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Age effects on associative memory for novel picture pairings

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ABSTRACT

Normal aging is usually accompanied by greater memory decline for associations than for single items. Though associative memory is generally supported by recollection, it has been suggested that familiarity can also contribute to associative memory when stimuli can be unitized and encoded as a single entity. Given that familiarity remains intact during healthy aging, this may be one route to reducing age-related associative deficits. The current study investigated age-related differences in associative memory under conditions that were expected to differentially promote unitization, in this case by manipulating the spatial arrangement of two semantically unrelated objects positioned relative to each other in either spatially implausible or plausible orientations. Event-related potential (ERP) correlates of item and associative memory were recorded whilst younger and older adults were required to discriminate between old, recombined and new pairs of objects. These ERP correlates of item and associative memory did not vary with plausibility, whereas behavioral measures revealed that both associative and item memory were greater for spatially plausible than implausible pair arrangements. Contrary to predictions, older adults were less able to take advantage of this memory benefit than younger participants. Potential reasons for this are considered, and these are informed by those lines of evidence which indicate older participants were less sensitive to the bottom-up spatial manipulation employed here. It is recommended that future strategies for redressing age-related associative deficits should take account of the aging brain's increasing reliance on pre-existing semantic associations.

1. Introduction

Converging evidence from behavioral and neuropsychological studies indicates the existence of age-related episodic memory impairment with a particular decline in memory for associations (Chalfonte and Johnson, 1996; Duarte et al., 2008; Naveh-Benjamin et al., 2003; Zheng et al., 2015a). Whilst there are some instances in which older adults have been shown to automatically bind irrelevant associations (Campbell et al., 2010), age-related memory decrements in traditional associative recognition paradigms are thought to arise because of deficiencies in strategic processing during both encoding and recall. It has been shown, for example, that age differences in memory are considerably reduced under incidental learning conditions when such processes are less likely to be engaged during encoding (Naveh-Benjamin et al., 2009). The associative deficit has been related to deficits in the functionality of a relational binding mechanism that integrates separate and relevant information into a coherent memory representation (Cohn et al., 2008; Shing et al., 2010). This deficit has been demonstrated for a large variety of associations relating to multiple events, and to events and contextual information (see Old and Naveh-Benjamin, 2008, for a *meta*-analysis), while memory for single item information remains relatively intact in old age (Chalfonte and Johnson, 1996; Naveh-Benjamin et al., 2003).

Since older adults have difficulty internally creating novel associations between information units and are less likely to self-initiate effective encoding/retrieval processes (Naveh-Benjamin et al., 2007, 2009; Shing et al., 2010), they have to rely more on external guidance during encoding and retrieval to reduce their memory decrement. Several lines of evidence support this idea: Badham et al. (2012) found that older adults' associative memory

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deficit was remarkably reduced when word pairs contained integrative (“horse–doctor” – unassociated words linked together to form a coherent phrase) or semantic (“article–book”) relations. Similarly Naveh-Benjamin et al. (2005) found the associative memory deficit in old adults to be reduced for semantically related word pairs compared to unrelated pairs. This relative improvement of associative memory in older adults was not associated with enhanced attentional costs to encode the related word pairs. Smaller age differences in associative memory for semantically related than unrelated word pairs have recently also been reported by Zheng et al. (2015a) and by Ahmad et al. (2014). In these situations, preexisting knowledge is thought to provide schematic support both for relating the two words at study, as well as when retrieving a target word upon presentation of a cue word at test (Naveh-Benjamin et al., 2005). Thus, by the use of semantic knowledge, episodic memory can be better preserved in old age. These findings are also consistent with a recent model of differential aging across memory systems, which posits that memory in the aging brain shows a lower capability to represent unique (perceptual and episodic) details and becomes more and more entrenched and reliant on pre-existing semantic knowledge that remains available in old age (Ofen and Shing, 2013).

In many learning situations, however, schematic support by semantic knowledge or other forms of prior knowledge is not available, as for example in the case of learning new face-name associations. In these situations, to-be-learnt associations are arbitrary, which can pose a challenge to the aging brain. One way to support the learning of arbitrary associations, however, is to employ encoding conditions that encourage unitization, which occurs when two separate items are encoded as a single coherent entity in memory. Unitization might occur to a greater or lesser degree, rather than in an all-or-none fashion, and seemingly can be effected by numerous types of stimulus relationships.

Several recent studies investigating young adults have shown that explicit associative memory can benefit from both top-down and bottom-up unitization. These studies have employed a variety of stimuli and unitization manipulations, including arbitrary word pairs that can be combined to form a new conceptual unit (Bader et al., 2010, 2014; Quamme et al., 2007; Haskins et al., 2008), fragmented objects that have to be integrated to form a coherent whole (Staresina & Davachi, 2010), instructions to imagine objects presented in an associated color (Bastin et al., 2013) or morphed face photographs that support the creation of unitized presentations of face components (Jäger et al., 2006). The effects of unitization on memory performance of older adults, however, have been less clear. Some studies using unitization manipulations have shown a significant reduction of the associative memory deficit in older adults. Using receiver operating characteristics (ROCs), for example, Bastin et al. (2013) showed that unitization encoding alleviated the age-related associative memory deficit in a source memory task in which items had to be imagined in an arbitrary color. Conversely, one associative memory study for face pairs revealed larger age differences in a condition that encouraged unitization of face components as compared to a condition in which two faces were difficult to unitize (Jäger et al., 2006). This may suggest that conditions that encourage unitization may not always be effective for older adults, particularly in cases when stimulus materials engender a high amount of feature overlap between to-be-unitized stimulus components.

The present study was conducted in order to further explore conditions under which encouraging unitization might attenuate age differences in associative memory. The guiding assumption of the current approach is that unitization manipulations which place high demands on self-initiated and top-down guided processing, such as explicit encoding instructions to process two arbitrary words as a single unit, or to use a compound definition to merge two arbitrary words, are less viable solutions for alleviating age-related memory impairments because older age is inherently associated with difficulty and decline in these self-initiated processes (Craik, 1986). From this it follows that unitization manipulations which impose lower demands on self-initiated processing, because they mainly depend on bottom-up processing of perceptual or semantic regularities of the to-be-associated components, may be of higher utility in reducing the age-related associative memory deficit. In one illustrative study also driven by this assumption, we employed semantically related and unrelated pairs of object pictures in an associative recognition task (Tibon et al., 2014). Rather than manipulating encoding instructions, differences in unitizability were derived from semantic regularities associated with object co-occurrences: two semantically associated objects were presented in their canonical spatial configuration (e.g., *ice cream over a cone*; *high unitization condition)* or two unrelated objects were presented at the same positions (e.g., *an iron above flowers; low unitization condition*). Supporting the view that schematic support provided by spatial and semantic regularities between two object pictures facilitates unitization and boosts memory, memory performance (d' values) was higher in the high unitization condition (see also Gronau and Shachar, 2015).

In the present study we set out to build on this work by exploring whether bottom-up driven unitization is also an efficient encoding strategy for minimizing age-related associative deficits in situations in which the learning of new arbitrary associations cannot be supported by prior knowledge or semantic memories, as is the case in many learning contexts. As in the Tibon et al. (2014) study, pairs of pictorial stimuli were used, but the critical manipulation employed here was the plausibility of the spatial relation between two objects. The two object pictures to be memorized were semantically unrelated but were positioned relative to each other in either spatially plausible or implausible orientations (e.g. a drill oriented towards or away from a donut; see Fig. 1). The spatial plausibility manipulation is based on the observation that unrelated objects positioned at familiar colocations in scenes can be grouped together and processed as a single entity (Biederman et al., 1982), particularly when the two objects possess an action relation (Humphreys et al., 2006; Bach et al., 2009; Riddoch et al., 2011). Thus, we assumed that this spatially plausible arrangement of the object pairs would facilitate the formation of a unitized representation of the two objects. The same object pairs located in spatially implausible locations served as a control condition.

