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Cross-situational statistical learning in younger and older adults

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ABSTRACT

Research investigating statistical learning, the process of tracking regularities in the environment, in older adults has been limited; with existing studies suggesting there are age-related declines. We aim to further understand older adults' statistical learning abilities using a cross-situational statistical learning paradigm in which learners map novel words to novel objects. In Experiment 1, we manipulated task difficulty and found an overall age deficit but no interaction between age and difficulty. In Experiment 2, after extended practice with a first set of object-word mappings, learners could remap a subset of previously learned words to novel objects. Based on hyper-binding, older adults might be more willing to remap previously learned words to novel objects. However, despite overall poorer learning, older adults were actually less likely to remap. Even though older adults may have an associative memory deficit, learned associations are not more weakly bound for older relative to younger adults.

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KEYWORDS
Cross-situational statistical learning; associative memory deficit

Introduction

Statistical learning, the process of learning from distributional regularities in sensory input, has become a prominent construct in cognitive science (see Frost et al., 2019). It is considered a core building block for many aspects of cognitive functioning, such as language acquisition (e.g., Maye et al., 2008; Saffran, Aslin et al., 1996) and visual processing (e.g., Fiser & Aslin, 2002; Saffran et al., 1999, for review see Saffran & Kirkham, 2018; Frost et al., 2019). The majority of this research has focused on characterizing statistical learning abilities during development and in young adulthood. Relatively few studies have focused on how this ability operates in older adulthood, though several studies have suggested that there are age-related declines in statistical learning (Janacsek et al., 2012; Schwab et al., 2016). The current study aims to extend our understanding of how older adults track statistical information using a statistical word learning paradigm that manipulates task difficulty (Experiment 1) and provides the opportunity for remapping newly learned labels to novel objects (Experiment 2), thereby affording new insights as to how older adults track distributional regularities over time.

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To date, many studies of statistical learning with older adults have focused on the acquisition of sequential statistical regularities, such as those encountered in the serial reaction time (SRT) paradigm (Nissen & Bullemer, 1987). In the typical SRT task, stimuli (e.g., asterisks) appear in one of four locations on a computer screen in a repeating sequence, and participants respond to each by pressing a corresponding key. Participants demonstrate learning of the sequential regularity through a reduction in reaction time (RT) on trials when the positions follow the sequence and by an increase in RT when the repeating pattern is replaced by random trials. When the pattern operates over adjacent trials, older adults exhibit learning of the patterns to similar levels of performance relative to younger adults (e.g., Howard & Howard, 1997). However, as difficulty increases, such as when regularities extend over non-adjacent trials (i.e. with 1 or more random events occur between elements of the sequence), older adults exhibit age-related deficits in learning. Moreover, there is no evidence for learning for older adults when the sequential structures are sufficiently complex, such as with probabilistic sequence structures, including those in which 2 or more random events occur between patterned elements in a sequence (Howard et al., 2004).

Statistical learning has also been measured in the context of speech segmentation paradigms that test implicit learning of regularities between syllables (e.g., Saffran, Aslin et al., 1996; J. R. Saffran, Newport et al., 1996). In these studies, infant and young adult participants have been found to be sensitive to syllabic transitional probabilities, inferring word boundaries when the cooccurrence probability between adjacent syllables is low (e.g., Saffran, Aslin et al., 1996; Saffran, Newport et al., 1996). With respect to aging, studies have found that older adults generally exhibit speech segmentation abilities, with some studies reporting comparable performance across age groups (e.g, Ong & Chan, 2019) and several studies finding deficits for older adults relative to younger adults (e.g., Penaloza et al., 2017). But, like findings from the SRT task, age-related deficits consistently arise under more difficult conditions, such as when cognitive load is increased by asking participants to complete another task simultaneously (Palmer et al., 2018). These segmentation paradigms can also be instantiated in the visual modality, using sequences of images or pictures. When older adults were asked to view two embedded streams of images and ignore one (based on the color of the images), they exhibited similar performance relative to younger adults on learning transitional probabilities between images in the attended stream. However, older adults also learned the transitional probabilities of the unattended stream, possibly as a result of their inability to ignore unattended information (Campbell et al., 2012), an effect termed hyper-binding (Campbell & Hasher, 2018; Campbell et al., 2010).

A related method that predated the segmentation paradigm is artificial grammar learning. In these tasks learners are typically exposed to sentences governed by a finite-state grammar, and learning is evidenced by higher acceptability ratings for novel grammatical sentences relative to ungrammatical sentences (Reber, 1967). Lukaks and Kemeny (2015) found age related deficits in performance on an artificial grammar learning task, such that participants under 65 years of age exhibited above chance learning, while participants over 65 did not. On a similar task, Schwab et al. (2016) showed that while both younger and older adults exhibit learning on an artificial grammar learning task, older adults' ratings of familiar and novel grammatical sequences were lower than those provided by younger adults. The authors suggest this may reflect that the older adults were less confident in their ratings relative to younger adults. Taken together, across multiple types of statistical learning tasks, statistical learning in older adults appears to be preserved under some conditions, although performance deficits emerge as task difficulty increases.

Cross-situational statistical learning (CSSL) is another well-established method in the developmental and young adult literature used to investigate how learners track associations in order to map words to their referents over time (Smith & Yu, 2008; Yu & Smith, 2007). In contrast to previously reviewed paradigms, the associations (mapping between novel word and object) are completely ambiguous on any given trial and can only be disambiguated by tracking associative regularities across trials. In the original CSSL paradigm (Yu & Smith, 2007), participants were presented with scenes containing 2 to 4 novel objects on a computer screen and the corresponding number of novel labels. Across repeated presentations, learners were found to successfully track the associations, which is exhibited by learning which labels belonged to which objects. While the CSSL paradigm has yielded successful learning in both adult and child learners across several studies (e.g., Fazly et al., 2010; Fitneva & Christiansen, 2011; Kachergis et al., 2009; Smith & Yu, 2008; Vlach & Sandhofer, 2014; Yu & Smith, 2007), Penaloza et al. (2017) conducted the only study we are aware of that examined associative learning in the CSSL task with older adults. They presented participants with two objects and two labels in each scene, and therefore only a single competitor was present for labeling ambiguity (i.e., a relatively easy task for younger adults, Yu & Smith, 2007). Younger adults showed an advantage early in learning, but after continued exposure older adults ultimately reached similar levels of performance relative to young adults. An overall deficit for older adults on a CSSL task is not necessarily surprising, as age-related deficits in associative learning are somewhat ubiquitous. For example, difficulty binding together discrete pieces of information (Mitchell et al., 2000, 2010) has been found using a wide range of experimental stimuli including picture-picture pairs (Chalfonte & Johnson, 1996), word-word pairs (Castel & Craik, 2003), face-name pairs (Naveh-Benjamin et al., 2004) and sentence-speaker pairs (Simons et al., 2004), among others (see Dennis & McCormick-Huhn, 2018; Old & Naveh-Benjamin, 2008).

