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Associative recognition memory for identity, spatial and temporal relations in healthy aging

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ABSTRACT
The ability to generate associative representations and to retrieve them from long-term episodic memory generally declines in healthy aging. However, it is unclear whether healthy aging has differential effects on associative memory for identity, spatial configuration, and temporal order relationships. In the current study, we assessed how healthy aging impacts on associative memory for identity, spatial, or temporal relationships between pairs of visual objects via discrimination of intact and rearranged pairs. Accuracy and response time performance of healthy older adults (aged 65–80) were compared with young adults (ages 19–30). Age-related declines in associative memory were observed equally for all types of associations, but these declines differed by associative status: aging most strongly affected ability to discriminate rearranged pairs. These results suggest that associative memory for identity, spatial, and temporal relationships are equally affected by healthy aging, and may all depend on a shared set of basic associative mechanisms.

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In the course of our lives, we may experience many changes in our cognitive abilities, notably including a decline in aspects of episodic memory during late adulthood (e.g., De Brigard et al., 2020; Fraundorf et al., 2019; Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008). Episodic memory involves the remembrance of personally experienced items or events associated with a specific spatiotemporal context (Tulving, 1983). Numerous studies have tried to understand the nature of age-related deficits in episodic memory (e.g., Benjamin, 2016; Bridger et al., 2017; Old & Naveh-Benjamin, 2008; Ratcliff et al., 2015). According to the associative deficit hypothesis, older adults can remember individual components of an episode relatively well, but often fail to encode or retrieve the associations among these components (Naveh-Benjamin, 2000; Smyth & Naveh-Benjamin, 2016). Older adults may have a fundamental deficit in integrating the separate components of an episode into a stable memorandum (Greene & Naveh-Benjamin, 2020; Lyle et al., 2006; Mitchell et al., 2000; Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008b; Ryan et al., 2007). In contrast, it is often reported that item memory is relatively spared in old age (Cheke, 2016; Fabiani & Friedman, 1997; Old & Naveh-Benjamin, 2008b; but see the meta-analysis of Old & Naveh-Benjamin, 2008, and more recently: Bridger et al., 2017; Diamond et al., 2018).

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Furthermore, it remains to be determined which associative aspects of episodic memory are more affected by age than others, and under which circumstances. Episodes generally incorporate multiple elements such as people and things, involved in actions over time in particular locations. It is important to establish whether healthy aging equally impacts on memory for all elements of an experience, or whether memory for some aspects of experience is more age-vulnerable than for others.

Examination of memory for temporal order, spatial location, and inter-item (identity) associations in older age has yielded inconsistent results. While some authors show spared temporal and spatial memory (Diamond et al., 2018) or impaired temporal but spared spatial memory (Cheke, 2016), other studies individually report temporal associative memory impairment (Cabeza et al., 2000: Fabiani & Friedman, 1997; Kausler et al., 1990; Parkin et al., 1995; Vakil et al., 1997), spatial associative memory impairment (Lemay & Proteau, 2003; Kessels et al., 2005), or both temporal and spatial associative memory impairment (Kessels et al., 2007; Vakil & Tweedy, 1994). A notable example is the study of Rajah et al. (2010), who report parallel differences between older and younger adults in a direct test of both explicit spatial and temporal retrieval and in accompanying prefrontal activations, with age-related activity in left dorsolateral PFC that correlated with spatial context retrieval accuracy, and right anterior PFC activity correlated with temporal context retrieval accuracy. Furthermore, many studies indicate impaired inter-item memory in older adults (Badham & Maylor, 2013; Bridger et al., 2017; De Brigard et al., 2020; Giovanello & Schacter, 2012; Greene & Naveh-Benjamin, 2020).

Possible explanations for these discrepancies are reviewed by Old and Naveh-Benjamin (2008). That meta-analysis found that the emergence of age-related associative deficits is dependent on the use of particular testing methods and binding types. For example, older adults' associative deficit was found when tests involved recognition but not recall, and was more pronounced under intentional encoding instructions rather than incidental learning conditions. These results are in accord with a large body of subsequent research suggesting that age differences in associative memory are sensitive to encoding and/or retrieval demands, (Ahmad et al., 2015; Badham & Maylor, 2013; Bridger et al., 2017; De Brigard et al., 2020; Castel, 2005; Giovanello & Schacter, 2012; Naveh-Benjamin et al., 2005; Zheng et al., 2015). In addition, binding type effects on age-related associative deficit seemed to be relatively small in studies involving memory for source and context, moderate in those involving memory for item pairs and modality, and large in studies involving memory for temporal order and location (Old & Naveh-Benjamin, 2008).

