads.

Another possibility is that, at higher associative loads, there is greater interference from competing associations. This relies on the assumption that each word within a pair has only one pair-wise association, whereas each word within a quadruplet has three pair-wise associations. Participants have been shown to make more false alarms and respond slower to stimuli with more competing associations (Schneider & Anderson, 2012). However, the current paradigm may have minimized the potential confounding effects of interference by using unrelated, randomly selected words within and across sets, interleaving presentation of the different set sizes in both task phases, and long (5 second) stimulus duration and response period.

In addition to associative memory, our novel task design allowed us to assess traditional recognition measures for each set size, referred to here as set recognition. Adults of all ages had worse set recognition (hits minus novel FA) at higher associative loads, driven by significantly fewer correct “old” responses to repeated sets (hits) as a function of set size as there were negligible differences in incorrect “old” responses to novel sets (novel FA). In

contrast to prior associative memory paradigms that have not presented novel sets beyond singletons at test, this approach allowed us to demonstrate that the effect of age on associative memory performance was specific to memory for sets of items that were presented *together* at study (repeated versus recombined sets; i.e., associative memory) because memory for sets that were previously studied (repeated versus novel sets; i.e., set recognition) was preserved in older adults. Other studies have similarly shown relatively preserved recognition memory in aging (Bennett, Huffman, & Stark, 2015; Craik & McDowd, 1987), albeit not at the set sizes examined here. The different pattern of results for novel FA and recombined FA is also inconsistent with participants having a response bias, which should have similarly affected both of these trial types (see also Supplementary Materials).

There are a number of other differences between the QuadMax paradigm and those used in the paired- and triplet-associative literatures that will require further examination to better understand effects of associative load and age on associative memory. In addition to the differences stated in the Methods (i.e., we did not include a singleton condition at test, participants studied sets of each size), previous associative memory studies have used various numbers of studied sets, set sizes at encoding (pairs only; triplets only; or pairs, triplets, and quadruplets), memory test formats (recognition, recall), and recognition response formats (two- and three-alternative choice). For example, participants studied and were tested on 10 word sets per size in the current study (30 word sets total), whereas prior work has used more studied sets (e.g., 26 word pairs; Bender et al., 2010). We speculate that the smaller number of studied sets used here may have made our task easier, which may explain why we did not observe an age effect on the associative memory measures for pairs, as seen in prior work (e.g., Bender et al., 2010; Dennis & McCormick-Huhn, 2018; Old & Naveh-Benjamin, 2008). It may have also reduced our power to detect significant effects by adding variability to our performance measures (Brysbaert & Stevens, 2018). To address this possibility, we are currently conducting a follow-up study that systematically varies the number of word sets presented at study. The current study also used a variable stimulus duration in the study phase that increased with set size but allowed less study time per item at higher set sizes. A control experiment in younger adults showed similar main effects of set size for associative memory and recombined FA measures when using a constant stimulus duration per item within the sets (i.e., 6,000 ms for pairs, 9,000 ms for triplets, and 12,000 ms for quadruplets; see Supplemental Material), providing confidence that the associative load effects observed here are not solely due to the variable stimulus duration at study, although future research in older adults is warranted.

Another difference is that the current study recruited and tested an online sample of adults across the lifespan. There are reported differences between in-person and online samples (Paolacci & Chandler, 2014), some of which may be exacerbated by personal and economic stressors associated with the ongoing pandemic, such as the motivation for participants to engage in online research (e.g., to supplement lost income). However, other differences, particularly those between younger and older adults, may have influenced the effects reported here. For example, younger adults may be more easily distracted in the uncontrolled online environment (Goodman, Cryder, & Cheema, 2013), whereas older adults who are proficient enough to seek out and navigate the online testing portals may be qualitatively different than community-based samples. Thus, it will be important to replicate the current study using traditional community-based recruitment and in-person

testing. Acquiring additional demographic (e.g., race/ethnicity, English proficiency) and cognitive (e.g., working memory capacity) information will also be important to characterize participants.

In closing, the present study introduced a novel QuadMax task that parametrically manipulated demands on associative load. Results revealed significant effects of associative load and age on the ability to recognize which studied words were previously seen together (associative memory, recombined FA), but only an effect of associative load on the ability to recognize previously studied word sets (set recognition). These findings replicate and extend the paired- and triplet-associative memory literatures by demonstrating memory deficits in adults across the lifespan at higher associative loads that place greater demands on binding processes, with these associative memory deficits being larger in older adults.

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Disclosure statement

The authors declare no interests.

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Data Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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