Despite deficits in associative memory, vocabulary size actually continues to increase across the lifespan (Alwin & McCammon, 2001; Verhaeghen, 2003), suggesting that older adults are able to learn associations between new words and their corresponding meanings at a time when they exhibit these other cognitive deficits. Thus, CSSL provides an ideal task for testing how learners track regularities across trials and comparing learning across age group, by using an associative task in a domain in which older adults have demonstrated continued success with learning. That is, previous statistical learning and associative memory research would suggest that older adults should exhibit deficits in CSSL, particularly as difficulty increases, as CSSL relies on both types of learning processes. However, as cross-situational statistical learning is predicated on learning novel names for novel objects, older adults' continued ability to learn new vocabulary might actually lead to smaller deficits and continued learning as difficulty increases (as compared to an SRT task in which learning diminishes as difficulty increases; Howard et al., 2004).

Another feature of CSSL that makes it useful for comparing performance across age groups is that items can be remapped, thereby providing insight into the strength of older adults' initial word-object associations. Specifically, in everyday life, words can refer to more than one object, such as "bat" referring both to a flying creature and an object used to hit a ball. When young adult learners are presented with these types of 2:1 mappings in the context of a CSSL task, participants exhibit difficulty learning both sets of mappings (Ichinco et al., 2009; Poepsel & Weiss, 2016), with learning biased toward the first of the two presented mappings even when remapping does take place (e.g., Yurovsky et al., 2013). Providing older adults the opportunity to remap previously learned words to novel objects can lend insight into the robustness of the initial word-object mappings and the flexibility of the learner. Specifically, this can be gauged by determining whether initial mappings can be overwritten or whether learners can expand mappings to include 2:1 mappings. Prior research in statistical learning has found young adult learners resistant to forming 2:1 mappings in the absence of a correlated contextual cue (e.g., Ichinco et al., 2009; Poepsel & Weiss, 2014, 2016). However, when learners are presented with multiple patterns and asked to attend to only one, older adults exhibited learning of the second, unattended pattern, while younger adults did not (Campbell et al., 2012). This phenomenon has been termed hyper-binding, and as alluded to above, suggests that age-related reductions in inhibition processes allow more information to be simultaneously active in working memory stores for older adults (Campbell et al., 2010). Hyper-binding therefore raises the possibility that older adults may be more prone to either expanding or overwriting initial mappings based on new available associative information. Accordingly, we might anticipate that older adults would be more likely to successfully remap word-object pairs relative to young adults. Further, older adults may be more likely to remap previously learned words to novel objects due to differences in the strength of the initial learned associations. If older adults are prone to weaker associative binding, as suggested by the Associative Deficit Hypothesis (see Old & Naveh-Benjamin, 2008), then it may be easier for older adults to remap previously learned words, as the original association would be weaker and more vulnerable to change. Our approach may also provide some insight into how mutual exclusivity, learner's preference for mapping one word to one object (Markman & Wachtel, 1988), operates in older adulthood, which to our knowledge has never directly been tested.

Thus, in the current manuscript, we aim to provide new insights into how older adults track regularities under conditions of increasing difficulty, using the CSSL paradigm. In Experiment 1, we manipulate task difficulty by increasing the number of competitors in a scene from 2 to 4 (across blocks). Penaloza et al. (2017) found an age-deficit under the simplest 2 object condition, and thus this condition represents a replication. By further increasing the difficulty for learners, we can expand upon this initial work and probe whether older adults continue to learn, in contrast to the SRT tasks described above in which learning in aging is entirely disrupted under more challenging conditions (Howard et al., 2004). In Experiment 2, we provided participants with the opportunity to remap previously learned words to novel objects; allowing us to directly test whether older adults exhibit better learning of these 2:1 mappings relative to younger adults as a consequence of age-related changes in associative memory or inhibitory processes. Participants also completed a battery of working memory and task switching tasks, as previous research suggests that executive function may differentially impact performance for younger and older adults (Ong & Chan, 2019; Palmer et al., 2018). We hypothesized that task switching abilities in particular (as measured by the Wisconsin Card Sorting Task) might predict remapping ability for both younger and older adults, as learning 2:1 mappings may require inhibiting a previously learned mapping to learn a second.

Experiment 1

Method

Participants

Eighteen younger and eighteen older adults participated in the current study. The younger adults were recruited from the Pennsylvania State University (mean age = 20.12, sd = 1.20, 3 males), and the older adults were recruited from the State College, Pennsylvania community (mean age = 72.06, sd = 4.55, 8 males). None of the participants self-identified as bilingual. Prior to the experiment, older adult participants completed the Mini-Mental State Exam to verify that they were cognitively healthy, see Table 1 (there were no exclusions). All experimental procedures were approved by The Pennsylvania State University's Institutional Review Board for the ethical treatment of human participants.

Stimuli

The stimuli and procedures for Experiment 1 were identical to those used by Poepsel and Weiss (2016). The stimuli consisted of fifty-four word-object pairs, created by randomly pairing a nonce word with a novel object. The objects were black and white images, eight of which were used by Creel et al. (2008) and served as a template for creating the remaining objects (using MS Paint©). All objects were converted to a .jpg file format with a size of 150 by 150 pixels. The words consisted of monosyllabic, disyllabic, and trisyllabic items chosen from the English Lexicon Project (ELP) non-word database (http://elexicon.wustl.edu), and were all used by Poepsel & Weiss, (2016). All words complied with phonological patterns of American English and were between 4 and 10 characters in length. Auditory pronunciations of the words were recorded using the Crystal voice, a female American English voice, via the AT&T Natural Voices text-to-speech synthesizer (http://naturalvoices.att.com). The 54 object-word pairs were divided into three sets of 18. Each set contained the same number of monosyllabic, disyllabic, and trisyllabic words.

