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Relational binding and holistic retrieval in ageing

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ABSTRACT
Episodic memory binds together diverse elements of an event into a cohesive unit. This property enables the reconstruction of multidimensional experiences when triggered by a cue related to a past event via pattern completion processes. Such holistic retrieval is evident in young adults, as shown by dependency in the retrieval success for different associations from the same event [Horner, A. J., & Burgess, N. The associative structure of memory for multi-element events. *Journal of Experimental Psychology: General*, *142*(4), 1370–1383. https://doi.org/10.1037/a0033626, 2013; Horner, A. J., & Burgess, N. (2014). Pattern completion in multielement event engrams. *Current Biology*, *24*(9), 988–992. https://doi.org/10.1016/j.cub.2014.03.012, 2014]. Aspects of episodic memory capacity are vulnerable to ageing processes, including reduced abilities to form linkages among aspects of an event through relational binding (Naveh-Benjamin, 2000). Here, we used dependency analyses to examine whether older adults retrieve events holistically, and whether the degree of holistic retrieval declines with old age. We found that both young and older adults retrieved events as an integrated unit, but older adults showed a lower magnitude of holistic retrieval compared to young adults. Holistic retrieval declined with advancing age, even after controlling for pairwise relational binding performance. These results suggest that a decline in holistic retrieval is an aspect of episodic memory decrements in cognitive ageing.

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KEYWORDS
Holistic recollection; ageing; pattern completion; episodic memory

Many aspects of human cognition decline with old age, with memory complaints being among the most prevalent (Fritsch et al., 2014; Hertzog et al., 2018). Not all forms of human memory are equally affected by advancing age, however (reviewed in Nyberg et al., 2012). Episodic memory capacities that support the recollection of specific past experiences show the largest age-related declines (Nyberg et al., 2003; Rönnlund et al., 2005). One key factor underlying episodic memory decline in ageing is a decrement in relational binding processes that link together unrelated units of an episode (associative deficit hypothesis: Naveh-Benjamin, 2000). A large meta-analysis showed that the age-related decrements in relational memory for multiple elements (e.g., item-context associations, item pairs) are disproportionately larger than those for individual items, in both verbal and nonverbal materials (Old & Naveh-Benjamin, 2008).

Most studies of episodic memory in ageing have focused on the retrieval success of pairwise relational memory in various paired-associate paradigms. However, episodes are composed of multiple elements, often involving the people we encounter, the objects we interact with, and the locations in which these interactions take place, making up a coherent event unit (Tulving, 2002). Thus, memories of specific episodes are made up of an interlinked network of relational structures, rather than disjointed individual links. This coherence enables the reconstruction of different aspects of an experience when triggered by a cue (Horner & Burgess, 2014). Holistic retrieval is thought to be subserved by pattern completion processes that recapitulate a complete event representation when a partial cue is reactivated (Norman & O'Reilly, 2003). According to these models, exposure to part of a past experience leads to recurrent connectivity in the hippocampal CA3 subfield, retrieving the entire event representation (Guzowski et al., 2004; Rolls, 2016).

The degree of holistic retrieval can be estimated based on the dependency in retrieval success for multiple associations from the same event. Horner and Burgess (2013, 2014) tested whether events are remembered holistically in young adults in a multi-element event paradigm. In this task, participants first learn unique "events", each of which is comprised of a scene, a person, and an object. Subsequently, participants perform a cued recognition

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task on every possible cue-test pair of each event. This design enables the assessment of whether the retrieval success of one pair (e.g., scene-person) statistically relates to the retrieval success of other pairs (e.g., scene-object) from the same event. Young adults indeed showed evidence of holistic retrieval, such that they were likely to remember or misremember different pieces of the same event altogether (Horner & Burgess, 2013, 2014).

Given that relational binding declines with advancing age, how may holistic retrieval be impacted by old age? One possibility is that binding deficits may lead to event retrieval being fragmentary as opposed to holistic in ageing. Another possibility is that even though memory for the overall *quantity* of associations decreases with age, the network of associations within the same event may still be retrieved successfully (or not) as a holistic event unit. Thus far, findings from two relevant studies are mixed. One recent study showed that older adults (aged 61–77) are less likely to remember the focal association and its associated context as integrated units compared to young adults (James et al., 2019). In this study, young and older adults learned object-occupation pairs (e.g., violin-teacher), and critically, some pairs were preceded with a context prompt (e.g., office). Participants were then tested on their memories for the object and occupation pairs and their associated contexts. For both young and older adults, when the pairs were successfully retrieved, the probability of also successfully retrieving their contexts exceeded the probability of misremembering the contexts. The difference between the two probabilities – conditional dependency – was greater in young adults than in older adults, providing some evidence that, while older adults retrieve events holistically, the degree of memory contingency between an association and its context is greater in young adults than in older adults. However, unlike in Horner and Burgess (2014), this design did not target the idea of holistic retrieval via mutual cuing by every association within a three-way binding structure. Instead, the object and occupation pairs were treated as one unit in cuing the context. Further, event memory coherence can also be indexed by misremembering multiple associations from the same event. Thus, approximating dependency from successful trials alone may closely reflect overall capacities in relational binding.