In most work in this area, associative memory is measured by asking subjects to distinguish between pairs that were either previously presented together at study (*old*), presented at study but not together (*recombined*) or not previously presented (*new*). In order to investigate the neural correlates of these processes under the current conditions, event-related potential (ERP) measures of memory were recorded while participants distinguished between old, recombined and new pairs of spatially plausible and implausible pairs. Whilst ERP differences between correctly responded to old and new pairs provide a correlate of general retrieval success as is widely reported in ERP recognition studies of this kind (see Friedman, 2013, for a review), here we supplement these measures with more precise operational definitions in order to further index item and associative memory processes. Specifically, associative memory should be reflected in differences between old and recombined items, whereas item memory should be indexed in differences between recombined and new items. According to dual process models of recognition memory, recognition memory can be supported by two functionally distinct processes (Yonelinas et al., 2010). Recollection refers to the retrieval of qualitative details of a prior event, whereas familiarity describes a context-free memory signal that can vary in strength. Of note, familiarity

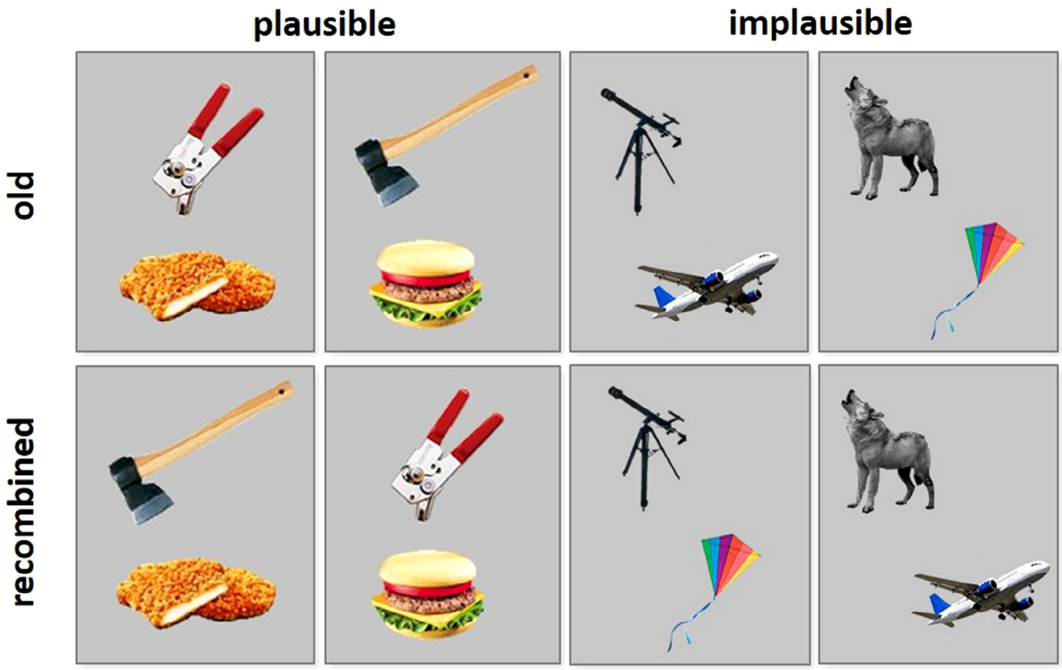

Fig. 1. Examples of plausible or implausible stimulus configurations depicted as old or as recombined pairings.

and recollection can be mapped onto qualitatively distinct ERP measures. Familiarity assessment is associated with an early (approximately 300–500 ms post-stimulus) mid-frontal old/new effect, whereas recollection is reflected in a later (500–800 ms) and parietally-distributed old/new effect (for reviews see Friedman and Johnson, 2000; Mecklinger, 2006; Rugg and Curran, 2007, but see Paller et al., 2007 for an alternative view).

Traditionally, associative memory was thought to be supported by recollection only, but work with ERP old/new effects has indicated a number of instances in which familiarity appears to also support associative memory in particular when unitization instructions were used in the study phase. Rhodes and Donaldson (2008), for example observed an early mid-frontal old/new effect in the test phase of an associative recognition task for semantically related word pairs that were previously encoded with an interactive imagery strategy (high unitization condition) but not in an item imagery condition (low unitization condition). In contrast, encoding instructions had no effect on the late parietal old/new effect in this study. Bader et al. (2010) investigated the impact of unitization instructions on familiarity-based remembering of newly formed conceptual units. Stimuli were presented together with a definition that described the word pair as a new concept (high unitization condition) or within a sentence frame (low unitization condition). An early old/new effect associated with familiarity-based recognition was obtained for unitized pairings, while the late parietal old/new effect reflecting recollection emerged for non-unitized pairings only. In our previous study in which unitization was probed by means of semantic and spatial regularities between object pictures (Tibon et al., 2014), ERP differences between intact and recombined stimuli emerged at frontopolar recording sites for related pairs only. Based on its early occurrence this effect was taken to reflect associative familiarity. ERP differences between recombined and new stimuli (presumed to reflect familiarity for single items) in this early time interval were more centrally located, and emerged for related and unrelated pairs. These findings add to the growing evidence that unitization increases associative memory performance mainly by increasing familiarity (Parks and Yonelinas, 2015; Zheng et al., 2015a,b).

The principal hypothesis for the current paradigm was that plausibly situated object pairs would facilitate unitization and lead to the creation of novel conceptual units, and that this would boost associative memory for these items relative to less plausibly situated object pairs, even in the absence of semantic relationships between items. To the extent to which familiarity supports associative memory for unitized representations, and differences between ERPs elicited by correctly responded to old and recombined items can be taken to index associative memory, it was also expected that the early ERP differences related to familiarity would be present for spatially plausible pairings but not in the control condition with spatially implausible pairings. ERP correlates of simple item familiarity were expected for both plausibility conditions, in the form of significant differences between recombined and new items.

If knowledge about spatially plausible object colocations is preserved in old age and associative memory for these pairs can be supported by familiarity, the age-related associative memory deficit should be alleviated for objects situated at plausible locations relative to the condition with implausibly located objects because this is presumed to require recollection, which is not preserved in older age. In addition, preserved early (familiarity) old/new ERP effects for both associative (old vs. recombined) and item (recombined vs. new) contrasts alongside attenuated late old/new ERP effects associated with recollection are expected for older adults. Attenuated correlates of the electrophysiological signature of recollection were expected in view of multiple previous reports of this kind, which extends to reports in which old pairs were contrasted with recombined pairs (Kamp and Zimmer, 2015; Zheng et al., 2015a). As a final test of the assumption that knowledge about spatially plausible object colocations is preserved in old age, overall ERP differences between the two spatial plausibility conditions are expected for both age groups. Alternatively, if aging individuals become more and more reliant on semantic associations between objects and lose the capability to represent unique perceptual and episodic details (Ofen and Shing, 2013), we would expect associative memory for spatially plausible object pairs, which are devoid of clear or obvious semantic associations, not to be disproportionally alleviated in old age. Consequently, the age-related differences in associative memory should be comparable for plausibly and implausibly situated object pairs.

2. Results

2.1. Neuropsychological test performance

Table 1 shows the demographic and neuropsychological data for the final two groups that entered all analyses. Groups did not significantly differ in years of education ($t(44) = 1.08$, $p = 0.29$) or in their gender distribution ($\chi^2(1) = 1.2$, $p = 0.31$). None of the participants reported a psychiatric or neurological disorder that could affect their cognitive functioning. To test whether our older participant sample was representative regarding normal age-related cognitive changes, all participants were tested on three psychometric tests subsequent to the associative recognition task: (1) the digit symbol (DS) of the WMS-R battery (Härting et al., 2000) that tests for speed of processing, and (2) a counting span task (CST, Conway et al., 2005; scores were built from the total number of sequences that were entirely reproduced) that measures working memory capacity; both of these tests were used to test for fluid intelligence. The third task was the Multiple-Choice-Knowledge-Test (MWT, non-standardized version with 30 items; see Lehrl, 1977, and Lindenberger et al., 1993 for a full description of the task) which uses measures of verbal knowledge as a proxy for crystallized intelligence. In line with the expectation that fluid but not crystallized intelligence should decrease with aging (see Baltes et al., 1999), younger adults showed better performance in the DS ($t(44) = 8.94$, $p < 0.001$) and CST ($t(44) = 3.26$, $p < 0.01$), whereas older adults performed better in the MWT ($t(44) = 2.57$, $p < 0.05$). To grade their cognitive state, older adults were additionally tested with the Mini-Mental State Examination (MMSE, subtest of the CERAD-Plus 1.0 that is used as a dementia screening) and scored within the average range ($M = 29.15$, $SD = 0.86$; the standardized z-value is not different from 0, $p = 0.29$; data is missing from two participants), suggesting that none of the current sample showed signs of severe cognitive impairment. Together, these results indicate a sample representative of normal age-related changes in cognition.