Procedure

Prior to the start of the experiment, participants were informed that they would be learning novel names for novel objects. During familiarization, participants viewed a number of objects on a computer screen (ranging from 2 to 4; see Figure 1) and

Table 1. Experiment 1 participant demographics. * denotes p <.05; ** denotes p <.001.

	Younger adults (n = 18)	Older adults (n = 18)
MMSE	–	28 (2.5)
WCST	20.89 (9.85)	17.2 (8.61)
Errors *	3 (1.5)	2.93 (1.3)
Number of categories		
WAIS – III	13.94 (1.8)	17.62 (3.66)
Digit span **	9.28 (1.98)	8.47 (3.6)
Letter-Number Sequencing		

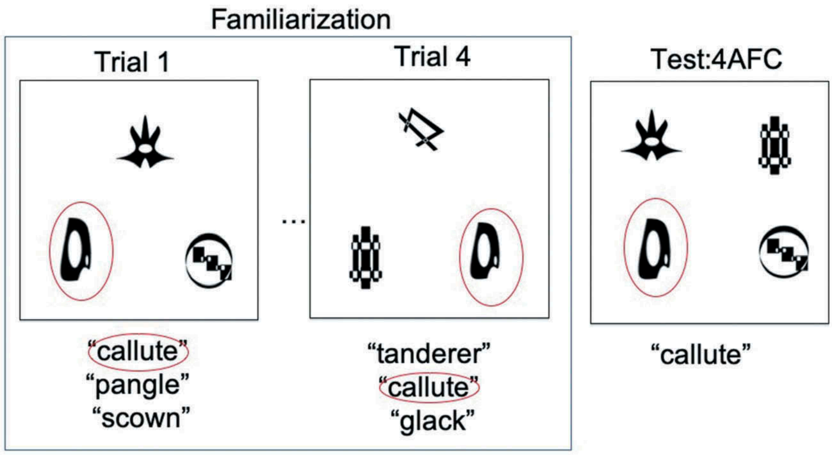

Figure 1. Structure of familiarization and test trials for Experiment 1 in the 3 × 3 condition. For the 2 × 2 condition, only two objects and words were presented each trial, and for the 4 × 4 condition, four objects and words. Regardless of condition, the test was always 4AFC. The circles did not appear during the experiment, but designate the correct mappings/responses. The words were presented auditorily, but are written in the figure.

heard a corresponding number of words presented over headphones. All participants completed three familiarization conditions, each containing 18 unique word-object pairs. The difference between each condition was the number of objects and corresponding words that were presented on the screen during each trial. There was a 2 × 2 familiarization condition (in which participants saw two objects and heard two words), a 3 × 3 condition, and a 4 × 4 condition. The order of the conditions was counterbalanced across participants.

For each trial, sets of objects appeared on the screen while the corresponding words were played serially every 2 seconds. The onset of the visual display was synchronized with the presentation of the first word. Objects could appear in one of the predetermined locations, depending on the condition (e.g., in the 2 × 2 condition, objects appeared at the midline on both the left and right sides of the screen). There was no systematic relationship between the position of the objects on the screen and the order of the presented words, such that object locations and word order were randomly assigned. The trials progressed automatically, with the onset of a new trial cued by the end of the previous trial. A fixation cross was presented for 750 ms before the start of each trial. Within each condition, every word-object pair was repeated 6 times, across trials. Accordingly, the number of trials in each familiarization phase varied: there were 54 trials in the 2 × 2 condition, 36 in the 3 × 3 condition, and 27 in the 4 × 4 condition.

Following each familiarization phase, participants completed a 4-alternative forced-choice (4AFC) test during which they saw four objects, presented simultaneously in each corner of the screen with a corresponding numeric label (1–4; see Figure 1). Each trial was accompanied by the auditory presentation of a single word drawn from the familiarization stimuli. One of the objects was the correct referent and the other three objects were distractors randomly chosen from the same familiarization condition. Participants completed 3 tests, one following each familiarization phase. Each of these tests consisted of 18 trials, one trial for each object-word pair learned during the familiarization phase. Participants were asked to choose which object the word referred to by pressing the button corresponding to the appropriate object on the screen. There was no time limit for participants to respond.

In addition to the word learning task, participants also completed a battery of neuropsychological tests including the Wisconsin Card Sort Test – 64 Card Version (WCST, Heaton, 1981) designed to measure task switching abilities, and the WAIS-III digit span and letter-number sequencing to measure working memory capacity.

Results

Young adults learned 76% (SD = 28%) of the mappings in the 2 × 2 condition, 66% (SD = 27%) of the mappings in the 3 × 3 condition, and 48% (SD = 16%) of the mappings in the 4 × 4 condition. Planned t-tests revealed that performance across all conditions exceeded chance, which was 25% given the four alternatives at test (all *ps* <.001). Older adult participants learned 59% (SD = 20%) of the mappings in the 2 × 2 condition, 44% (SD = 20%) of the mappings in the 3 × 3 condition, and 35% (SD = 14%) of the mappings in the 4 × 4 condition. Planned t-tests revealed that performance across all conditions exceeded chance (all, *ps*<.01; see Figure 2).

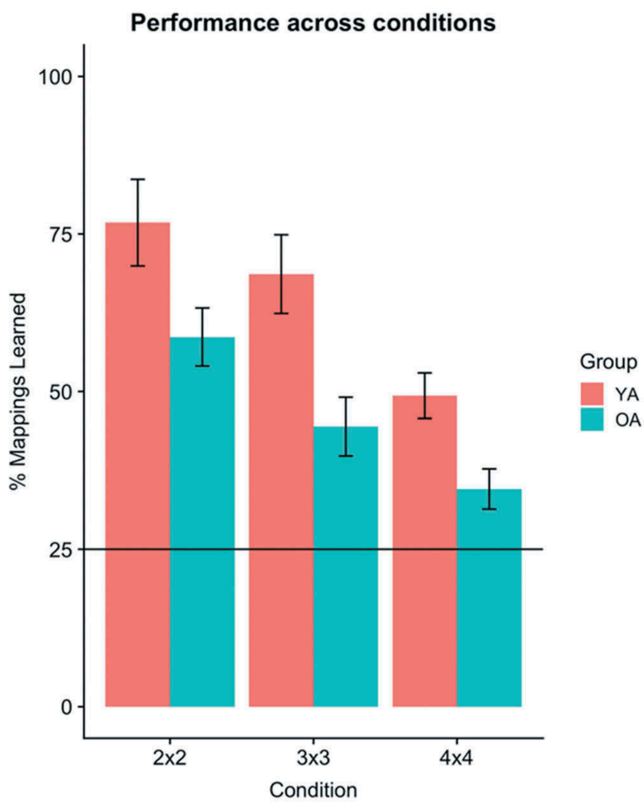

Figure 2. Younger and older adult performance across all three conditions.