The context of changes in behavioral indices of memory for diverse associative relations in aging is the brain substrates of such associative memory functions in general (Ekstrom et al., 2011). Several studies have examined brain mechanisms (Ekstrom & Bookheimer, 2007; Staresina & Davachi, 2009) and cognitive processes (Tolentino et al., 2012; Van Asselen et al., 2006) supporting separable episodic memory representations of temporal order, spatial location, and item identity associations. Many such studies have highlighted the roles of the hippocampus and the prefrontal cortex, and the interactions between them (see Eichenbaum, 2017, for a review). Human and non-human models have identified the key role of the hippocampus in remembering events in the spatial and temporal context in which they occurred (e.g., Butterly et al., 2012; Eichenbaum, 2004, 2017). In addition, hippocampal–medial prefrontal cortex interactions were also found to be crucial in remembering where and when stimuli were previously experienced (Barker et al., 2017; Chao et al., 2016). Interestingly, a recent study (Chao et al., 2020) suggested that a specific circuit connecting the medial prefrontal cortex, lateral entorhinal cortex, and hippocampus encodes the information for an event's content, place, and time of occurrence into one memory, and can be distinguished from the neuronal component memory systems for processing the individual items of information about the object, time and place. Importantly, and highly relevant to the current work, Barker et al. (2017) investigated two hippocampal–medial prefrontal cortex pathways in rodents and reported that deactivation of one pathway selectively disrupted temporal order judgments whereas deactivation of a second pathway disrupted spatial memory. Hence, episodic memory deficits in humans might be attributed to impairments associated with healthy aging of prefrontal cortex areas as well as to the weakening of bidirectional connections between these areas and the medial temporal lobes structures, including the hippocampus (Campbell et al., 2012; Dennis et al., 2008; Silva et al., 2020). These studies provide a context for the understanding of changes in types of associative memory in healthy aging in light of what has been found regarding functional changes in those areas across the lifespan.

While the abovementioned studies have examined the effects of aging on memory for spatial or temporal information associated with experienced items, they have not addressed the question of the relative impact of aging on associative spatial or temporal relations between items, relative to associative identity relations. Reconstructing events which we have experienced – remembering under ecological conditions – requires remembering the relative placement of people or objects, and their relative precedence of appearance or occurrence, within a larger context. So, for example, we may need to remember which two people entered a meeting together (associative identity relations), which of those two sat down first (associative temporal relations), and who sat to the left of the other (associative spatial relations). Previous studies have theorized that these three types of associations are functionally dissociable (e.g., Ekstrom et al., 2011; Konkel et al., 2008; Lee et al., 2016) and may engage separable cognitive processes (Tolentino et al., 2012; Van Asselen et al., 2006), and different brain networks (Ekstrom & Bookheimer, 2007; Staresina & Davachi, 2009).

Therefore, in the present work, we aim to investigate whether one or more of those types of associations is more susceptible to age-related memory changes. To enable direct comparisons between these conditions, we have developed an "episodic minimal pairs" paradigm, involving discrimination between probes, which are either identical to encoded stimulus pairs or differ from them in only one of the three relational dimensions: item identity, spatial, or temporal order location. Using this paradigm, we examined the extent to which each element is affected by healthy aging. We predicted that while age-related differences would be found for all three associative memory components, age-related differences in performance would be greater for temporal and spatial relations compared to identity relations. This hypothesis was based on evidence that temporal and spatial association are more frequently used as contextual elements and based on frontal lobe functions, hence more vulnerable to age effects than identity association (Hayes et al., 2004; Rajah et al., 2010).

Methods

Participants

The study was conducted with the participation of 40 self-reportedly healthy young adults (28 women and 12 men), ages 19–30 (*M* = 23.5, *SD* = 1.8) and 44 self-reportedly healthy older adults (27 women and 17 men), ages 65–80 (*M* = 69.6, *SD* = 3.9), all with normal or adjusted-to-normal vision. Two participants of the older adults group failed to complete the assignment, one through misunderstanding the instructions and one deciding to withdraw before the experiment was completed. The young adults were undergraduate students at the Interdisciplinary Center Herzliya, who volunteered in return for academic requirement credit or payment. The older adults were independent community-dwelling individuals, recruited at public lectures, and via internet advertisement, who volunteered in return for travel expense reimbursement. Candidates reporting psychiatric or neurological disorders or current use of psychotropic medication were excluded from participation. To rule out neurodegenerative disorders, older adult participants were screened with a Hebrew version of the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), participants who scored less than the standard cutoff of 26 were excluded from participation. All participants provided written informed consent for a protocol approved by the human subjects research ethics committee of the Interdisciplinary Center Herzliya.

Materials

The experimental stimuli comprised a set of 96 common object pictures (examples are seen in Figure 1) from the Bank of Standardized Stimuli (BOSS) (Brodeur et al., 2014). All images employed were rated highly nameable by an independent panel of participants who did not take part in the main study. Each image was resized to 200 × 200 pixels and edited to have an all-white background. Stimuli were assigned to three sets of 32 pairs of semantically unrelated pictures. These three sets were assigned to identity, spatial, and temporal task conditions counterbalanced across participants. Additional pictures were added and paired as required for examples and practice, as described below.