2.1.1. Behavior: Recognition performance and response times

Fig. 2 shows the means and standard errors of the mean (SEMs) of accuracy whilst Table 2 reports Pr-scores and RTs to correct responses of the test phase. Table 3 shows the pattern of responding across the three response categories (old, recombined, new) separated according to Memory Status, Plausibility and Age Group. Proportion of correct responses were subjected to an ANOVA with factors Plausibility (plausible, implausible), Memory Status (old, recombined, new) and Age Group (young, old) and revealed main effects of Memory Status ($F\ (2, 88) = 44.90$, $p < 0.001$, $\eta_p2 = 0.51$), Plausibility ($F\ (1, 44) = 82.34$, $p < 0.001$, $\eta_p2 = 0.65$) and Age Group ($F\ (1, 44) = 32.855$, $p < 0.001$, $\eta_p2 = 0.43$). Alongside an interaction between Plausibility and Memory Status ($F\ (2, 88) = 47.10$, $p < 0.001$, $\eta_p2 = 0.52$), these main effects were also moderated by an interaction between Plausibility and Age Group ($F\ (1, 44) = 18.05$, $p < 0.001$, $\eta_p2 = 0.29$). The first of these interactions was followed-up with group-specific and plausibility-condition-specific contrasts. The effect of Plausibility was larger in younger adults ($F\ (1, 18) = 85.17$, $p < 0.001$, $\eta_p2 = 0.83$) than in older adults ($F\ (1, 26) = 13.08$, $p = 0.001$, $\eta_p2 = 0.34$), indicating a greater memory benefit from plausible pairings in the former group. Age differences were therefore more pronounced in the plausible ($F\ (1, 44) = 41.47$, $p < 0.001$, $\eta_p2 = 0.49$) than the implausible condition ($F\ (1, 44) = 19.99$, $p < 0.001$, $\eta_p2 = 0.31$).

Table 1
Sample characteristics and psychometric test results. Means are given with standard deviations in parentheses.

	Younger adults	Older adults
N	19	27
Gender distribution (m/f)	6/13	15/12
Mean age (years)	23.95 (3.15)	72.00 (4.21)
Age range (years)	19–30	60–79
Education (years)	16.76 (2.52)	15.65 (3.97)
Cognitive Variables		
Digit Symbol	46.6 (5.54)	30.04 (6.62)
Counting Span Task	5.63 (2.29)	3.74 (1.65)
Multiple-Choice Knowledge Test	24.26 (5.01)	27.33 (3.09)

The second interaction (Plausibility × Memory Status) was followed-up by separate analyses for old, recombined and new pairs. There were simple effects of Plausibility for old ($F\ (1, 44) = 115.77$, $p < 0.001$, $\eta_p2 = 0.73$) and for recombined pairings ($F\ (1, 44) = 13.43$, $p = 0.001$, $\eta_p2 = 0.23$), suggesting better performance in the plausible than in the implausible condition for these pairings, whilst the opposite pattern emerged for new items ($F\ (1, 44) = 7.33$, $p = 0.01$, $\eta_p2 = 0.14$), indicating that plausibility yields a bias towards false endorsement.

Separate Pr-scores were calculated for item memory and associative memory to explore general age differences for both memory types, and subjected to an ANOVA with the factors Plausibility, Pr-Type and Group. There was a main effect of Plausibility ($F\ (1, 44) = 80.87$, $p < 0.001$, $\eta_p2 = 0.65$), a main effect of Pr-Type ($F\ (1, 44) = 224.26$, $p < 0.001$, $\eta_p2 = 0.84$), a main effect of Age Group ($F\ (1, 44) = 28.77$, $p < 0.001$, $\eta_p2 = 0.40$) and an interaction between Plausibility and Age Group ($F(1, 44) = 9.86$, $p < 0.001$, $\eta_p2 = 0.18$). Plausibility-specific follow-up analyses revealed larger age differences in the plausible ($F\ (1, 44) = 40.26$, $p < 0.001$, $\eta_p2 = 0.48$) than in the implausible condition ($F\ (1, 44) = 13.84$, $p < 0.001$, $\eta_p2 = 0.24$). Furthermore, there was an interaction between Pr-Type and Age Group ($F(1, 44) = 14.37$, $p < 0.001$, $\eta_p2 = 0.25$). Pr-type-specific follow-up analysis revealed simple effects of Age Group for both the associative ($F(1, 44) = 40.87$, $p < 0.001$, $\eta_p2 = 0.48$) and item Pr-Score ($F(1, 44) = 12.36$, $p < 0.002$, $\eta_p2 = 0.22$). Thus, while Pr scores were higher for younger than older adults across both measures of item and associative memory, the corresponding effect sizes indicate that age differences were larger for associative memory, in line with the frequently reported finding of larger age-related differences in tests for associative than item memory (Chalfonte and Johnson, 1996; Naveh-Benjamin et al., 2003).

For RTs to correct responses, there was a main effect of Plausibility ($F\ (1, 44) = 28.93$, $p < 0.001$, $\eta_p2 = 0.40$), indicating overall faster responses in the plausible than implausible condition, and a main effect of Memory Status ($F\ (2, 88) = 42.88$, $p < 0.001$ $\eta_p2 = 0.49$). There was no main effect of or interactions with the factor of Age Group. The effect of Memory Status was followed-up by separate contrasts, which showed that whereas responses to recombined items were significantly slower than to new ($F\ (1, 44) = 73.11$, $p < 0.001$, $\eta_p2 = 0.62$) or old items ($F\ (1, 44) = 64.89$; $p < 0.001$, $\eta_p2 = 0.59$), there was no significant difference in speed of responding to old and new items ($p = 0.123$). There was also an interaction between Plausibility and Memory Status ($F\ (2, 88) = 17.23$, $p < 0.001$, $\eta_p2 = 0.28$), which was followed-up with corresponding Bonferroni-corrected t-tests. Whilst responses to old and recombined trials were slower in the implausible than the plausible condition (p-values < 0.0055), there was no significant difference between plausibility conditions for new items.

2.1.2. Behavior: Plausibility ratings

Participants' plausibility judgments at study (from 0 to 5) were sorted according to whether they were congruent or incongruent

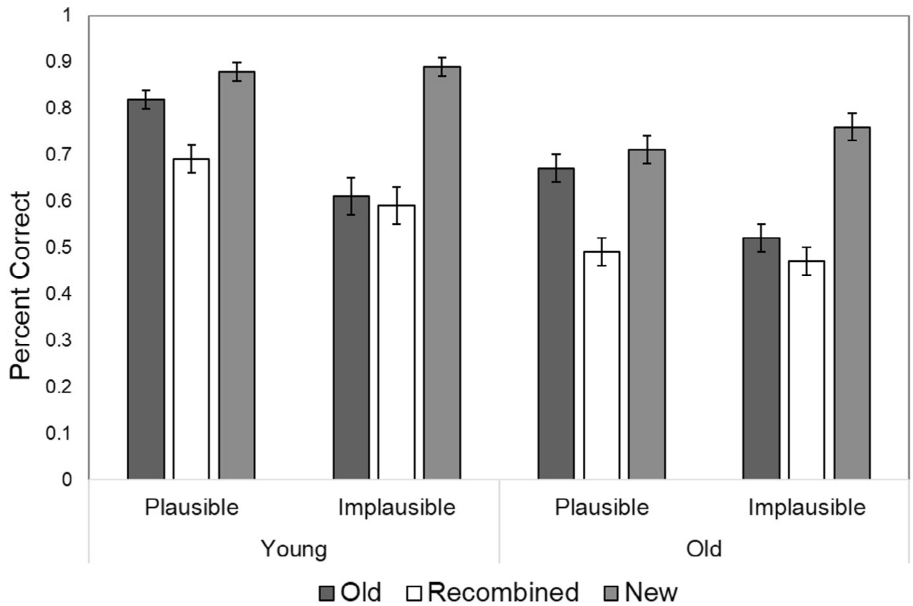

Fig. 2. Percent of correct responses for each of the three categories of Memory Status, separated for Plausibility Condition and Age Group. Error bars show ±1 standard error of the mean.