We conducted a 2 (Group: younger or older adults) by 3 (condition, 2x2, 3x3, or 4×4) ANOVA in order to test for learning differences across conditions and age groups. There was a main effect of group, $F(1, 102) = 18.09$, $p < .001$, such that young adults (M = 63%, SD = 27%) outperformed older adults (M = 46%, SD = 20%) overall. There was also a main effect of condition, $F(2, 102) = 13.77$, $p < .001$, such that performance was highest for the 2 × 2 condition (M = 67%, SD = 25%), followed by the 3 × 3 condition (M = 55%, SD = 26%), and the 4 × 4 condition (M = 41%, SD = 16%). The interaction between Condition and Group was not significant, $F(2, 102) = 0.4$, $p = .672$.

We also tested to see whether performance on the working memory tasks (Digit Span and Letter Number Sequencing) or components of the WCST (Errors and Number of categories learned) correlated with performance within any of the test conditions. Performance across conditions was not related to working memory or WCST for either group, after Bonferroni correction for multiple comparison, all *ps* > .013 (as each condition was correlated with 4 executive function tasks). As evidenced by older adults' performance on these measures relative to younger adults (see Table 1), the older adults included in this sample were high performing and motivated.

Discussion

In Experiment 1 we examined learning in younger and older adults on a CSSL task across 3 levels of increasing difficulty. While both groups exhibited above chance performance in all 3 condition, consistent with previous work examining CSSL learning under easy task conditions (Penaloza et al., 2017), we identified an age-related deficit in learning novel words across all levels of task difficulty. Despite significant effects of age and difficulty, we found no age by difficulty interaction, indicating that older adults were not differentially impacted by increasing task difficulty. Taken together results suggest that, while performance on this task is impacted by healthy aging, task difficulty appears to impact both groups similarly.

Experiment 2

As discussed in the Introduction, while the majority of CSSL research to date has presented participants with uniform input in which a novel word refers to a single novel object, some words can refer to multiple objects (e.g., "mouse" to refer to a rodent or a computer device). When presented with the opportunity to remap previously learned words to a novel object, young adults have difficulty learning the second mapping, or continue to prefer the first learned mapping when both are learned (e.g., Ichinco et al., 2009; Poepsel & Weiss, 2016; Yurovsky et al., 2013). Here we ask whether older adults exhibit the same pattern or are more likely to accept new mappings for previously learned words as a result of hyper-binding. In Experiment 2, we provided both younger and older adults with several familiarization sessions to acquire an initial set of mappings with the goal of promoting robust learning prior to introducing a second set of mappings for a subset of the objects and labels from the initial familiarization.

Methods

Participants

Eighteen younger and eighteen older adults participated in this experiment, none had participated in a previous experiment. The younger adults were recruited from the Pennsylvania State University (mean age = 20.14, SD = 1.07, 4 males), and the older adults were recruited from the State College community (mean age = 70.31, SD = 4.45, 5 males). None of the participants self-identified as bilingual. Prior to the experiment, older adult participants completed the Mini-Mental State Exam to verify that they were cognitively healthy, see Table 2 (none were excluded). All experimental procedures were approved by The Pennsylvania State University's Institutional Review Board for the ethical treatment of human participants. An additional 2 older adults and 3 younger adults were recruited but excluded from the analyses for not meeting the criteria for Phase 2 (see below).

Stimuli

The stimuli used in this experiment were a subset of those used in Experiment 1. Specifically, thirty-six of the objects and novel words were taken from Experiment 1 and used in Experiment 2.

Procedure

Prior to starting the experiment, participants were informed that they would be learning nonce names for novel objects, and that the experiment would consist of multiple training and testing blocks. Experiment 2 consisted of two phases. The first phase consisted of three familiarization sessions, each followed by a test, whereas the second phase consisted of a single familiarization session, followed by a test (see Figure 3).

Phase 1. During the first familiarization session, participants were familiarized with 18 novel object-word pairs. Participants viewed three objects on the screen and heard a corresponding number of words presented over headphones (akin to the 3 × 3 condition from Experiment 1, based on previous similar research, Ichinco et al., 2009; Poepsel & Weiss, 2016). Following the first familiarization session, participants completed a 4AFC test, identical to Experiment 1. Each word-object mapping was tested once (for a total of eighteen test trials), and there was no time limit for responding to each trial. Following this test, participants received two more identical familiarization sessions, each followed by a test. In order to advance to Phase 2, participants were required to produce a minimum of 10 correct responses (out of 18) on the third test of Phase 1, as in previous studies (Ichinco et al., 2009;

Table 2. Experiment 2 participant demographics. ** denotes p <.001.

	Younger adults (n = 18)	Older adults (n = 18)
MMSE	–	29.13 (1.4)
WCST	10.94 (4.64)	16.88 (7.01)
Errors **	4.12 (1.1)	3.36 (1.3)
Number of categories **		
WAIS – III	18.39 (4.14)	17.77 (3.78)
Digit span	10.71 (3.49)	9.28 (3.0)
Letter-Number Sequencing **		