Indeed, a recent study investigated age-related differences between young and older adults in holistic retrieval using dependency measure in a multi-element event paradigm (Hou et al., 2019). Here, the authors did not find an age difference in retrieval dependency between young and older adults. However, given that this study aimed to test the impact of self-reference (self versus others) on event memory coherence, every learned event shared an overlapping element (person) with other events on the study list, creating a critical design departure from previous studies that employ the multi-element event paradigm. In fact, it has been shown that memories for overlapping events may result in anti-dependency, such that the likelihood of retrieval success of one event is negatively correlated with its related event (Zotow et al., 2020). Thus, age-related profiles in retrieval dependency for unique event memory in senescence remained unclear.

The current work targeted two main questions: (i) whether older adults exhibit the tendency to remember events holistically, and (ii) whether the degree of holistic retrieval declines in old age. Importantly, in this investigation, holistic event memories are indexed by retrieval success or failure of event memory as a coherent unit. This approach enables an assessment of the cohesive characteristic of episodic memories that accounts for differences in relational binding. We employed the multi-element event task originally devised by Horner and Burgess (2014) and adapted to pictorial materials by Ngo et al. (2019). Two key memory measures were computed: (1) *relational binding* – the overall number of associations remembered correctly, irrespective of event membership, and (2) *dependency* – the degree to which different associations from the same event are remembered or misremembered together.

Methods

Participants

Our sample consisted of 32 undergraduate students (18F, $M_{age} = 19.66$; $SD = 1.36$, range = 18–23) from Temple University who participated for partial course credit, and 32 older adults (23F, $M_{age} = 74.59$; $SD = 6.11$, range = 62–85) who enrolled in the Temple University's Osher Lifelong Learning Institute. All older adults were free of neurological damage and any history of health impairments related to memory decline. Old adults were screened for cognitive impairments with the Mini-Mental State Examination (MMSE; Folstein et al., 1975) with 24 being set as the cutoff to minimise the risk of including older adults with preclinical dementia (Tombaugh & McIntyre, 1992). All participants gave informed consent and reported having normal or corrected-to-normal vision. This experiment was completed in accordance with and approved by, the Institutional Review Board committee at Temple University.

Memory task

Materials

We sampled 24 cartoon images of distinct scenes (12 indoor and 12 outdoor scenes, e.g., waterfall, library), 24 cartoon images of common objects (e.g., wallet), and 24 images of cartoon characters from non-overlapping movies/books (12 males, e.g., Pinocchio, and 12 females, e.g., Alice) from Google image search engine. From this pool of selected images, we constructed one fixed set of 24 "events", with the criterion that the elements from each event were not thematically related (e.g., a library and a book). For each "event", the scene, person, and object images were placed on the top, bottom left, and bottom right of the screen, respectively (see Figure 1(a)). The set of 24 events was divided into two separate sets of 12 events: one set with female characters, and the other with male characters. Each set was used for one of the two encoding-test cycles in the experiment. For the test phase, we created six retrieval types per event, wherein each element of an event took turn as the cue or the tested item. We created four randomised orders of the study trials for each set, and four randomised orders for the six retrieval type blocks, as well as the order for the test trials within each block. Participants were randomly assigned to one of the four versions at encoding and test. The experimental materials are identical to those of a previous study (Ngo et al., 2019).

Procedure

All participants were tested individually. The task procedure entailed two consecutive encoding-test blocks. Each block consisted of 12 encoding and 72 test trials. Participants were first instructed that they would see many different "stories" and that they should pay close attention to all of the different elements including the scene, person, and object altogether in each "story". Prior to the encoding phase, one example event (playground – Elastigirl – hat) preceded the encoding phase in order to acquaint the participants with the encoding task (Figure 1(a)). In this example trial, while the event was being presented, a pre-recorded audio narrated: "Elastigirl went to the playground. She brought her hat with her. It was the only hat at the playground". The implementation of the example trial was to draw participants' attention to every element of a given event. Then, participants completed two encoding-test blocks with non-overlapping stimuli between the two blocks. In the encoding phase, participants viewed 12 event trials sequentially (6 s/each; 0.5 ITI) per block, and were not explicitly instructed to self-create stories for the encoding events or that there would be an upcoming memory test.