Table 2
Behavioral performance measures for young and older adults.

	Young adults		Old adults	
	Plausible	Implausible	Plausible	Implausible
Pr-score				
Item (PrI)	0.80 (0.03)	0.60 (0.04)	0.60 (0.03)	0.49 (0.03)
Associative (PrA)	0.61 (0.04)	0.41 (0.05)	0.26 (0.03)	0.17 (0.03)
RT				
Old	1645 (134)	2154 (177)	2098 (127)	2469 (179)
Recombined	2268 (171)	2553 (219)	2769 (193)	2872 (224)
New	1762 (139)	1801 (147)	2117 (156)	2218 (218)

Note. SEMs are given in parenthesis.

Table 3
Mean (standard deviations in parenthesis) proportion of responding in each response category (old, recombined, new) separated according to plausibility, memory status and age group.

	Plausible			Implausible		
	Old	Recombined	New	Old	Recombined	New
Younger adults						
Old Response	0.82 (0.10)	0.22 (0.11)	0.02 (0.04)	0.61 (0.17)	0.20 (0.12)	0.02 (0.04)
Recombined Response	0.13 (0.08)	0.69 (0.15)	0.10 (0.09)	0.25 (0.11)	0.59 (0.14)	0.10 (0.09)
New Response	0.04 (0.04)	0.09 (0.06)	0.88 (0.11)	0.14 (0.10)	0.21 (0.12)	0.89 (0.10)
Older adults						
Old Response	0.67 (0.16)	0.40 (0.17)	0.06 (0.05)	0.54 (0.14)	0.34 (0.13)	0.04 (0.03)
Recombined Response	0.25 (0.12)	0.49 (0.16)	0.23 (0.14)	0.31 (0.10)	0.47 (0.13)	0.20 (0.13)
New Response	0.08 (0.07)	0.12 (0.09)	0.72 (0.15)	0.16 (0.11)	0.19 (0.12)	0.76 (0.14)

with the stimulus pair assignment in the encoding condition. That is, rating a (pre-experimentally defined) plausible pair with 3, 4, or 5 would be considered a congruent response, whereas rating it with 0, 1, or 2 would be considered an incongruent plausibility judgment. The mean number of plausibility judgments for each plausibility condition is summarized in Table 4. The proportions of congruent plausibility judgments were submitted to an ANOVA with the factors Plausibility and Age Group. The analysis revealed a significant main effect of Age Group (F (1, 44) = 10.55 p = 0.001), demonstrating that young participants made significantly more congruent plausibility judgments than old adults.

Two steps were taken to determine whether group differences in experienced plausibility at study might relate to age-related differences in recognizing plausible and implausible pairs at test. Firstly, we defined a variable "Rating Congruency" as the difference between congruent and incongruent judgments at study collapsed across conditions, and added this as a covariate to the initial Plausibility $\times$ Memory Status $\times$ Age Group ANOVA with accuracy as the dependent variable. The ANCOVA revealed that there was no significant effect of Rating Congruency (p = 0.51) or interaction with this variable (all $ps \geq 0.11$). The principal outcomes of the initial ANOVA: main effects of Plausibility and Age Group (F (1, 43) = 11.50, p = 0.002, $\eta_p 2$ = 0.21) and the interaction of Plausibility and Memory Status (F (1, 86) = 3.23, p < 0.05, $\eta_p 2$ = 0.07) remained significant when this covariate was included. Controlling for Rating Congruency as a covariate, therefore, did not change the pattern of

Table 4
Upper row: proportion of all items given correct plausibility judgments at study. Bottom row: Proportion of old pairs given the correct plausibility judgment (at study), that were later correctly responded to as old (at test). SEMS are given in parenthesis.

	Young adults		Older adults	
	Plausible	Implausible	Plausible	Implausible
Correct plausibility judgment at study	0.90 (0.01)	0.91 (0.02)	0.79 (0.03)	0.81 (0.03)
Proportion of correct old judgments of pairs given the correct plausibility judgment at study	0.83 (0.02)	0.60 (0.04)	0.68 (0.03)	0.52 (0.03)

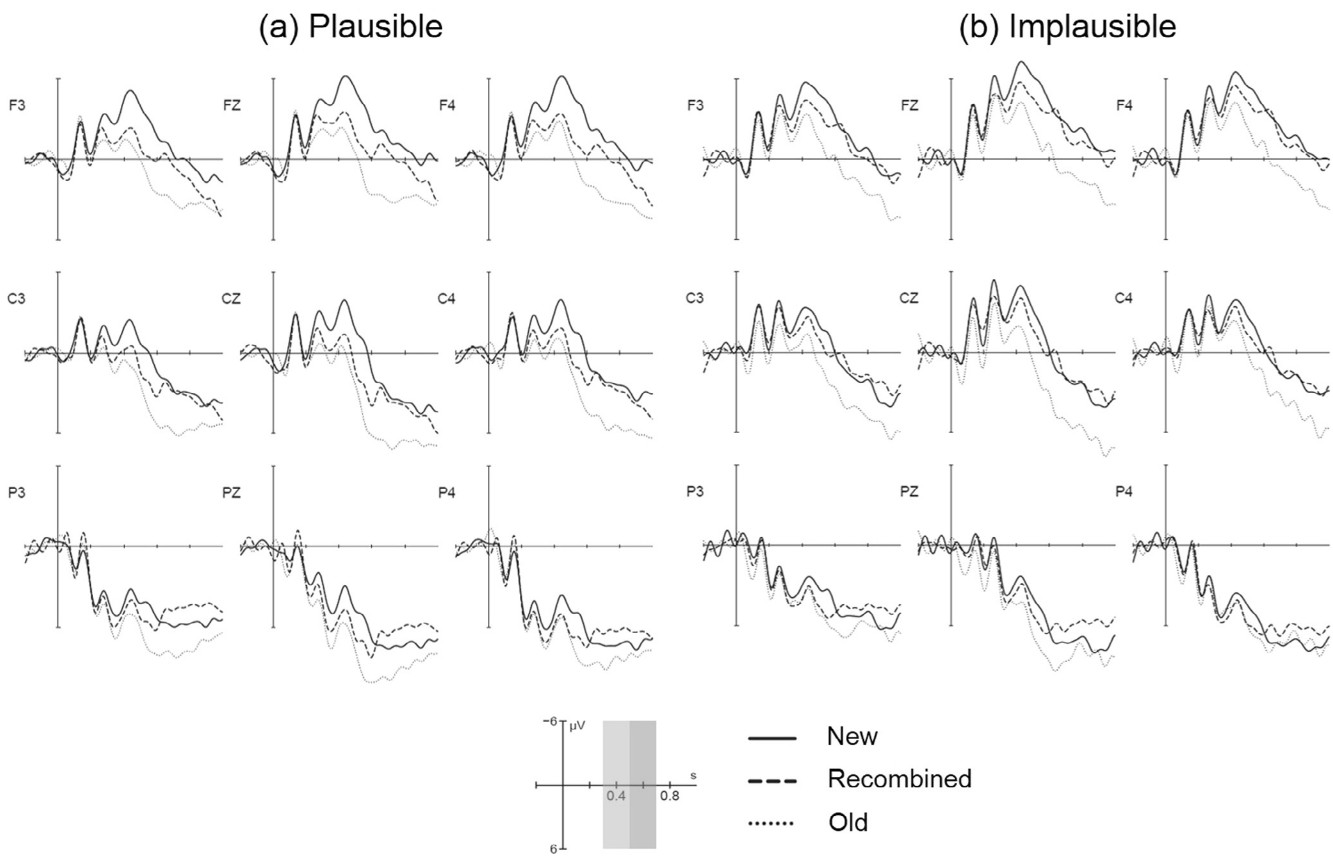

Fig. 3. ERP waveforms associated with correctly responded to new, recombined and old pairs in the plausible (a) and implausible (b) conditions for younger adults. Data are depicted at the nine electrodes employed for all ERP analyses. A 12-Hz low-pass filter was applied for illustrative purposes.