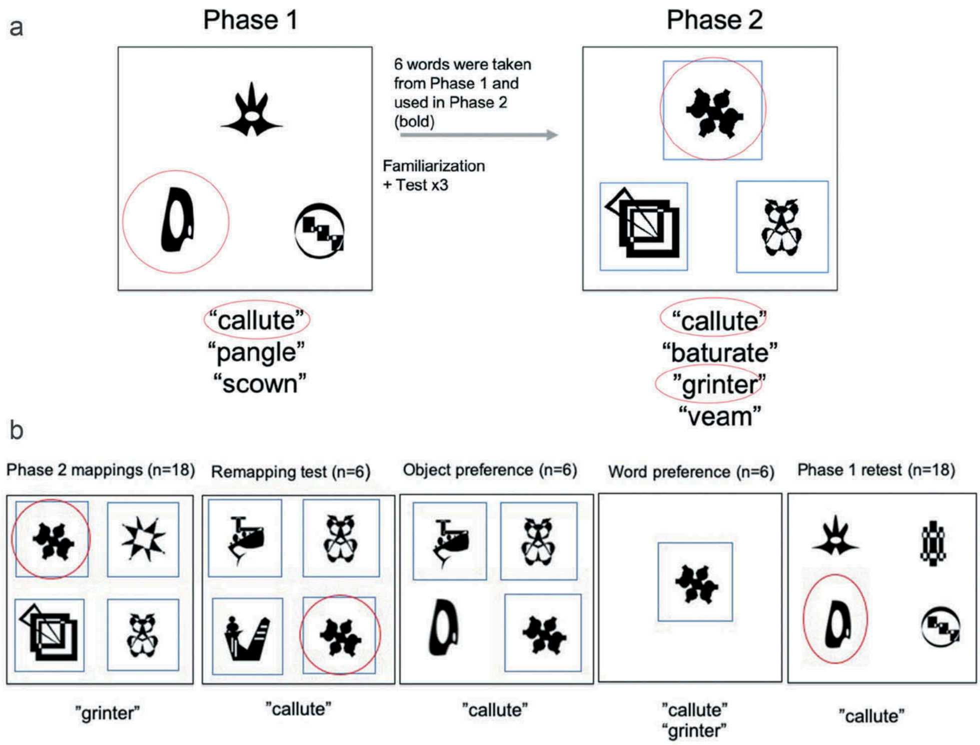

Figure 3. Experiment 2 Phases. A. Phase 1 familiarization and test, and Phase 2 familiarization. Phase 1 familiarization and test were identical in structure to the 3 × 3 condition in Experiment 1 and the familiarization-test cycle was repeated 3 times. In Phase 2 four words were heard, one of which was transferred from Phase 1 (e.g., "callute"). B. Different tests after Phase 2. Across both A. and B., objects from Phase 2 are identified with a blue border for clarity but the blue borders were not seen by participants. Intended mappings are identified by a red circle, which was not provided to participants during the experiment. The words were presented auditorily.

Poepsel & Weiss, 2016). The experiment ended for participants who did not meet this requirement (this was the case for 2 older adults and 3 younger adults, mentioned above).

Phase 2. In Phase 2, participants received a novel set of 18 word-object pairs. In addition to these new mappings, six of the words used in Phase 1 were transferred to Phase 2. Thus, in Phase 2 each trial included three objects displayed on the screen while learners heard four words (three corresponding to the new word-object pairs, and an additional transferred word). The transferred words from Phase 1 were each paired exclusively with a single object in Phase 2. This resulted in the possibility of mapping the transferred words to two objects, the original object from Phase 1 and the new paired object from Phase 2. Similarly, the six Phase 2 objects that were associated with the transferred words could subsequently be mapped to both their novel Phase 2 word as well as the transferred Phase 1 word. In other words, our manipulation resulted in 6 words that could be mapped to two objects (a Phase 1 object and a Phase 2 object, each occurring in a distinct phase), and 6 objects that had two possible labels (a Phase 2 label and a label transferred from Phase 1; both co-occuring during the same trial). The familiarization session of Phase 2 was otherwise identical to the ones used in Phase 1.

Following the Phase 2 familiarization session, participants completed a test consisting of fifty-four trials. An initial set of 18 4AFC trials tested the pairings between the nonce words from Phase 2 with their corresponding objects (Phase 2 mappings), none of the transfer words were presented on this test. Next, six 4AFC trials tested the set of words appearing in both Phases (Remapping test). In these trials, a word transferred from the first familiarization was presented with four objects from the second familiarization, one was the referent from Phase 2 and other three were distractors. Following these test items, participants completed two sets of six preference test trials (henceforth "object preference" and "word preference"). Object preference trials presented a transferred word with a visual array containing both its Phase 1 and Phase 2 object mappings, as well as two other distractors. Word preference trials presented a Phase 2 object along with both its Phase 2 and transferred Phase 1 word mappings. A final set of eighteen 4AFC test items retested the word-object mappings learned in the Phase 1.

Results

Phase 1. Both groups exhibited significantly above chance (25%) performance following the first block of Phase 1 word-object learning, and continued to for each successive learning block (young adults: Block 1 = 77% (SD = 19%), Block 2 = 93% (SD = 14%), Block 3: 96% (SD = 10%); older adults: Block 1 = 58% (SD = 13%), Block 2 = 75% (SD = 18%), Block 3 = 88% (SD = 13%), all ps < .001; see Figure 4). We established the trajectory of learning the first set of mappings for both the younger and older adults by conducting 2 (group: older or younger adults) by 3 (block, 1, 2 or 3) ANOVA on the three blocks during Phase 1. The main effect of Group was significant, $F(1, 102) = 28.89$, $p < .001$, such that younger adults (M = 89%, SD = 17%) outperformed older adults (M = 73%, SD = 19%) overall. There was also a main effect of Block $F(2, 102) = 25.11$, $p < .001$, such that performance significantly increased from Block 1 (M = 68%, SD = 19%) to Block 2 (M = 84%, SD = 18%), $t(35) = 6.36$, $p < .001$, and significantly increased from Block 2 to Block 3 (M = 92%, SD = 12%), $t(35) = 4.45$, $p < .001$. The Group by Block interaction was not significant, $F(2,102) = 1.62$, $p = .203$.

Phase 2. Participants exhibited above chance performance on the novel word-object mappings from Phase 2 (young adults: M = 69%, SD = 26%, $t(17) = 7.32$, $p < .001$; older adults: M = 53%, SD = 22%, $t(17) = 5.44$, $p < .001$). An ANOVA revealed a marginal effect of group on learning the mappings from Phase 2 ($F(1,34) = 4.087$, $p = .051$), such that younger adults trended toward outperforming older adults. With respect to the Remapping test, which tested whether participants remapped the Phase 1 word to a novel object in Phase 2, young adults did not exceed chance performance on remapping (M = 33%, SD = 23%, $t(17) = 1.55$, $p = .14$); whereas older adults exhibited significantly below chance performance (M = 18%, SD = 13%, $t(17) = 2.2$, $p = .04$). While chance performance may be interpreted as an absence of remapping, below chance performance actually suggests an avoidance of mapping a previously learned label to a new object. Additionally, an ANOVA revealed a significant effect of group on trials testing learning of the 2:1 mappings in the second familiarization phase ($F(1,34) = 5.79$, $p = .022$), such older adults performed significantly lower than younger adults.