Procedures

Task structure

In order to assess the possible differential effects of healthy aging on associative recognition of identity, spatial, and temporal relations, we strove to construct a paradigm in which the tasks assessing those forms of associative memory would be as closely matched as possible. The basic task in all cases was to intentionally form associative memories for a set of several pairs of object pictures using a deep encoding task, and thereafter to make confidence-scaled recognition judgments on a set of probe pairs, each of which was either identical to a studied pair or rearranged in the fashion relevant to the type of memory being assessed.

At the beginning of each task participants were informed that they were about to see on the screen a pair of photos, memory of which they would later be tested. There were told that each photo would appear twice, and that each time a different photo would be

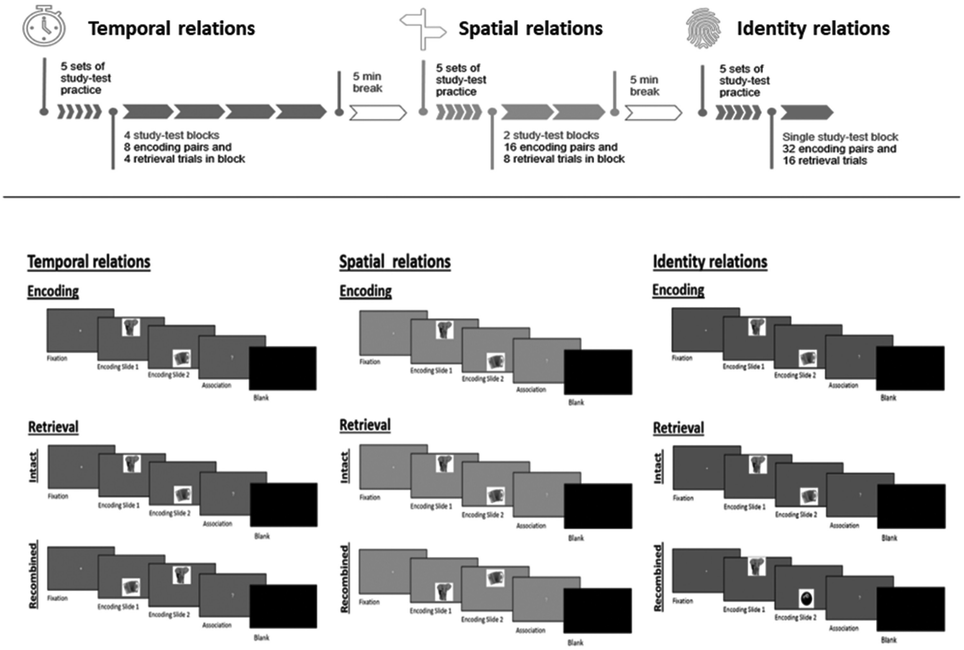

Figure 1. Experimental design. Participants performed three minimal pair associative recognition tasks for temporal, spatial and identity relations. In each task, participants learned to associate two consecutively presented object pictures and were instructed to focus only on the task-relevant dimension (order, location, or identity). Every picture appears twice in each encoding block, each time paired with a different picture.

presented with it. At encoding, in each trial, one picture was presented above or below fixation for a certain exposure time (detailed in Table 1), followed immediately by a second picture in the opposite location (as depicted in Figure 1). For the deep encoding procedure, participants were instructed to make an association for each pair that related to the aspect of the associative relationship (identity, spatial, or temporal) being tested in that part of the experiment. They were asked to make the association as vivid as possible in order to remember the pictures' relationship. So, for example, in the temporal condition, if the participants saw a picture of a candle and then a shoe, they were to think about themselves first lighting a candle and then proceeding to use the light to look for their shoe. The experimenter demonstrated the first practice trial, after which the participant performed four rounds of practice aloud while receiving feedback on the associations. After the practice phase, all associations were made silently. Importantly, in each

Table 1. Stimulus display time (ms) for the Identity, Spatial, and Temporal relations in each condition.

Group	Associative type	Fixation	Encoding	Association	Retrieval	Blank
Young Adult	Identity relations	500 ms	1750 ms	1750 ms	1500 ms	250 ms
	Spatial relations	500 ms	2000 ms	3000 ms	1500 ms	500 ms
	Temporal relations	500 ms	2000 ms	4000 ms	1500 ms	500 ms
Older Adult	Identity relations	500 ms	2750 ms	2750 ms	2500 ms	250 ms
	Spatial relations	500 ms	3000 ms	4000 ms	2500 ms	500 ms
	Temporal relations	500 ms	3000 ms	5000 ms	2500 ms	500 ms

encoding block, each constituent picture was used twice, to construct two associative pairs, with a different pair-associate in each of the two pairs. A single aspect of the identity, spatial, or temporal characteristics of each picture differed between the two pairs in which it appeared. For example, when paired with a car, a picture of a dog might appear first and above fixation, while in its second appearance, paired with a banana, it might appear second and above fixation (in blocks testing temporal associative memory), or first and below fixation (in blocks testing spatial associative memory), or it might appear in the same place and order (in blocks testing identity associative memory). The effect of this double-pairing was to require encoding and retrieval of spatio-temporal and identity information that was *specific to each associative pairing*, such that neither single-item location, nor single-item temporal order information, nor memory for a single identity association would enable successful subsequent retrieval.