the initial ANOVA, namely the larger age differences in associative memory for plausible pairings. Secondly, we calculated the proportion of the old pairs to which a correct plausibility judgment was given at study that were subsequently correctly responded to at test. These values, split according to age group and plausibility condition, can be found in the lower panel of Table 4 and show again that subsequent memory was higher for younger than older adults and that memory was higher for plausible than implausible pairs. This pattern was confirmed by a mixed ANOVA which yielded main effects of Age Group (F (1, 44) = 8.88, $p < 0.01$, $\eta_p 2 = 0.17$) and plausibility (F (1, 44) = 105.82, $p < 0.001$, $\eta_p 2 = 0.71$) and a marginally significant interaction ($p = 0.086$). These data show that despite differences between groups in plausibility responding at study, when analyzing only those items for which correct plausibility judgments were made at study, both age groups showed a memory advantage for plausible items at test.

2.1.3. Behavior: Summary

To sum, the behavioral results showed that age differences were larger for associative than for item memory and more pronounced in the plausible than in the implausible condition. In support of the view that spatial plausibility enhances processing fluency, correct old responses were shorter for plausible than implausible pairings in both age groups. However, older adults were less likely to make plausibility ratings at study that were congruent with pre-experimental ratings of plausibility. Critically, controlling for these group differences in experienced plausibility did not change the pattern of larger age differences in memory for plausible than implausible pairings. It was also shown that a memory advantage for plausible compared to implausible items was consistent across both age groups when analyses were limited to those old pairs to which correct plausibility judgments were given at study. In line with this approach, ERP analyses to old items in turn were limited to those pairs given the correct plausibility judgment at study.

2.2. ERP results

Fig. 3 shows averaged ERPs at all analyzed electrodes of the plausible (Fig. 3a) and implausible (Fig. 3b) conditions for the young adults, whilst Fig. 4 shows the same contrasts for the older adults. Visual inspection reveals robust differences between old, recombined and new items from approximately 350 ms onwards in young adults for both plausibility conditions. In older adults, old/new differences in both conditions are much smaller, with

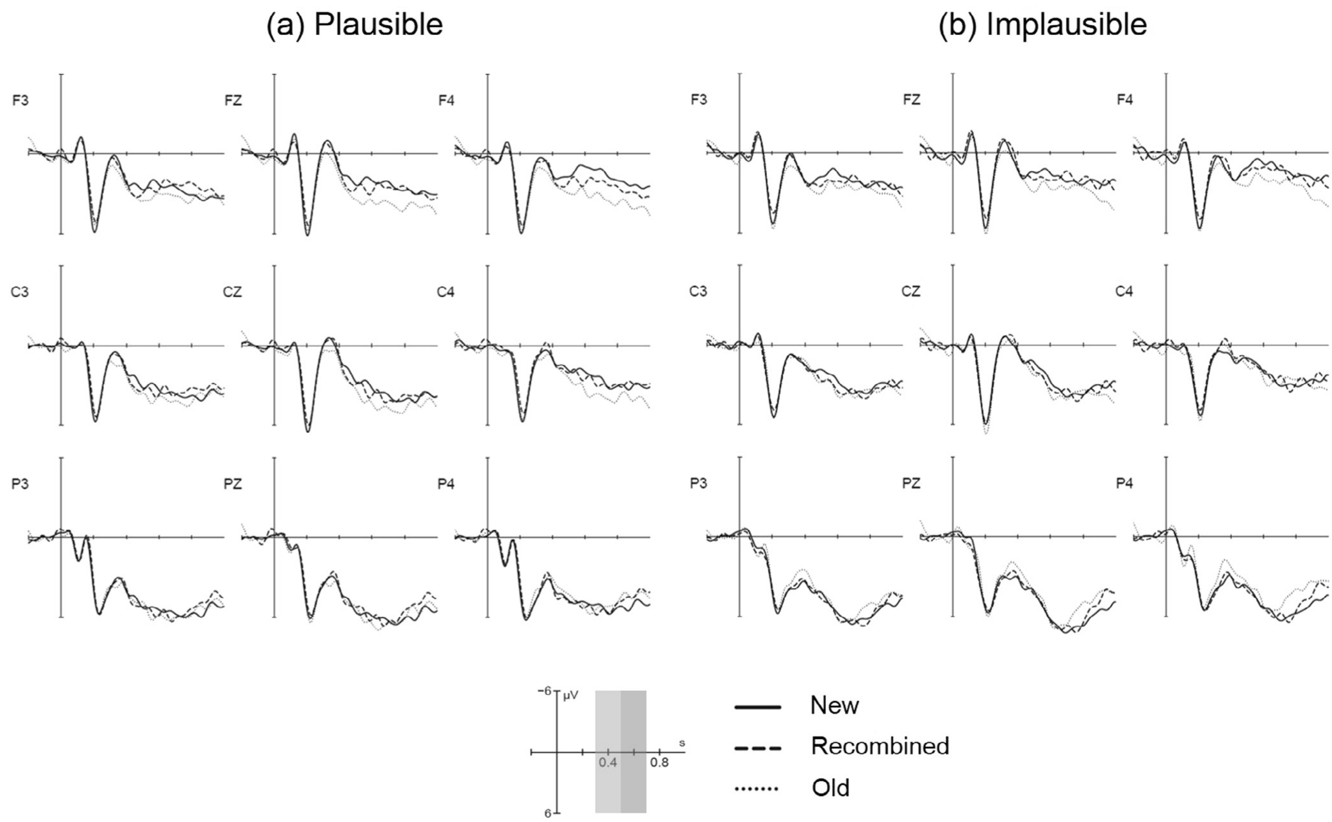

Fig. 4. ERP waveforms associated with correctly responded to new, recombined and old pairs in the plausible (a) and implausible (b) conditions for older adults. Data are depicted at the nine electrodes employed for all ERP analyses. A 12-Hz low-pass filter was applied for illustrative purposes.

Table 5
Outcomes of global ANOVA and subsequent follow-up analyses in each time window.

	Global ANOVA	Early 300-500 ms	Late 500-700 ms
MS, F(2,88)	25.67***	16.80***	27.81***
MS × AG, F(2,88)	13.14***	11.78***	12.02***
MS × Loc, F(4176)	14.79***	11.97***	13.87***
MS × Lat, F(4,176)	7.40***	6.84***	5.96**
MS × AG × Lat, F(4,176)	3.80**	–	4.17**
MS × Loc × Lat, F(8,352)	3.30**	2.65*	4.48***
MS × TW, F(2,88)	12.89***		
MS × TW × AG, F(2,88)	5.01*		
MS × TW × Loc × Lat, F (8,352)	7.68***		
PL, F(1,44)	21.37***	17.01***	15.75***
PL × AG, F(2,88)	5.51*	–	4.71*
PL × Loc, F(2,88)	4.83*	–	16.64***
PL × Lat, F(2,88)	5.99**	7.55**	3.31*
PL × AG × Lat, F(2,88)	–	3.27*	–
PL × Loc × Lat, F(4,176)	–	–	
TW × PL × Loc, F(2,88)	27.28***		
TW × PL × Loc × Lat, F (4,176)	7.29***		

Note: shown are only significant effects and interactions including the factors Memory Status (MS) or Plausibility (PL) in the global ANOVA and subsequent follow-up analyses in each time window.
MS = Memory Status, AG = Age Group, PL = Plausibility Condition, Loc = Location, Lat = Laterality, TW = Time Window.
*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.

mnemonic effects taking the form of old items differentially eliciting an early negativity over posterior sites in the implausible condition.