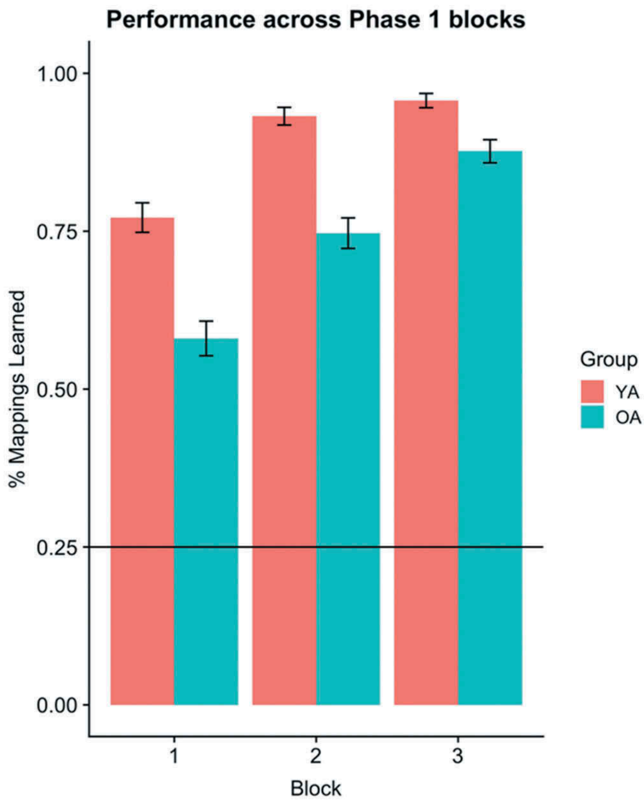

Figure 4. Performance across the three blocks during Phase 1 for both younger (Group 1) and older (Group 2) adults.

Preference trials. On the object preference trials, learners were asked to choose between the Phase 1 and Phase 2 objects for a transferred word. On this test, both groups chose the object from the first familiarization phase significantly more than would be predicted by chance (50%, younger adults: $M = 84\%$, $SD = 37\%$, $t(17) = 6.75$, $p < .001$; older adults: $M = 91\%$, $SD = 15\%$, $t(17) = 18.16$, $p < .001$), which is not surprising considering their at chance (for younger adults) or below chance (for older adults) performance on the Remapping test reported above. A one way ANOVA comparing performance across groups revealed no effect of group, $F(1, 34) = .46$, $p = .50$, such that older adults and younger adults did not differ in their preference for the original mapping. On the word preference trials, participants were asked to choose between the transferred label (the label from Phase 1 that could be remapped) and the novel Phase 2 label for the corresponding Phase 2 object. Participants exhibited a preference for the novel Phase 2 label, choosing the transferred label (the label from Phase 1) for the tested Phase 2 object significantly below chance (50%; younger adults: $M = 22\%$, $SD = 29\%$, $t(17) = 4.12$, $p < .001$; older adults: $M = 27\%$, $SD = 18\%$, $t(17) = 5.39$, $p < .001$). An ANOVA revealed that there was no effect of group on performance for the word preference trials, $F(1,34) = .37$, $p = .57$.

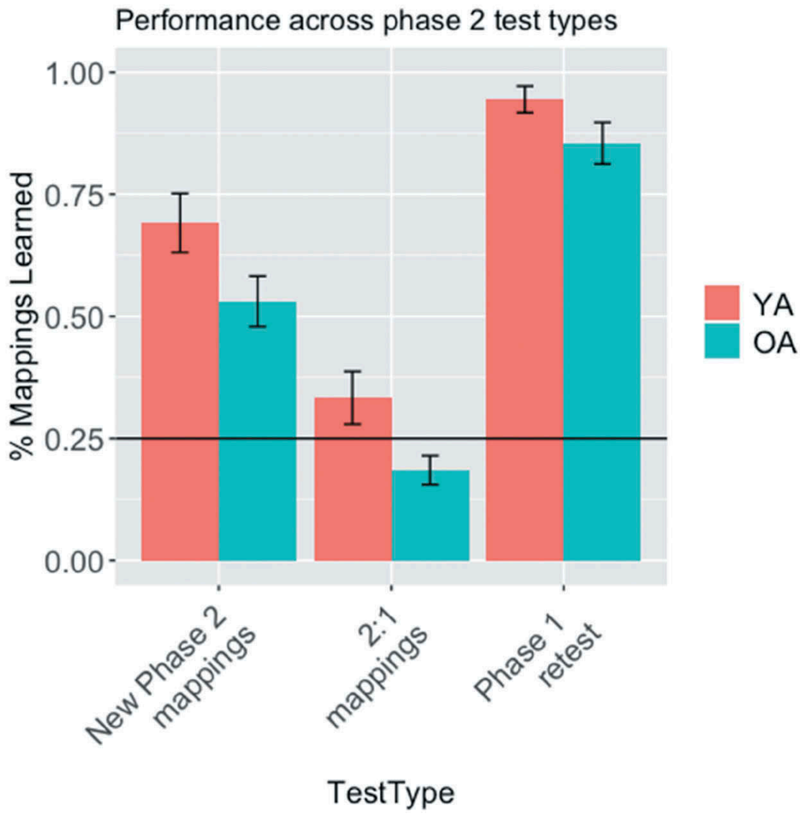

Figure 5. Performance across phase 2 test types for younger and older adults.

Phase 1 retest. Participants exhibited above chance performance on the retest of the Phase 1 object-word mappings (young adults: M = 94%, SD = 12%, $t(17) = 25.42$, $p < .001$; older adults: M = 85%, SD = 18%, $t(17) = 14.04$, $p < .001$; see Figure 5), suggesting that they retained the Phase 1 mappings across the Phase 2 learning and test trials. An ANOVA revealed a marginal effect of group for performance on the retest of the mappings from Phase 1, $F\,(1{,}34) = 3.12$, $p = .086$, such that younger adults trended toward outperforming older adults. We also compared performance on the retest of the Phase 1 mappings at the end of Phase 2 to performance on the same set of mappings after the third block of exposure in Phase 1. Neither younger or older adults exhibited significant forgetting over Phase 2, as performance did not differ across the two tests for younger adults ($t(33.11) = .34$, $p = .73$) nor older adults ($t(31.03) = .41$, $p = .68$). We also tested whether correctly learning to remap a word during Phase 2 came at the cost of remembering the original mapping. Specifically, for those items that participants correctly remapped (those they answered correctly in the Remapping test), did they retain the original mapping during the Phase 1 retest? Across both groups, participants retained the original mapping 93% (SD = 26%) of the time after learning the remapping, however younger adults retained more of these original mappings (M = 97%, SD = 8%) relative to older adults (M = 82%, SD = 37%), though this difference was not significant ($F\,(1{,}28) = 2.73$, $p = .11$), likely due to younger adults' better performance on the Phase 1 mappings.