A test block immediately followed each encoding block. At test, each probe pair was presented in the same format as at encoding (i.e., serial presentation of pictures in different locations on the screen), and was either identical to a studied pair in all dimensions, or differed in a single dimension (identity, spatial, or temporal), in accordance with the type of memory being assessed in the relevant block. Thus, a rearranged pair in the trials assessing associative memory for spatial relations would display the same two pictures as at encoding, each appearing in the same serial order position as at encoding, but with the locations of the pictures switched. A rearranged pair in the trials assessing associative memory for temporal relations would display the same two pictures as in encoding, each appearing in the same spatial position as at encoding, but with the order of appearance of the pictures switched. A rearranged pair in the trials assessing associative identity memory would display two pictures that were not paired at encoding, but with each appearing in the same linked spatial position and temporal order as it did in an encoding trial. Importantly, at test, each item was only presented once, in one of the two configurations used at the study. Thus, none of the associative recognition judgments could be informed by decisions made on earlier trials.

Task procedure

After providing informed consent, participants received instructions explaining the procedures to be followed during the study and test stages of the experiment. They were further instructed on how to form an effective association between stimuli, and how to answer using the confidence rating scale in the test stage. They then executed five sets of study-test practice trials for the first memory-type test (the temporal condition, focusing on presentation order), with the first trial demonstrated by the experimenter, and the other four done by the participant audibly, to practice forming associations. Feedback and further guidance were provided by the experimenter. In the main part of the experiment, participants formed study-trial pair associations silently. Subsequently, before the presentation of the first study block in each following part of the experiment, participants were explicitly instructed to only focus on the study on the relevant dimension of that task condition: either the relative screen locations or the identity of the pair members. Furthermore, since each relationship requires a different kind of effective association, as illustrated above, practice informing relevant kinds of associations to encode the task-critical factor properly was provided before each task.

Within each task-section of the experiment, each block began with study trials. At the beginning of each trial, participants viewed a fixation cross in the middle of the screen for 500 ms. As noted above, this was followed by one of the object pictures of the pair, presented either on the top or bottom of the screen, then the second corresponding picture on the opposite part (bottom or top) of the screen, followed by a question mark to indicate that the participant should now make an appropriate association, and finally a blank screen inter-trial interval. To help remind participants which task they should be doing, the object pairs were presented against a color background specific to the condition (temporal – dark blue, spatial – dark green, identity – dark red).

Each encoding block was immediately followed by a test block. As noted, the test trials of each block presented each stimulus only once (and therefore there are only half as many test trials as encoding pairs). Half of the test trials were identical to encoding, and half were rearranged in a single dimension. After the second stimulus of each test pair appeared, participants ranked by a keypress from one to six whether the pair presented was rearranged (1 – definitely rearranged, 2 – fairly sure rearranged, 3 – guess rearranged) or intact (4 – guess intact, 5 – fairly sure intact, 6 – definitely intact). Test pair order was randomized within the block across participants. A 5-minute rest break was given after each task.

Pilot testing indicated that all other things being equal, the temporal task was the most challenging, followed by the spatial task, with the identity condition task being easiest. In order to determine whether aging (or other factors such as brain damage, currently being assessed in parallel studies) differentially affect these memory types, and to identify brain substrates and time courses of processes required for these types of memory, it is important that task difficulty be comparable across task conditions. Therefore, we engaged in extensive iterative pilot testing with the participation of over 100 young adult volunteers who did not participate in the main experiment, in an attempt to balance the difficulty of the tasks using various structural adjustments. The upshot of that adjustment process was that we designed the experiment such that the three experimental tasks were executed in a fixed order, with the easiest task given at the end, when exhaustion and interference are greatest: the temporal task first, then the spatial task, then the identity task. Additionally, each of the tasks employed different numbers of blocks, with different numbers of stimulus pairs in each block. Consequently, the temporal order task had 8 encoding pairs and 4 retrieval trials in each of 4 blocks, the spatial relations task had 16 encoding pairs and 8 retrieval trials in each of 2 blocks, and the associative identity task used a single block of 32 encoding and 16 retrieval trials. In addition, each of the tasks employed different numbers of encoding repetitions. In the identity task, each pair was presented once, and in the temporal and spatial tasks, each pair was presented for encoding twice, in two consecutive but randomly varied sequences. Finally, as noted above, the amount of time given for stimulus display and association formation also differed between conditions (Table 1). We note that in practice there continued to be some differences in task difficulty in the young adult group. Seemingly, these differences would have been even more extreme had we not implemented the differential encoding procedures.