Table 6
Outcomes of pairwise comparison ANOVAs in each time window.

	Early 300-500 ms	Late 500-700 ms
Old vs. New		
MS, F(1,44)	38.76***	49.43***
MS × AG, F(1,44)	26.69***	20.76***
MS × Loc, F(2,88)	23.83***	22.56***
MS × Lat, F(2,88)	12.69***	8.18**
MS × AG × Lat, F(2,88)	4.42*	6.53**
MS × Loc × Lat, F(4,176)	3.55*	7.58***
Old vs. Recombined		
MS, F(1,44)	5.28*	21.61***
MS × AG, F(1,44)	–	10.50**
MS × Loc, F(2,88)	10.41**	11.12***
MS × Lat, F(2,88)	5.64**	8.76***
MS × AG × Lat, F(2,88)	–	4.51*
MS × Loc × Lat, F(4176)	3.13*	3.82**
Recombined vs. New		
MS, F(1,44)	11.34**	6.69*
MS × AG, F(1,44)	9.76**	–
MS × Loc, F(2,88)	–	5.44*

MS = Memory Status, AG = Age Group, Loc = Location, Lat = Laterality, TW = Time Window.
*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.

The outcomes of the global ANOVA with the factors Plausibility (plausible, implausible), Memory Status (old, recombined, new), Location (frontal, central, parietal), Laterality (left, midline, right), Time Window (early, late) and Group (YA, OA) are summarized in Table 5. The outcomes of the global ANOVA indicate robust old/new and plausibility effects, both of which interact with age group and with time window. Critically, however, the old/new and plausibility effects do not interact with one another. Subsequent analyses conducted within each time window were therefore conducted firstly to address old/new main effects and their interactions before separately investigating plausibility effects and their interactions with time and electrode location.

2.2.1. ERP Old/New effects

The right-hand side of Table 5 reveals effects of Memory Status which interact with Age Group, Location and Laterality in both the early and the late time window. Follow-up analyses comprised separate 2 × 2 × 3 × 3 ANOVAs with factors of Age Group, Memory Status, Location and Laterality within each time window. For these analyses only two levels of Memory Status were included in each ANOVA, in order to enable characterization of each of the critical functional contrasts: old vs. new as item + associative memory, old vs. recombined as a measure of associative memory, and recombined vs. new as a measure of item memory. The outcomes of these analyses are shown in Table 6, which reveals main effects of memory status for all three contrasts in both time windows. These effects were moderated by significant interactions between Memory Status and Age Group for most contrasts and time windows, except for old vs. recombined in the early and recombined vs. new in the late time window. These interactions were further investigated with group-specific contrasts (2 × 3 × 3 ANOVAs) within each time window.

2.2.2. Early time window

For young adults for the old vs. new contrast, there was a significant main effect of Memory Status (F (1, 18) = 57.12; $p < 0.001$, $\eta_p 2 = 0.76$), and interactions between Memory Status × Location (F (2, 36) = 11.37; $p < 0.01$, $\eta_p 2 = 0.39$), Memory Status × Laterality (F (2, 36) = 11.30; $p < 0.001$, $\eta_p 2 = 0.39$) and Memory Status × Location × Laterality (F (4, 72) = 3.69; $p < 0.05$, $\eta_p 2 = 0.17$). Follow-up t-tests were significant at all 9 electrodes, except P3 and P4 (all ps < 0.0055). The interaction with scalp locations likely reflects the fact that differences were largest over left frontal and midline sites. For older adults, Memory Status interacted with Location (F (2, 52) = 12.14; $p < 0.01$, $\eta_p 2 = 0.32$) and no contrasts at any level of Location survived correction for multiple comparisons ($p < 0.0167$) although the differences at frontal sites approached significance ($p = 0.03$).

For the old vs. recombined contrast there were no significant interactions with Age Group and follow-up analyses were collapsed across group. There was a marginally significant main effect of Memory Status (F (1, 45) = 4.05; $p = 0.05$, $\eta_p 2 = 0.083$), which was moderated by interactions between Memory Status × Location (F (2, 90) = 11.16; $p < 0.05$, $\eta_p 2 = 0.20$), Memory Status × Laterality (F (2, 90) = 4.75; $p < 0.05$, $\eta_p 2 = 0.10$) and Memory Status × Location × Laterality (F (4, 180) = 2.91; $p < 0.05$, $\eta_p 2 = 0.06$). Follow-up Bonferroni corrected pairwise t-tests at each electrode revealed that old and recombined ERPs in this time window differed only at electrodes Fz and Cz (p-values < 0.0055).

Finally, for the recombined vs. new contrast only a main effect of Memory Status for young adults was observed (F (1, 18) = 15.69; $p < 0.01$, $\eta_p 2 = 0.47$). Together these contrasts indicate significant indices of both associative and item memory for young adults in this time window, with maxima over frontal sites. Although item memory effects approached significance at frontal sites for older adults, there were no significant main effects or interactions of any kind for this group in this time window.

2.2.2.1. Late time window. For the old vs. new contrast in young adults, a significant main effect of Memory Status (F (1, 18) = 41.78; $p < 0.001$, $\eta_p 2 = 0.70$) was moderated by interactions with Location (F (2, 36) = 14.83; $p < 0.001$, $\eta_p 2 = 0.45$), Laterality (F (2, 36) = 12.22; $p < 0.001$, $\eta_p 2 = 0.40$) and Location × Laterality (F (4, 72) = 3.61; $p < 0.05$, $\eta_p 2 = 0.17$). Follow-up corrected contrasts were again significant at all electrodes except P4, and the effects were largest at left frontal and midline central sites. For older adults, there was a main effect of Memory Status (F (1, 26) = 4.98; $p < 0.05$, $\eta_p 2 = 0.16$), which was moderated by interactions between Memory Status × Location (F (2, 52) = 7.51; $p < 0.05$, $\eta_p 2 = 0.22$) and Memory Status × Location × Laterality (F (4, 108) = 4.65; $p < 0.01$, $\eta_p 2 = 0.15$). Follow-up Bonferroni corrected pairwise t-tests at each electrode revealed that old and new ERPs in this time window differed at electrodes Fz and F4 only (p-values < 0.0055).

For young adults for the old vs. recombined contrast, the significant main effect of Memory Status (F (1, 18) = 21.05; $p < 0.001$, $\eta_p 2 = 0.54$), was moderated by interactions between Memory Status × Location (F (2, 36) = 3.82; $p < 0.05$, $\eta_p 2 = 0.18$), Memory Status × Laterality (F (2, 36) = 14.17; $p < 0.001$, $\eta_p 2 = 0.44$) and Memory Status × Location × Laterality (F (4, 72) = 2.96; $p < 0.05$, $\eta_p 2 = 0.14$). Follow-up t-tests were significant at all 9 electrodes except P4 (all p-values < 0.0055). The interaction with scalp locations likely reflects the fact that differences were largest over left central sites. For older adults, Memory Status again interacted with Location (F (2, 52) = 8.25; $p < 0.01$, $\eta_p 2 = 0.24$), but no contrasts survived correction at each level of Location.