Working memory and WCST. Finally, we tested whether performance on any component of Phase 2 was related to working memory abilities or to task switching, as measured by the WCST, after Bonferroni correcting for multiple comparisons (Bonferroni corrected p-value = .013). Performance on the Phase 1 Retest was significantly correlated with performance on Digit Span for the older adults ($r = .64$, $p = .004$), but was not related to any other cognitive measure for either the older or younger adults (all $p > .013$). Number of categories learned and number of errors on the WCST were not significantly correlated with learning the Phase 2 mappings, nor the 2:1 mappings for either group (all ps > .013). As in Experiment 1, based on their performance on these measures (see Table 2), we believe that the older adults in the current experiment were high functioning and motivated.

Discussion

Across both phases of Experiment 2, younger adults outperformed older adults. In Phase 1, younger adults reached near ceiling accuracy on the word-object associations after the second familiarization block, whereas older adults' performance continued to increase across all three familiarization blocks in Phase 1, reaching 88% correct after the third block of familiarization. In Phase 2, despite older adults exceeding chance on both the Phase 2 mappings and retention of Phase 1 mappings, younger adults still outperformed older adults on learning the new set of 1:1 mappings, as would be predicted by an age deficit in associative binding. Younger adults also exhibited marginally better retention for the Phase 1 mappings, though notably neither group exhibited any forgetting relative to their final Phase 1 accuracy. With regards to the 2:1 mappings, neither group exhibited above chance performance on remapping Phase 1 words to novel objects in Phase 2. Additionally, compared to younger adults, older adults were actually less likely to remap previously learned words to novel objects. Taken together, the results from all tests in Experiment 2 suggest a deficit in cross-situational statistical learning for older adults, and do not provide supporting evidence for the notion that older adults may be more willing to remap previously learned words to novel objects relative to younger adults. To the contrary, the fact that older adults were below chance on forming 2:1 mappings, suggests a reluctance on the part of older adults to learn multiple mappings.

General discussion

Across two experiments, we tested older adults' ability to track statistical regularities using a cross-situational statistical learning paradigm allowing learners to map novel words to novel objects. In Experiment 1, we extended previous research by increasing task difficulty to test learning of novel object-word pairings. We found that both younger and older adults exhibited learning across all levels of task difficulty, although younger adults outperformed older adults. We also found that task difficulty similarly impacted both groups of participants.

Previous research using this paradigm in older adults presented participants with 2 objects and 2 words on any one trial (Penaloza et al., 2017), equivalent to our 2×2 condition, and found an overall deficit such that after the initial exposure phase younger adults outperformed older adults. We replicated this finding and extended it by also testing participants on our 3 × 3 and 4 × 4 conditions, each of which further increased task difficulty. Across all three task conditions, both younger and older adults exhibited above chance learning, and the costs associated with increasing task difficulty did not interact with age. Our findings contrast studies that have used higher order statistical learning in SRT paradigms (e.g., Howard et al., 2004) which report larger deficits for older adults relative to younger adults as difficulty increases, as well as no acquisition of complex dependencies (i.e., learning of the most difficulty statistical sequence). While it is possible that higher-order dependencies used in the SRT literature are more challenging than the 4 × 4 condition used in the current paradigm, our overall pattern of results suggests that cross-situational statistical learning, across multiple levels of task difficulty, remains a robust learning mechanism for older adults.

In Experiment 2, we provided participants with extended practice with a first set of mappings before testing whether older adults may be more likely to remap previously learned words to novel objects following initial learning. As in Experiment 1, older adults exhibited signifciant learning and showed increased learning across blocks, though learning after the final block was lower (88%) than that observed in younger adults (96%). These results suggest that, like younger adults, older adults can take advantage of extended practice to increase overall learning. However, the fact that an age deficit in overall learning remained even after 3 training blocks suggests that, while pratice improves performance across groups, it does not mitigate age deficits in overall learning. Despite differences in performance across all blocks of Phase 1, older adults did not always exhibit significanl deficits in performance (although their scores were consistently lower than those of younger adults). For example, younger adults and older adults did not significantly differ on Phase 2 word learning. Comparing performance on Phase 2 word learning to performance on Block 1 of Phase 1 reveals that accuracy was lower for both groups for Phase 2 learning, though younger adults exhibited a larger decrease in accuracy. This could be due to how each group treated the presence of the transferred Phase 1 word during Phase 2 word learning, which we return to below, though we cannot definitively say based on the current paradigm.

After reaching high levels of accuracy during initial learning of object-word pairs, participants were exposed to a second set of mappings which contained a subset of previously learned words that could be remapped to novel objects. This resulted in 6 words that could refer to two objects, which occurred in distinct phases, and 6 objects that could have two labels, which occurred during the same trial. These temporal differences in when each of these types of 2:1 mappings could be learned likely lead to different task demands, as the former allows for more time between when the mappings are presented, while the latter presents the in short succession. Despite these possibly different task demands, there were no age differences in participants' performance on trials testing these two different types of 2:1 mappings, suggesting that these different task demands may not have interacted with age.

Offering participants the opportunity to remap previously learned words to novel objects allowed us to test predictions made by hyper-binding (Campbell et al., 2010). Previous research on hyper-binding (Campbell et al., 2010) suggests that older adults maintain more irrelevant information in working memory relative to young adults. When faced with this remapping task, younger adults may be ignoring or suppressing the previously learned word, as they do not see the previously learned referent on the screen. Under this assumption, older adults may be expected to be more likely to learn a new mapping for the previously learned word, due to their inability to ignore what might be considered irrelevant information. Additionally, overall binding deficits for older adults would also predict that older adults may have more weakly bound associations (see Old & Naveh-Benjamin, 2008), which may in turn suggest that older adults would be more willing to overwrite a previously learned object-label mapping to remap the label to a new object.