To compensate for the generalized slowing in old age (for a review, see Salthouse, 1996a), the older adult participants were given more time (+1000 ms) for encoding, association, and retrieval than younger adults (see Table 1). That amount of additional time was assumed to provide enough opportunity to compensate for any generalized slowing required in the ancillary cognitive processing (e.g., attention, response selection, motor processes) necessary for each of the task (Salthouse, 1996b). That additional time was added in such a way as to maintain the relative relationship between the tasks as designed for the younger adults. We note that we chose to display stimuli above and below fixation, rather than to the right and left of that point, for the benefit of comparison with parallel studies being conducted with the participation of stroke patients who might have hemispatial visual neglect. The entire experiment was presented on a computer running E-Prime 2.0 experimental software (Psychology Software Tools, Pittsburgh, PA, USA).

Dependent measures and statistical analysis

We collected data enabling calculation of mean accuracy, confidence ratings, and response times across conditions and groups. Regarding RTs, in prior research (Zivony et al., 2020), we have considered the question of how age differences in cognitive functions might be assessed chronometrically, given the overall general slowing of cognitive processes in older age (Faust et al., 1999; Salthouse, 1996a). Such overall slowing, and the greater intersubject variance it involves, makes it difficult to assess interactions between age and memory conditions, as the same absolute differences have very different significance in older adults and younger adults. That imbalance also makes it challenging to detect if speed-accuracy tradeoffs are strategically pursued differently across age groups. Accordingly, in RT analyses we applied Z-transformation, in which a participant's RT in a specific condition is expressed in terms of its standard deviation from their overall RT. This method was endorsed by Faust et al. (1999), and is commonly used in the study of age differences in attention (e.g., Olk & Kingstone, 2015; Williams et al., 2016). Although we consider examination of untransformed RTs not to be the optimal approach to characterizing age effects, we additionally report those data in Table 2.

Differences in discrimination accuracy, confidence, and RTs between groups, tasks, and associative status were analyzed in repeated measures ANOVA using the SPSS 25 statistics program (IBM Corp., Armonk, NY, USA). Bonferroni-corrected pairwise post hoc comparisons were conducted for significant interactions and main effects.

Results

We began our analyses with an examination of the manipulation employed to equate the difficulty of identity, spatial, and temporal associative memory tasks in the young adult group (serving as the baseline condition for examining the effects of healthy aging), as detailed in the Methods. We did this by comparing the average accuracy rates across the three task conditions (Identity 83.6%, Spatial 79.8%, and Temporal 80.0%, respectively). These accuracy rates did not differ significantly, $F(2, 78) = 1.17$, $p = .32$, η_p $2 = .03$. This indicates that the structural manipulation designed to reduce inter-task difficulty differences was successful.

Table 2. Analysis of variance results for accuracy and response time.

		F	df	*p*	*η2*
(1) Accuracy	Type	2.21	(2,164)	.11	.03
	Status	88.15	(1,82)	< .001***	.52
	Age	21.64	(1,82)	< .001***	.21
	Type x Age	.34	(2,164)	.71	.00
	Status x Age	10.38	(1,82)	.002**	.11
	Type x Status	3.86	(2,164)	.02*	.04
	Type x Status x Age	3.02	(2,164)	.32	.01
(1) Response Time	Type	38.88	(1.5,114.9)	< .001***	.33
	Status	67.96	(1,77)	< .001***	.47
	Age	4.75	(1,77)	< .03*	.06
	Type x Age	2.64	(1.5,114.9)	.09	.03
	Status x Age	.08	(1,77)	.78	.00
	Type x Status	1.42	(1.6,121)	.24	.02
	Type x Status x Age	.92	(1.6,121)	.40	.01
(1) Adjusted Response Time (zRT)	Type	74.43	(2,154)	< .001***	.49
	Status	143.36	(1,77)	< .001***	.65
	Age	8.41	(1,77)	< .01**	.10
	Type x Age	2.12	(2,154)	.12	.03
	Status x Age	.14	(1,77)	.71	.00
	Type x Status	.24	(1.9,143)	.77	.00
	Type x Status x Age	1.48	(1.9,143)	.23	.02

(1) Three-way repeated-measures ANOVA of percent correct responses, with factors of associative type (identity, spatial, temporal), associative status (intact, rearranged), and age group. (2) Three-way repeated-measures ANOVA of responses times, with factors of associative type, associative status, and age group. (3) Three-way repeated-measures ANOVA of adjusted responses times, with factors of associative type, associative status, and age group.