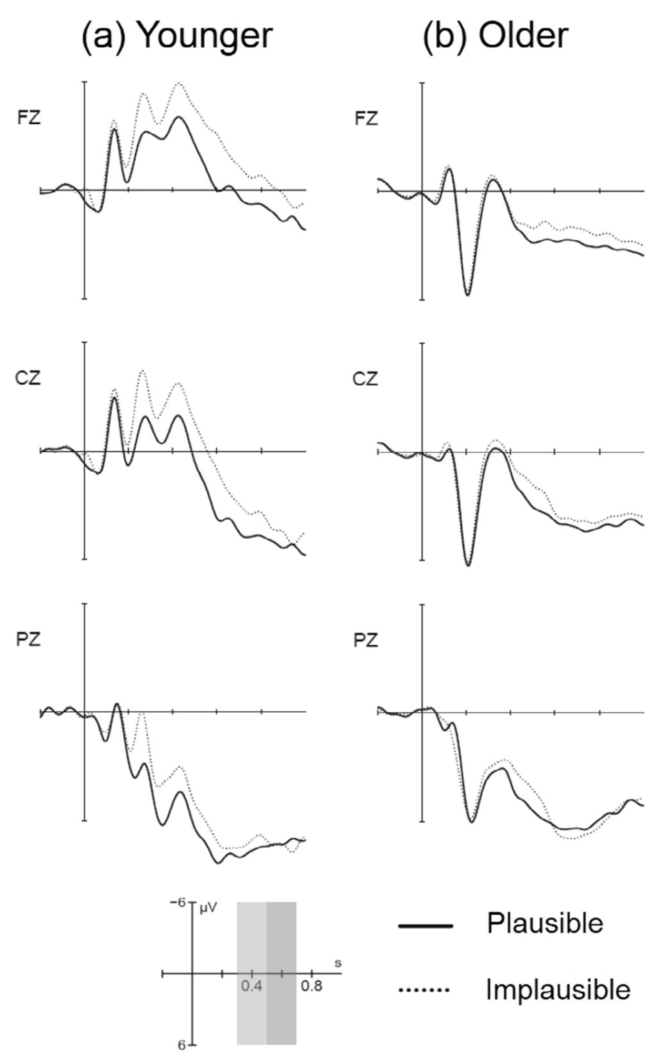

Fig. 5. ERP waveforms separated according to plausibility condition and collapsed across memory status for (a) young and (b) older adults. Data are depicted for the three midline electrodes, Fz, Cz and Pz. A 12-Hz low-pass filter was applied for illustrative purposes.

The final recombined vs. new contrast was conducted across age groups and revealed a main effect of Memory Status (F (1, 45) = 5.55; $p < 0.05$, $\eta_p 2 = 0.11$) moderated by an interaction between Memory Status and Location (F (2, 90) = 4.38; $p < 0.05$, $\eta_p 2 = 0.09$). Follow-up corrected contrasts at each level of Location revealed significant differences at frontal locations only (p-values < 0.0167). Together, these outcomes indicate significant effects of item memory for young and old adults over frontal sites, whereas associative memory effects were evident only in younger adults.

2.2.3. ERP plausibility manipulation effects

Fig. 5 shows the grand average waveforms for younger (Fig. 5a) and older adults (Fig. 5b) for the plausible and implausible conditions, collapsed across memory status. For both age groups, ERPs elicited in the plausible condition are relatively more positive-going than those in the implausible condition although these effects are much larger for younger adults, and are most evident at Pz for the older adults. The outcomes of the follow-up ANOVAs in each time window for the plausibility effects are shown at the bottom of Table 5. Significant effects of Plausibility in both time windows were moderated by significant or marginally significant interactions with Age Group. These interactions were further investigated with group-specific contrasts ($2 \times 3 \times 3$ ANOVAs) within each time window.

In the early time window, for younger adults, a main effect of Plausibility (F (1, 18) = 10.24; $p < 0.01$, $\eta_p 2 = 0.36$) was moderated by an interaction between Plausibility and Laterality (F (2, 36) = 6.95; $p < 0.01$, $\eta_p 2 = 0.28$). Corrected follow-up contrasts revealed differences between ERPs to spatially plausible and implausible objects which took the form of more positive going waveforms for plausible than implausible word pairs and were significant at all levels of Laterality (ps < 0.0167), but were largest at midline and left scalp sites. For older adults, there was a main effect of Plausibility only (F (1, 26) = 4.60; $p < 0.05$, $\eta_p 2 = 0.15$).

In the late time window, a main effect of Plausibility (F (1, 18) = 11.80; $p < 0.01$, $\eta_p 2 = 0.40$) was moderated by an interaction between Plausibility and Location (F (2, 36) = 12.58; $p < 0.01$, $\eta_p 2 = 0.41$) for younger adults. Corrected follow-up contrasts revealed Plausibility ERP differences only at frontal and central sites (ps < 0.0167). For older adults, a similar pattern emerged: there was a significant interaction between Plausibility and Location (F (2, 52) = 4.65; $p < 0.05$, $\eta_p 2 = 0.15$) and follow-up contrasts were significant only at frontal sites ($p < 0.0167$).

2.3. ERP results summary

The outcomes of the preceding ERP analyses reveal a number of principal findings. Firstly, in contrast to the effects of plausibility on behavioral expressions of memory, there were no interactions between ERP old/new effects and ERP plausibility effects at any point. Secondly, ERP old/new effects and plausibility condition effects interacted with age group in both time windows. Younger adults showed robust differences between ERPs to old, recombined and new pairs in both the early and late time windows. Whilst there were early differences between old and recombined pairs in both groups in the early time window, there were no differences of this kind in the later time window for the older group, in line with an age-related impairment in associative recognition in this time window. Moreover, in line with behavioral evidence of larger age differences for associative than item memory, whilst electrophysiological correlates of associative memory were absent for the elderly in the later time window, both groups showed item memory effects in this time window. Thirdly, plausibility effects were present for both the young and older group, but were larger for the young as based on differences in effect size. ERP plausibility effects took the form of a relative positivity for spatially plausible as compared to implausible pairs, which were left-lateralized in the early time window, becoming more frontal in the late time window.

3. Discussion

Manipulating the positioning of objects in pairs to modulate the plausibility of their potential interaction was found to have a significant impact on behavioral measures of memory. Both behavioral measures of associative and item memory were significantly stronger for spatially plausible than implausible arrangements, despite the absence of clear semantic relationships between the two objects. This finding extends previous reports in which action relations, which comprise an important spatial component, have been found to facilitate joint attention to pairs of objects (Humphreys et al., 2006; Riddoch et al., 2011) to the field of recognition memory. However, contrary to our predictions, this memory benefit for spatially plausible arrangements was greater for younger than for older adults.

3.1. Spatially plausible colocations and associative memory

Before discussing age differences in the current data, it is necessary to consider potential mechanisms by which the current plausibility manipulation might boost memory performance. It is clear from the current data that the greater memory benefit for these items was not specific to associative recognition. This is mirrored across the behavioral and electrophysiological data: the plausibility manipulation did not interact with memory-type (associative vs. item memory) as measured by Pr-type, nor were there any interactions between the plausibility manipulation and the old/new effects in either time window for the electrophysiological data. This presents an interesting pattern: whilst younger adults were clearly sensitive to the plausibility manipulation at study and test, as revealed by the elevated plausibility rating (study) and speeded response times (test), the relative boost to memory that this manipulation conferred, however, was comparable for both associative and item memory processes. This might indicate that the memory advantage conferred by presenting two objects at spatially plausible colocations including action relations among object pairs does not necessarily make these pairs easier to bind together and retrieve individual associations (i.e. a particular boon for associative retrieval) but that they are generally easier to process and identify, perhaps by virtue of the increased joint attention these pairs receive at study (Riddoch et al., 2006).

An important caveat regarding this interpretation, however, is that the amplitudes of ERP old/new effects were not found to interact with the spatial plausibility manipulation, which is what would be expected if memory signals were stronger for spatially plausible items. Although spatially implausible items are responded to correctly less often as revealed by the lower item and associative memory performance for these object pairs, when they are correctly identified it may be that the signal is as strong as for spatially plausible items. Even though we do not have an interpretation for this disconnect between memory performance and the ERP data, the data at least suggest that there is only a weak relationship between the memory advantage for spatially plausible pairs and the processes involved in the generation of the ERP old/new effects.