Immediately after the encoding phase, participants performed a self-paced four-alternative forced-choice task on every possible pairwise cue-test combination of each studied event. This resulted in six test types per event (e.g., [1] cue: scene; test: person; [2] cue: scene; test: object; [3] cue: person; test: scene; [4] cue: person; test: object; [5] cue: object; test: scene; [6] cue: object; test: person) and totalling 72 test trials per block. The 6 test types were administered in a blocked manner, each consisted of 12 trials (one from each studied event). On each test trial, a cue and four options were presented simultaneously on the screen (Figure 1(b)). Among the four options, one was a target – the correct item that belonged to the same event as the cue. The three lures were same-category elements from other studied events. All elements served as foils an equal number of times across all 144 test trials. Participants were asked to point to one of the four options that belonged to the same story that they previously saw as the cue on the left side of the screen. The orders of test types and the trials within each test block

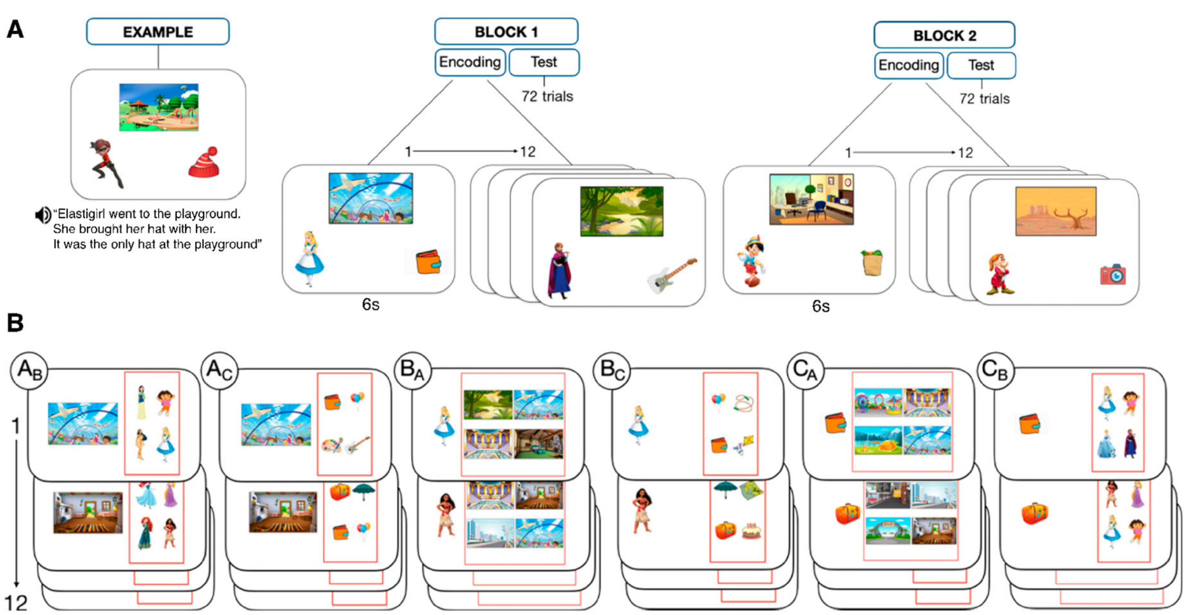

Figure 1. A schematic depiction of the multi-element event task procedures. Prior to encoding, an example trial was introduced with a narrative to highlight every element and association within an event. At encoding, participants viewed 24 unique events presented in two encoding-test blocks, each comprised of 12 events (a). Examples of six test types per event in the test phase per block (b). Each element of a studied event took turn serving as the cue (shown on the left side of the screen) and the tested item (one of the four options shown inside a red outlined box). Letters A, B, and C denote the scene, person, and object element, respectively. The different test types are notated such that the first letter denotes the cue item, and the second subscripted letter denotes the tested item (e.g., A_B denotes the retrieval type in which the scene element served as the cue, whereas the person element was the to-be-retrieved element).

differed across the four experimental versions. The order of two sets of 12 events was counterbalanced across participants.

Verbal intelligence

Participants were administered the 45-item American National Adult Reading Test (AMNART [Grober & Sliwinski, 1991]). This test measures the ability to read aloud irregular words. Pronunciation errors were tallied and AMNART-estimated verbal IQ scores were calculated using Grober & Sliwinski's formula, which accounts for years of education (i.e., 118.2–0.89*(pronunciation error) + 0.64*(years of education)). This test was included as a control variable to assess whether verbal intelligence would account for age-related differences in memory performances.