Despite these predictions, neither younger nor older adults reliably remapped previously learned words to novel objects. More specifically, while both groups exhibited a preference for the first learned mapping, we did find a group difference in that older adults were less likely to remap previously learned words, showing a bias against choosing a previously learned word for a novel object, whereas younger adults performed at chance during this test. Older adults' below chance performance could be due to participants remembering the Phase 1 mapping and actively ignoring the previously learned Phase 1 word when it is presented during Phase 2, or due to an overall inability to learn 2:1 mappings in this context. While the current study does not allow us to tease apart which of these reasons underlied the group difference in performance, this is an important avenue for future research to explore. Thus, in Experiment 2 we provide the first evidence that older adults are not more likely to remap previously learned words relative to younger adults. These results suggest word-object associations learned by older adults are not more weakly bound nor more easily overwritten relative to those of younger adults. This finding contributes to our understanding of the nature of learned associations in aging. Specifically, our evidence suggests that older adults' binding deficit may reflect a possible limit on the amount of associative information that can be learned (resulting in less binding overall) and is not driven by a reduction in the overall strength of their associations, as their bindings may be just as strong if not stronger than those of young adults (as evidenced by older adults' reluctance to remap in Experiment 2).

Our results also point to an interesting intersection between the current understanding of the processes underlying cross-situational statistical learning and hyper-binding. The initial conception of cross-situational statistical learning was that it reflected the process of tracking labels and referents across many situations, with the highest co-occurrences yielding the correct mapping (e.g., Roembke & McMurray, 2016; Yu & Smith, 2007, 2012). Contrasting this statistical or associative account, an explicit learning account has argued that learners form hypotheses about which word maps with which object and subsequently attend to any disconfirming evidence (Medina et al., 2011; Trueswell et al., 2013). Another possibility is that cross-situational statistical learning may rely on multiple types of processing (e.g., Roembke & McMurray, 2016; Yurovsky et al., 2013), a notion that has been recently supported by a cross-situational study of patients with hippocampal damage (Warren et al., 2020). Notably, hyper-binding has recently been hypothesized to occur only under implicit learning conditions, suggesting that the binding process is relatively preserved in aging, but that age deficits occur in explicit learning conditions (Campbell & Hasher, 2018). As we did not find evidence for hyper-binding in our paradigm, we view our findings as lending support to the notion that cross-situational statistical learning is indeed not a purely implicit process (as older adults did not appear to learn the second mapping offered in Phase 2). Future work at the intersection of these fields might better elucidate the role of the hippocampus in cross-situational statistical learning (Covington et al., 2018) and its consequences for learning in older adulthood.

Relative to other statistical learning research with older adults, here we show that older adults exhibit a continued ability to track statistical regularities even as task difficulty increases. This could be due to the fact that learning novel words and their corresponding meanings may be more reflective of older adults' day-to-day experience. As older adults have been shown to perform better on associative memory tasks when the information is relevant to their everyday life (Amer et al., 2018; Matzen & Benjamin, 2013), testing learning of novel words may put younger and older adults on more equal footing. In fact, previous word learning research with older adults finds similar patterns of results, with older adults exhibiting learning under a variety of conditions, though sometimes to a lesser degree than younger adults. For example, Whiting et al. (2011) found that younger and older adults did not differ on their ability to learn novel words for either familiar or novel objects (Whiting et al., 2011), while Service and Craik (1993) found that younger adults outperformed older adults on learning lists of translation equivalents, pairs consisting of a familiar English word and an English nonword or real Finnish word. While these other word learning studies relied on explicit learning (as there was no ambiguity about the possible target), older adults also exhibit learning under more implicit conditions. For example, when younger and older adults heard a sentence containing a novel word while seeing an array with a familiar and a novel picture (which should be interpreted as the referent for the novel word), older adults still exhibited learning, though to a lesser degree than young adults (and to a lesser degree still than performance on an explicit learning condition where the target object is the only possible mapping; Greve et al., 2014). Thus, taken together with the results presented here, word learning abilities seem to be maintained in older adulthood, across a variety of tasks.

Previous statistical learning research has also investigated how changes to executive function may impact differences in performance between younger and older adults. For example, Ong and Chan (2019) found differences in how working memory was associated with younger and older adults' performance on their speech segmentation task, which they interpret to mean that older adults may be using different strategies relative to younger adults when performing the task. Similarly, Palmer et al. (2018) found that working memory was implicated in statistical learning performance, and suggest that older adults' inferior performance on the statistical learning task may be related to their poorer performance on the working memory task relative to younger adults. In the current study we found that while executive function was not related to task performance, better working memory performance in older adults did predict better retention of the first set of mappings after Phase 2 exposure and test (for similar results in other tasks see also Bo et al., 2009; Bo & Seidler, 2009; Unsworth & Engle, 2005). Several theories of statistical learning propose differential involvement of working memory based on the task demands (e.g., Erickson & Thiessen, 2015; Hsu & Bishop, 2011), as statistical learning encompasses a wide variety of learning phenomena (see Frost et al., 2019). This relationship might be particularly important for understanding age related changes to statistical learning abilities, and developing a deeper understanding of this interaction is a promising avenue for further research.

In summary, we have shown that, while older adults do exhibit a deficit in learning novel object-word associations relative to younger adults, their ability to track statistical regularities is preserved even under the most difficult conditions, and they exhibit similar retention rates to younger adults. We also showed that hyper-binding and more general binding deficits do not, in this paradigm, result in older adults being more willing to remap previously learned words to novel objects, suggesting that older adults' object-label mappings are not more easily overwritten than those of younger adults. As we found consistent evidence for learning on our word learning task and found that learning continued to improve over repeated exposure for older adults, future learning and memory research should consider how the material to be learned, and the presentation of that material, may impact age-related deficits in performance. Taken together, these results suggest that once older adults do form an association (in this case between a nonce word and a novel object), that association is not quickly forgotten nor overwritten, speaking to the facility of older adults to robustly learn over time. While previous research suggests that associations formed by older adults are more weakly bound than those of younger adults (Old & Naveh-Benjamin, 2008), future research will need to explore whether older adults' resistance to remap previously learned words to novel objects is actually evidence that older adults' associations are not more weakly bound relative to younger adults.

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