Discrimination accuracy

For an initial examination of accuracy rates in the various test types across age groups, we calculated the *d′* measure of discrimination for each participant in each condition, using the hit rates (for certain and fairly sure responses, without guess responses) for intact pairs and (1 – hit rate) for the rearranged pairs representing false alarms, and entered those values into a repeated measures ANOVA, with a within-subject factor of associative type (identity, spatial, temporal) and a between-subjects factor of group (older vs. younger adults). This analysis revealed a main effect of associative type, $F(2,164) = 10.89$, $p < .001$, partial $\eta^2 = 0.12$, and a main effect of age group, $F(1,82) = 30.04$, $p < .001$, partial $\eta^2 = 0.27$. The interaction between these effects was not significant, $F(2,164) = .05$, $p = .95$, partial $\eta^2 = .001$. Bonferroni-corrected pairwise comparisons revealed that across age groups, discrimination of identity relations was better than discrimination of spatial and temporal relations, but the discrimination of spatial and temporal relations did not differ. We examined response bias by entering values for C in a repeated measures ANOVA with a within-subject factor of associative type (identity, spatial, temporal) and a between-subjects factor of group (older vs. younger adults). This analysis revealed a main effect of associative type, $F(2,164) = 9.03$, $p < .001$, partial $\eta^2 = 0.10$, and a main effect of age group, $F(1,82) = 7.77$, $p < .01$, partial $\eta^2 = 0.09$. The interaction between these effects was not significant, $F(2,164) = .1$, $p = .47$, partial $\eta^2 = 0.01$. Thus, age effects on associative memory did not differ for identity, spatial and temporal relations. We note that the same pattern of effects was found when analyzing A′ and DA measures of discrimination and the B′′D measure of response bias (Donaldson, 1992; Verde et al., 2006).

While this type of analysis is standardly used to examine recognition memory performance, the signal detection approach underlying *d′* measures may not be the most appropriate way to examine data of this study. That is because performance on associative recognition tests is functionally and neuroanatomically dissociable from patterns characterizing item recognition tests (Yonelinas et al., 2010). To examine whether that was the case for the current paradigm, we used the distribution of correct endorsement of intact and rearranged pairs (hits in the *d′* calculation) and mistakes regarding the associative status (false alarms in the *d′* calculation) across the six levels of confidence available to participants to plot ROC curves for each associative type, for older and younger adults (Figure 2). Examining these plots reveals a very high X intercept for the most stringent confidence level, which is indictive of a strong recollective component in the retrieval process (Yonelinas et al., 2010; Yonelinas & Parks, 2007). This accords with the notion that associative recognition generally involves recollection, except when unitization enables use of associative familiarity (Quamme et al., 2007; Tibon et al., 2014; Yonelinas, 1999). Recollection is important not only for the endorsement of intact pairs. "Recollect-to-reject" strategies (Mayes et al., 2007) may be used to identify a rearranged pair as such. Differences between associative types in accurate discrimination of intact and rearranged pairs may have been based on differences in the recollective endorsement of intact pairs, the identification of rearranged pairs as being associatively novel, or recollecting that the items in the rearranged probe had been seen in a different configuration. We therefore proceeded to separately examine performance for intact and rearranged pairs across associative types and age groups.

We conducted a repeated-measures ANOVA on the dependent measure of percent certain and fairly sure responses (i.e., excluding guess responses), with a between-subjects factor of group (older vs. younger adults) and within-subject factors of associative type (identity, spatial, temporal) and associative status (intact, rearranged). These data are portrayed in Figure 3.

This analysis (Table 2) revealed main effects of associative status and age group, but no main effect of associative type. The ANOVA did not yield a three-way interaction between associative type, status, and age group, nor a two-way interaction between associative type and age group. In other words, age effects were equivalent in identity, spatial and temporal association. However, the interaction between associative status and age group

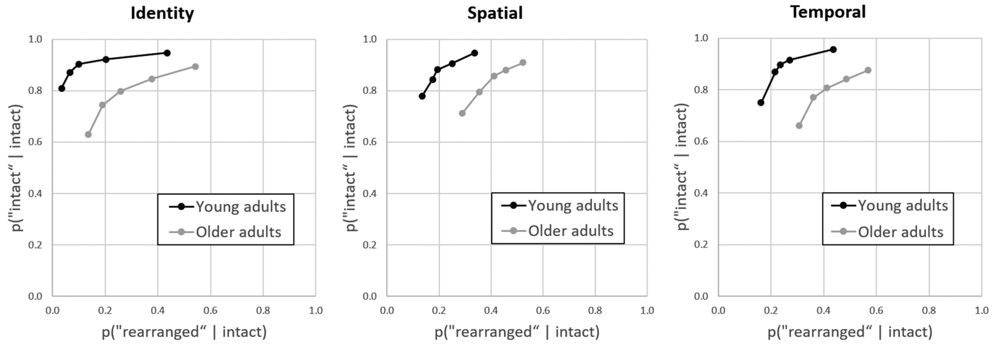

Figure 2. Receiver operating characteristic (ROC) curves for young adults (dark color) and older adults (light color) for each associative type.