Estimating dependency

Dependency was computed using the same methods as in previous studies (Horner & Burgess, 2014; Ngo et al., 2019). We computed six 2 × 2 contingency tables for the data and the independent model for each participant based on their joint retrieval accuracy of trials sharing a common cue (A_BA_C; i.e., cue with A and retrieve B and cue with A and retrieve C) or a common test item (B_AC_A; i.e., cue with B and retrieve A, and cue with C and retrieve A). Each 2 × 2 contingency table for each participant's data showed the proportion of events (out of 24) that fell within the four categories: both A_B and A_C were correct or incorrect, A_B correct and A_C incorrect and vice versa. The proportion of joint retrieval in each participant's data was defined as the proportion of events in which both associations were either correctly or incorrectly retrieved in each contingency table. We then averaged the proportion of joint retrieval across six contingencies tables (three tables for the A_BA_C analysis, for each element-type, and three tables for the B_AC_A analysis, for each element-type) for an individual participant.

The independent model of retrieval estimated the degree of statistical dependency if retrieval success for specific cue-test pairs is independent of retrieval success of other cue-test pairs in relation to the participants' overall accuracy. The independent model predicted the proportion of joint retrieval, given a participant's overall level of performance, if retrievals of event pairs were independent, such that the probability of the successful retrieval for both A_B and A_C was equal to P_{AB}*P_{AC}, where P_{AB} was the probability of retrieving B when cued by A across all events, and similarly for P_{AC} (Table 1). The independent model served as a predicted baseline for which we compared the proportion of joint retrieval in the data. Given the proportion of joint retrieval for the data scales with accuracy, the main index of holistic retrieval was *dependency*, defined as the difference between the proportion of joint retrieval in the data and the independent model for each participant. A dependency value that is greater than 0 would provide evidence for holistic retrieval. Further, the difference between the proportion of joint retrieval in the data and the independent model reflects the degree of retrieval dependency for each participant, while controlling for their accuracy. Thus, we took the dependency value to signify the extent of holistic retrieval, similar to previous studies (e.g., Horner & Burgess, 2014; Ngo et al., 2019; Zotow et al., 2020).

Table 1. Contingency table for the predicted independent model for proportion of correct and incorrect cued recognition over the total number of events for elements B and C when cued by A.

		Retrieving B	
Cued by A		Correct	Incorrect
Retrieving C	Correct	$\Sigma_{i=1}^{N} P_{AB}P_{AC}$	$\Sigma_{i=1}^{N} P_{AC}(1-P_{AB})$
	Incorrect	$\Sigma_{i=1}^{N} P_{AB}(1-P_{AC})$	$\Sigma_{i=1}^{N}(1-P_{AB})(1-P_{AC})$

Note: P_{AB} denotes the probability of retrieving B when cued by A.

Results

Similar to previous studies on retrieval dependency (e.g., James et al., 2020), participants who performed at ceiling level on the task (≥95%) were not included in the analyses (all $n = 8$ young adults) because ceiling performance would result in dependency scores approximately 0. Outlier analyses on the two main dependent variables: pairwise relational binding accuracy and dependency identified one older adult whose dependency score was above 3SD from the mean of the whole sample, and thus this participant was excluded ($n = 1$ older adult). A final sample of $n =$ 24 young adults and $n = 31$ older adults were entered into the analyses.

The density of age distribution, and the distribution of AMNART and MMSE scores are presented in Figure 2. First, we found that AMNART score was higher in older adults ($M = 123.95$, $SE = 0.92$) than in young adults ($M = 112.21$, $SE = 0.95$), $t(57) = -8.74$, $p < .001$, $d = -2.28$. Age did not relate to AMNART score among older adults, $r(29) = -0.02$, $p = .92$, $BF_{01} = 4.46$. Age also was not associated with AMNART score in young adults, $r(22) = 0.33$, $p = .11$, $BF_{01} = 1.19$, although we note that Bayesian statistics were equivocal. Age was negatively associated with MMSE score among older adults, $r(29) = -.51$, $p = .003$. No sex differences were found in either the young or older adults on pairwise relational binding accuracy ($ps > .61$, $BF_{01} = 2.43$) or dependency ($ps > .88$, $BF_{01} = 2.74$).