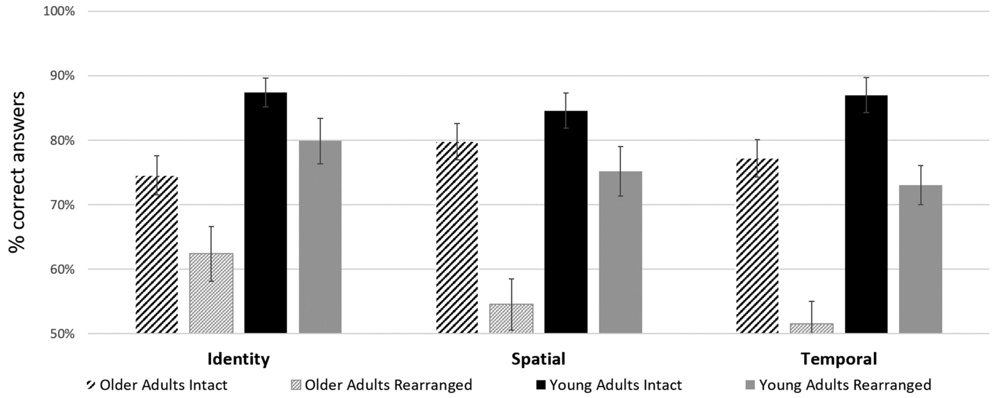

Figure 3. Accuracy percentage for intact (dark color) and recombined (light color) pairs in each associative type for young adults (full color) and older adults (striped). Error bars indicate SEM.

was significant, indicating that older adults had relatively greater difficulty in correctly identifying rearranged pairs than intact pairs, across all three associative types. We note that the same pattern of interactions was found when including “guess intact” and “guess rearranged” responses to the analyses. Thus, the current results indicate that associative relations of all kinds – for identity, spatial, or temporal relations – are equally challenged in healthy aging. Furthermore, while identifying pairs as rearranged is more challenging than endorsing intact pairs for all ages (young adults: paired sample $t(39) = 4.73$, $p < 0.001$; older adults: paired sample $t(43) = 8.44$, $p < 0.001$), older adults are relatively more challenged in identifying rearranged pairs as such.

Response time

We conducted a three-way repeated-measures ANOVA, with the participants’ Z-score response time (zRT) for correct responses as the dependent variable, associative type (identity, spatial, temporal) and associative status (intact, rearranged) as within-subjects factors, and age group (older and younger adults) as the between-subject factor. Five older participants were removed from this analysis because they made no correct responses in one or more conditions. Those data are presented in Figure 4.

Analysis of those data (Table 2) revealed main effects of associative type, associative status and age group, but no significant interactions between these effects. We note that the same pattern of effects was found when excluding “guess intact” and “guess rearranged” responses from the analyses. For raw RTs, analyses indicated main effects of associative type, associative status, and age, with a marginally significant ($p = .09$) interaction between associative type and age.

Discussion

In the current study, we examined whether healthy aging has differential effects on associative memory for identity, spatial, and temporal relations. We found that age-related declines in accuracy were observed for all types of relations equally, but that

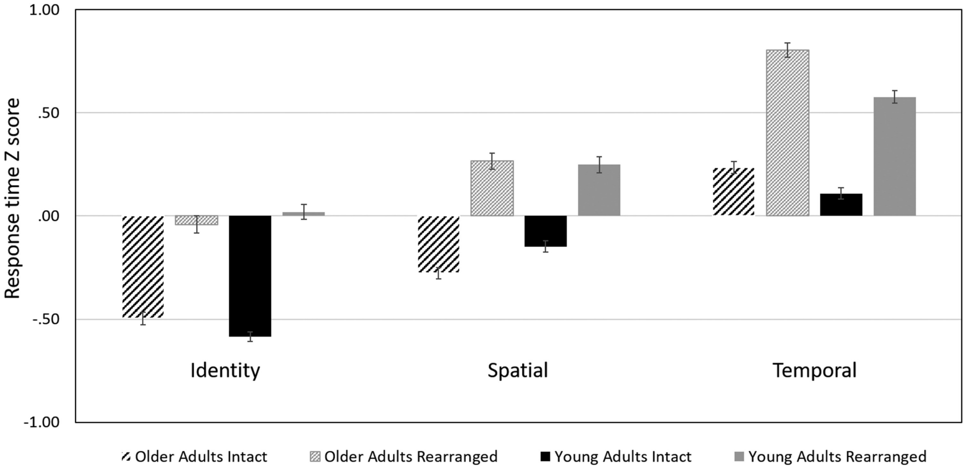

Figure 4. Z-score response times (zRT) for intact (dark color) and recombined (light color) pairs at each associative type for young adults (full color) and older adults (striped). Error bars indicate SEM. As indicated in Table 3, main effects of associative type, status, and age were significant, all *ps* < 0.01, while no interactions were significant.

Table 3. *D′* (discrimination) and C (bias) means and standard deviations for the three associative types, for younger and older adults.

	Identity				Space				Time			
	d′		C		*d′*		C		*d′*		C	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Young adults	2.44	*0.67*	0.02	*0.28*	2.06	*1.0*	0.14	*0.3*	1.96	*0.84*	0.23	*0.35*
Older adults	1.6	*0.85*	0.11	*0.48*	1.29	*0.91*	0.36	*0.4*	1.53	*0.94*	0.34	*0.36*

these declines differed by the status of association. Specifically, the ability to identify rearranged pairs was impaired in older adults in comparison to young adults more than was the ability to identify intact pairs. Our hypothesis that spatial and temporal associative memory would be more impaired than identity associative memory was not borne out by these results. Instead, these findings accord with the Associative Deficit Hypothesis (Naveh-Benjamin, 2000), which posits that a major contributor to older adults' deficiencies in episodic memory is their relative inability to form and retrieve links among individual bits of information; in principle, that approach would consider memory for all types of associative relations to be equally challenging.

Associative remembering requires both endorsement of intact pairs and rejection of rearranged pairs. It might be intuitively assumed that novelty detection and familiarity – for both items and for associations – are two sides of the same coin. However, there is evidence that novelty and familiarity processes are fundamentally different and involve distinct neural networks (Daselaar et al., 2006; Habib et al., 2003; Kafkas & Montaldi, 2014). This may especially be true of judgment and reporting processes that comprise the strategic components of the act of remembering. Indeed, in the current data, the identification of the associative novelty of rearranged pairs is challenging across all tasks and ages. As impaired strategic retrieval plays an important role in age-related associative deficits (Cohn et al., 2008), rejecting recombined associative pairs may be harder in healthy aging due to the declines in associative novelty detection and evaluation mechanisms.

We also wish to suggest that in associative memory for complex spatio-temporal and identity relations, and for cases in which discrimination is required between multiple instances in which a stimulus has been paired with others, recollection plays the major role. This seems to be supported by the ROC analysis, which revealed the preponderance of highest confidence judgments in correct identification of intact pairs, a pattern associated with a strong contribution of recollection to recognition judgments (Yonelinas et al., 2010; Yonelinas & Parks, 2007). Older adults' particular difficulty in identifying rearranged pairs as such might be attributable to failure in "recollect-to-reject" processes (Mayes et al., 2007). Seemingly, younger adults are better able to endorse the rearranged pairs as such as they can better recollect the configuration in which the stimuli in question were actually experienced at encoding. Indeed, in other studies of associative memory in old age, it has been demonstrated that when stimulus pairs may be unitized, enabling the use of associative familiarity in recognition judgments, aging has less detrimental effects (Bridger et al., 2017; Kamp et al., 2018).

It is instructive to compare the results of the current investigation of healthy aging effects with a study of the effects of hippocampal lesions on memory for spatial, temporal, and associative relations (Konkel et al., 2008). Konkel and colleagues report that hippocampal lesions lead to equivalent impairment of spatial, temporal, and identity-associative memory over short delays. This is in contrast to the developmental study of Lee et al. (2016), which employed a similar paradigm as Konkel and colleagues. Lee and colleagues report found age-related accuracy improvements in childhood for all associative relation types, which differed by type of relation. Children did not exhibit young adult accuracy levels for item-item binding, while item-space and item-time memory was similar to those young adults. Interestingly, memory for item-space relations reached adult levels of performance earlier than item-time relations. In contrast to our results, these discrepancies in children may imply distinct early developmental trajectories for these types of relations.

One reservation about the current study is that it employed associative recognition probes, but the literature indicates that age differences in free recall are greater than item recognition (Danckert & Craik, 2013; Rhodes et al., 2019). Therefore, using testing techniques that require associative reconstruction (more akin to cued recall tests) might yield different patterns of age effects.

In summary, we have found that healthy aging equally affects associative memory for spatial, temporal, and identity relationships. While it has been established that episodic memory decline substantially during aging, especially associative aspects of such memory (Naveh-Benjamin, 2000), this study demonstrates that such aging effects are similar across memory for identity, spatial, and temporal relations, and that aging presents specific challenges in judging novel associative configurations of all three types as not having been experienced. These findings provide a more nuanced perspective on episodic binding operations, and elucidate the manifold nature of aspects of episodic memory that may undergo changes across the lifespan.

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Disclosure statement

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