Pairwise relational binding accuracy

Young adults ($M = 0.74$, $SE = 0.03$) outperformed older adults on the overall number of pairs correctly retrieved ($M = 0.52$, $SE = 0.03$), $t(53) = -5.35$, $p < .001$, $d = 1.45$, suggesting an age-related decline in pairwise relational memory from young adulthood to old age (see Figure 3 (a), Left).

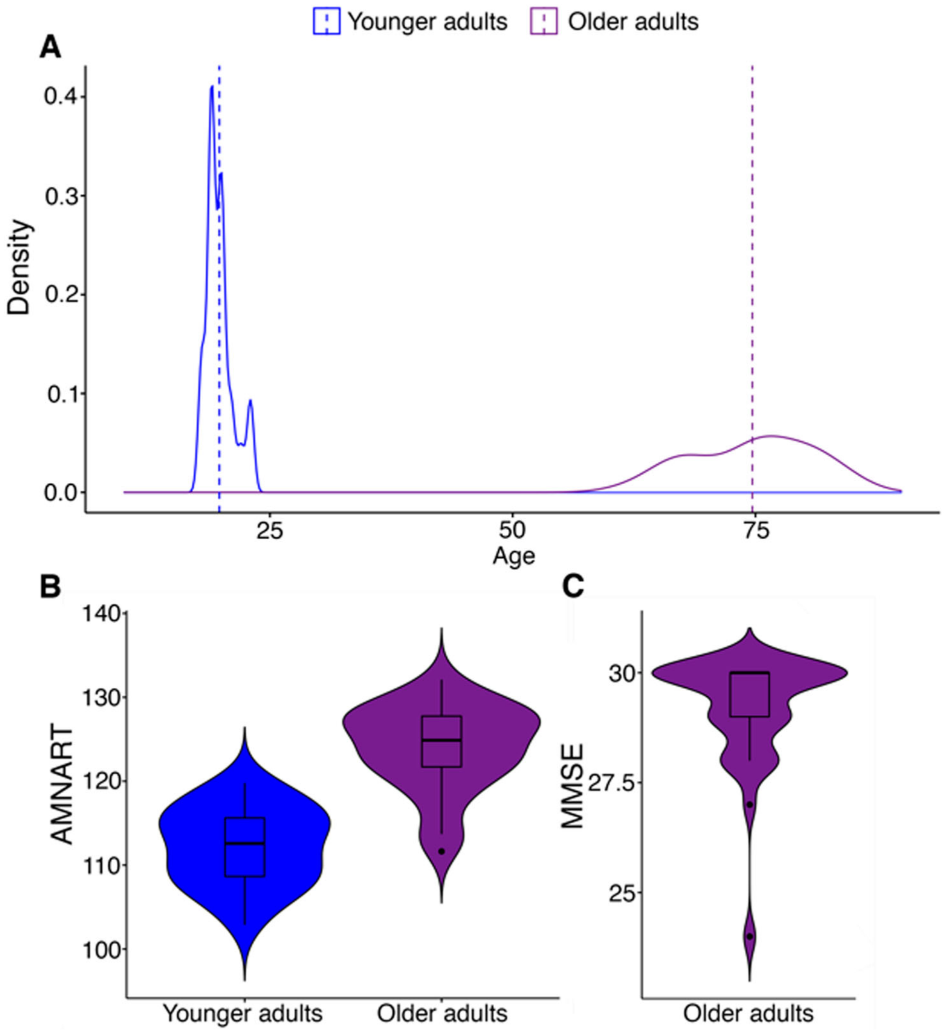

Figure 2. A density plot of the age distribution in our samples (a). Distributions of verbal skills (measured by AMNART) in young and older adults (b, Left) and a distribution of MMSE scores among older adults (b, Right).

We also tested whether the effect of age on accuracy differed across the two blocks. A 2 (block: 1, 2) × 2 (age: young adults, older adults) mixed ANOVA yielded a main effect of block, $F(1, 53) = 17.95$, $p < .001$, partial $\eta^2 = 0.25$, main effect of age, $F(1, 53) = 28.67$, $p < .001$, partial $\eta^2 = 0.35$, and a significant interaction, $F(1, 57) = 7.11$, $p = .01$, partial $\eta^2 = 0.12$. Tukey post-hoc tests revealed that performance on block 2 was greater than that on block 1 for young adults $t = -4.60$, $p < .001$, but not older adults $t = -1.19$, $p = .24$. These results suggest that young adults improved after performing one encoding-test block, whereas older adults did not.

Dependency

To test whether holistic retrieval is evident in young and older adults, we conducted a one-sample *t*-test to test whether dependency (joint retrieval in the data – independent model) exceeded 0 for each age group.

As expected, dependency in young adults ($M = 0.07$, $SE = 0.01$) was significantly greater than 0, $t(23) = 7.99$, $p < .001$, $d = 1.63$, therefore replicating previous studies using verbal materials (Horner & Burgess, 2013; 2014) and the same set of stimuli (Ngo et al., 2019). Interestingly, dependency in older adults ($M = 0.04$, $SE = 0.01$) also exceeded 0, $t(30) = 5.74$, $p < .001$, $d = 1.03$. Thus, evidence for holistic retrieval seen in both age groups demonstrates that memories for multi-element events may be represented as an integrated episodic unit even in late adulthood.

Importantly, dependency was greater in young adults compared to older adults, $t(53) = -2.36$, $p = .02$, $d = 0.64$, suggesting that the degree of holistic retrieval declines with old age (see Figure 3(a), Right). When controlling for age effects on pairwise relational binding accuracy in an ANCOVA, the age effect on dependency was no longer significant, $F(1,52) = 2.47$, $p = .12$. These findings suggest that the age-related difference in dependency could be accounted for by age-related differences in pairwise relational binding accuracy. Note that the relationship between dependency and accuracy showed a trend towards significance across all participants, $r(53) = .24$, $p = .08$ (see Figure 3(b)).

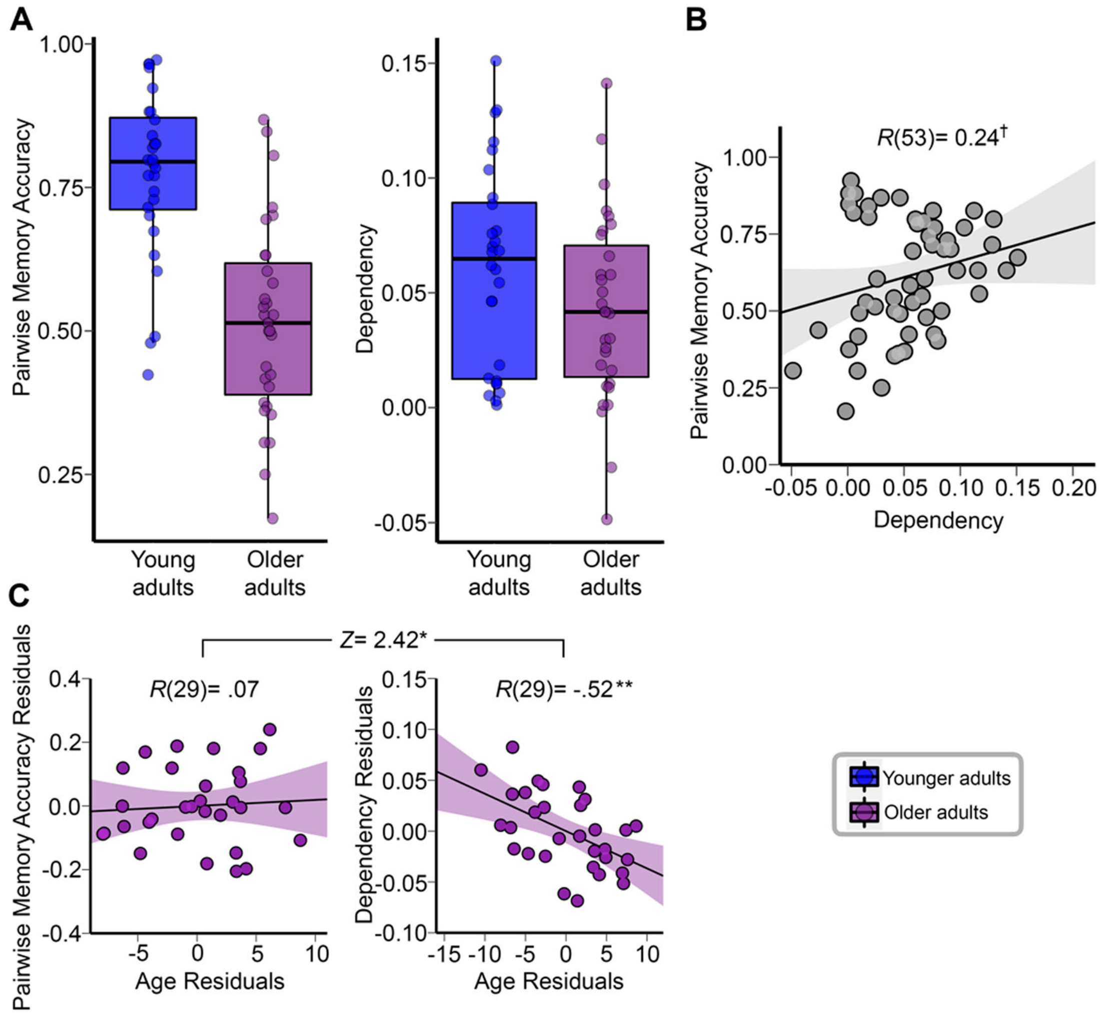

Figure 3. The distribution of pairwise relational binding performance and retrieval dependency separated by young and older adults (a). A scatterplot of a bivariate correlation between pairwise relational binding accuracy and dependency (b). Scatterplots depicting the relation between age and pairwise relational binding accuracy residuals after controlling for dependency, MMSE, and AMNART (c, Left), and the relation between age and dependency residuals after controlling for pairwise relational binding accuracy, MMSE, and AMNART (c, Right) among older adults. Significance notation: †$p < .08$, **$p < .01$.

It is also worth noting that the group difference in retrieval dependency was less robust when a higher ceiling performance was applied (accuracy ≥ 98%). With the exclusion criterion of accuracy ≥ 98% (all $n = 4$ young adults from the total of 32 young adults), all findings were consistent with those reported with one exception: the difference in dependency young and older adult groups became nonsignificant, $t(57) = 1.66$, $p = .10$, $d = 0.43$, $BF_{01} = 1.21$. This difference was primarily due to the fact that ceiling performance on the task could cause dependency to be approximately 0, thereby dampening the dependency level in young adults who performed extremely well on the task.

Retrieval dependency among older adults

Next, we tested whether holistic retrieval declines at the upper end of the ageing spectrum by only examining the older adult group. A linear regression predicting dependency, with age, MMSE, verbal IQ, and pairwise relational binding as predictors showed that the model predicted dependency, $F(4, 30) = 4.34$, $p < .01$. Interestingly, age was the only significant predictor, $p = .004$, whereas MMSE, AMART, and pairwise relational binding were not related to dependency, all p's > .23. This result suggests that the degree of holistic retrieval decreases as age increases among older adults, and that this relation cannot be accounted for by age-related decline in cognitive status, verbal IQ, or pairwise relational memory. In contrast, a linear regression predicting pairwise relational binding accuracy with age, MMSE, verbal IQ, and dependency as predictors, showed that pairwise relational binding was not associated with age among older adults, $p = .72$.

To test whether age-related decline in dependency significantly exceeded that in pairwise relational binding accuracy, we compared the correlation coefficients (i) between age and dependency while controlling for accuracy, AMNART score, and MMSE, and (ii) between age and accuracy while controlling for dependency, AMNART score, and MMSE. The association between age and dependency was significantly greater than the association between age and pairwise relational binding accuracy, $z = 2.42$, $p = .02$ (see Figure 3(c)). This result suggests that there is a steeper age-related decrement in holistic retrieval compared to relational binding in old age.

Discussion

Age-related declines in holistic retrieval

One defining feature of episodic memory is that complex and multi-element events are stored as coherent representations, so that episodic memory retrieval entails the holistic re-experience of all constituents of an event (Tulving, 2002). Here we asked whether holistic retrieval is vulnerable to ageing processes. Three key findings are highlighted. First, aligning with previous findings, we found that older adults remember a fewer number of associations compared to young adults, suggesting that relational binding decreases with advancing age (Naveh-Benjamin, 2000). One potential mechanism for the associative deficits in ageing is older adults' propensity to hyper-bind, that is, erroneously linking elements from different associations that were learned in temporal proximity (Campbell et al., 2010; Campbell et al., 2014). Given that the lures in the 4AFC task were elements from different events learned in the same block, it is possible that hyper-binding may lead to lower pairwise relational memory accuracy in our study. It is worth noting that the current study did not assess item memory, therefore we cannot estimate the extent to which the age effects on relational binding is attributed by memory decline in item memory.

Despite the reduced memory performance in pairwise relational binding, older adults showed a tendency to remember multi-element events as integrated units. That is, when successfully retrieving one association from an event, both age groups were more likely to also successfully retrieve other associations of that event. These results are in line with previous findings (James et al., 2019), in which older adults were more likely to successfully retrieve the associated context if they also successfully remembered the object-occupation associations. These findings conceptually replicate those by Hou et al. (2019), suggesting that both young and older adults may store coherent event memory representations that result in an all-or-none retrieval success pattern and mutual cuing of elements within networks of associations.

Second, the degree of holistic retrieval declines in ageing such that older adults showed a lower magnitude of dependency compared to young adults. These findings align with those by James et al. (2019), which showed that relative to young adults, older adults showed a lesser degree of contingency between the focal event and its contexts (James et al., 2019). However, our findings are inconsistent with those by Hou et al. (2019), wherein young and older adults showed comparable degrees of dependency. This misalignment is likely due to the key design difference between the two studies, namely the use of overlapping versus unique events. It is possible that the overlapping element among a subset of the events in the Hou et al.'s (2019) study additionally taxed pattern separation processes, leading to anti-dependency among overlapped events (Zotow et al., 2020).

At the group level, the age-related difference in pairwise relational binding accuracy explained the age effect in dependency between young and older adults. These findings suggest that older adults' reduced memories for the linked elements that co-occurred in the same events significantly explained a reduction in holistic retrieval of multi-element events. Importantly, the degree of event coherence decreased with advancing age among older adults. In contrast to the group-level comparison, we found that this association could not be accounted for age-related declines in relational binding, general cognitive status, or verbal skills. Further, the association between age and dependency exceeded that between age and pairwise memory accuracy, suggesting a steeper decline in holistic retrieval compared to relational binding within the ageing group. Evidence on the decline onset from cross-sectional (Park et al., 2002) and longitudinal (Rönnlund et al., 2005) investigations suggest that episodic memory remains relatively stable until about 60–65 years of age, after which accelerating decline is typically observed. However, these findings are based on different paradigms ranging from verbal free recall to relational binding of individual pairwise associations. Future investigations should directly test the possibility of dissociable age patterns between pairwise relational binding and holistic event retrieval in senescence with a longitudinal design.

Variations in pattern completion assessments

Our findings provide complementary data to previous work that employed different paradigms and conceptualisation of pattern completion in ageing. In addition to studies that examined holistic retrieval to estimate pattern completion (Hou et al., 2019; James et al., 2020), other investigators have employed other kinds of paradigms that estimate pattern completion using cue completeness manipulations. For instance, Vieweg and colleagues (2015) showed that relative to young adults, older adults were less able to pattern complete learned scenes based on partial cues (e.g., fragmented scenes), especially when the cues were increasingly sparse (Vieweg et al., 2015). Similarly, on a face-name associative memory, older adults were less able to retrieve the names when cued by fragmented face images, relative to young adults (Nyberg et al., 2020). The same age effect was found on a task that required the retrieval of target locations in a virtual environment with a manipulation of distal cue removal (Paleja & Spaniol, 2013). The interpretation of pattern completion in ageing using behavioural measures would benefit from a systematic examination of whether different paradigms yield high behavioural co-variance. This effort would be fruitful in bridging pattern completion behavioural indices of event retrieval dependency versus retrieval success based on cue completeness.

Specificity in memory declines with ageing

Characteristics of episodic memory declines in ageing are multifaceted because the processes that support episodic memory capacities are componential (Ngo et al., 2019). Studies have reported that normal ageing is accompanied by decrements in memory precision (Korkki et al., 2020), specificity (Greene & Naveh-Benjamin, 2020), pattern separation (Stark et al., 2013), and relational binding (Naveh-Benjamin, 2000). Our findings highlight that despite being conceptually related, the tendency of remembering a past event in its totality may not show the same age patterns as remembering individual links of an event with ageing. Thus, a delineation of factors that contribute to episodic memory impairment in ageing requires multiple assays that target specific episodic memory processes. Such an approach promotes a deeper understanding of common factors of broad mnemonic declines, and specificity in processes that are vulnerable to ageing.

Limitations

Two limitations of this work should be addressed in future studies. First, our sample size was relatively small. Our posthoc power analyses showed a power of .64 for detecting the age difference in dependency between young and older adults, and a power of .85 for detecting the effect of age on dependency among older adults in the regression model. Second, the current multi-event paradigm did not approximate memory for individual items. Therefore, we cannot rule out the possibility that age-related declines in item memory could have attributed to the age effects on pairwise relational binding performance.

Conclusions

Although age-related declines in episodic memory have been tightly linked to binding deficits with ageing (Naveh-Benjamin, 2000), older adults' memories for complex events do not appear to be stored as disjointed pairs of associations, but rather as integrated units. The current work provides support for the value of the dependency measure in addition to examining pairwise relational binding when characterising the multifaceted profiles episodic memory in senescence. Such an approach offers intriguing insights into how different facets of episodic memory may maintain and decline from young adulthood to ageing.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

This experiment was not formally pre-registered. Experimental materials (https://osf.io/arphg/) and deidentified second-level data (https://osf.io/k97ur/) have been made publicly available through the Open Science Framework.

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