That the plausibility manipulation nevertheless impacted the processing of pairs and the ERP measures is evident in a number of aspects of the current data, most notably the robust ERP plausibility effects. These took the form of more positive-going amplitudes for plausible than implausible pairs from 300 ms onwards;

a broadly distributed effect with a left/midline maximum in the early time window, becoming more frontally distributed in the later time window. The broad distribution in the earlier 300–500 ms and the relative positivity for spatially plausible pairs raises the question as to whether the processes that give rise to this effect are similar to those that elicit the N400, an ERP component related to semantic access or fluency (Kutas and Federmeier, 2000). The N400 has been found to be attenuated for words or pictures with high semantic accessibility even when those items are only presented once within an experiment. The N400 effect takes the form of an attenuated negativity, is observable between 300 and 500 ms at posterior recordings and by this shows remarkable similarities in its functional, temporal and topographic characteristics with the plausible-implausible ERP differences in the current study. Similarities between the current ERP plausibility effects and the N400 raise the possibility that the current effects may reflect increased processing fluency for spatially plausible pairs that emerges from processing the two objects as a coherent entity. Convergent evidence for this comes from the observation that response times were generally faster for plausible relative to implausible pairings. Increased processing fluency for spatially plausible pairings would thus make these pairings easier to process, and attend to and remember later.

The likelihood of increased processing fluency for spatially plausible pairs also relates to the observation that participants had a tendency to make more "old" responses when the spatial configuration was more plausible whereas they tended to respond "new" when the configuration was less plausible (see Fig. 2). One interpretation of this biased response pattern is that it may indicate that participants have a tendency to confuse relative plausibility with familiarity during test. The potential for confusing sources of fluency during memory tests is common to many perspectives of fluency perhaps most notably Jacoby's memory attribution model (Jacoby et al., 1989; see also Verleger et al., 2011, for similar arguments). Alternatively, the framing of the plausibility task during encoding may have led participants to encode pairs with a "yes-plausible" or "no-implausible" tag (for plausible vs. implausible pairings), which may have primed old vs. new responses, respectively, at test.[1]

3.2. Associative memory for object pairs in young and older adults

There are a number of potential (and not necessarily mutually exclusive) reasons as to why the memory advantage for spatially plausible objects might be less robust for older individuals. Firstly, it has been shown that the aging brain becomes increasingly reliant on pre-existing semantic knowledge in order to support declarative memory (Ofen and Shing, 2013). Manipulations which enable older individuals to use semantic knowledge to support associative memory, for example, have been found to reduce age-related memory deficits (e.g. Zheng et al., 2015a; Ahmad et al., 2014; D'Angelo et al., 2016). In the present study, pairs of stimuli were associated by means of their spatial, and/or action relations. Removing semantic associations from the current stimulus set, however, excludes important information that older participants generally rely on both for making sense of stimuli at study as well as for more specific memory judgments of this kind. As a consequence, although the current study is characteristic of many learning situations in which arbitrary associations have to be acquired, it would be disproportionately difficult for older adults and would explain why they were unable to generate robust associative memory signals.

Relatedly, it appears that the older participants were generally less sensitive to the bottom-up spatial plausibility manipulation than the younger participants. Clear indicators of this reduced sensitivity to the manipulation can be seen in the reduced correspondence between older participants' plausibility responses at study and the experimental manipulation (i.e., older participants were less likely to say a pairing from the plausible condition was in fact plausible and vice versa for implausible items). Moreover, whilst there was evidence of neural differentiation of plausible vs. implausible pairs in the group of older adults in the form of significant ERP plausibility effects, these were smaller than for younger participants. The notion that the aging brain is overly reliant on semantic associations may also explain this reduced sensitivity – not only does the absence of semantics make this task particularly difficult for older adults, but they are also less able to take advantage of manipulations designed to boost unitization that do not operate along semantic lines. Combined, reduced sensitivity to the manipulation indicates that spatial plausibility alone may not be a useful approach for boosting associative memory in older adults.

In the early time window, differences between ERPs to old and recombined items were evident in both plausibility conditions for both age cohorts. Insofar as it is reasonable to assume that memory signals occurring in the early time window reflect familiarity-based recognition, this pattern may be taken as evidence of familiarity-supported associative memory. Further support for this inference comes from the relatively fronto-central distribution of these effects in the early time window, which tallies with the mid-frontal distribution of the early effect generally associated with familiarity (Rugg and Curran, 2007; Bridger et al., 2012). This pattern is noteworthy for two reasons. Firstly, it is consistent with intact early familiarity-based associative memory for older participants in line with the initial rationale for this paradigm. Secondly, however, this pattern was consistent across plausibility conditions. Whilst we have previously reported that early familiarity-related effects of this kind appear to support associative memory in younger adults (Tibon et al., 2014), critically, where this was observed it was found to be evident only for semantically related pairs, not for semantically unrelated ones. Note that the semantically unrelated pairs in the Tibon et al. (2014) study were similar to the spatially plausible pairs in the current study, although their spatial plausibility was not explicitly manipulated. Whilst the reasons for the discrepancy between this pair-type and the spatially plausible pairs of the current study are not currently clear, one possibility is that the presence of strong semantic relations may have outweighed the more subtle spatial arrangement (e.g., Gronau et al., 2008) and rendered it less able to support familiarity in the Tibon et al. (2014) study. This is not the same, however, as saying that it is not possible for familiarity to support associative memory when pairs have no pre-existing semantic association: the current data clearly indicate for the first time that early associative memory signals *can* be evident in the ERP for correctly responded to semantically unrelated object pairs.

In the later time window, however, the old vs. recombined contrast was significant only for younger participants, in line with age-related deficits in recollection-based association. This pattern - reported widely (Eppinger et al., 2010; Friedman et al., 2010; Scheuplein et al., 2014) – may go some way to explain the larger age differences for behavioral measures of associative than item memory, in line with predictions and previous reports (Naveh-Benjamin et al., 2003; Old and Naveh-Benjamin, 2008). Interpretation of differences between ERPs to old and recombined items is complicated by the possibility that participants may sometimes use recall-to-reject strategies in which recombined items are correctly responded to because one or both of the original pairings was recalled at test (Rotello and Heit, 2000). We note that

[1] We thank Rolf Verleger for pointing out these alternative views of the behavioral results.

recall-to-reject mechanisms would be expected to be employed by younger but, to a much lesser extent, by older participants, following previous reports showing that older adults have difficulties engaging in these strategies (Gallo et al., 2006). If younger participants engaged recall-to-reject strategies, however, the effect would be to diminish the amplitude of observed differences between old and recombined items rather than to amplify the pattern observed. We note that despite this, robust differences between old and recombined items are reported for younger participants here.

In sum, it was shown that bottom-up unitization conditions in the form of arranging semantically unrelated objects in spatially plausible locations can significantly improve memory performance compared to these same pairs of objects presented in spatially implausible locations. This memory boost, however, was not found to be driven solely by familiarity-driven associative memory but by an overall boost to both item and associative memory. Moreover, older individuals were less able to take advantage of this memory benefit than young participants, presumably because of the non-semantic nature of the stimuli used. It is suggested that for unitization strategies to successfully address age-related associative memory deficits they will need to be designed to support the aging brain's disposition towards pre-existing semantic associations.

4. Experimental procedures

4.1. Participants

Sixty-five adults (25 young and 40 older adults) participated in this study. All were recruited at Saarland University or from the local community. Behavioral and ERP data are reported for 46 of these adults: six younger and thirteen older participants had to be excluded because of a high amount of eye and body movement artifacts (>32% rejected trials; $n = 3$), technical problems during EEG recording ($n = 2$), use of ataractics ($n = 2$), high misclassifications at study that suggest a lack of understanding the task ($n = 7$), and insufficient trial numbers to contribute to ERP analyses ($n = 5$). The final sample that entered behavioral analysis included 19 younger and 27 older adults (see Table 1). All participants were right-handed (all scored positively on the Edinburgh Handedness Inventory; Oldfield, 1971), with normal or adjusted-to-normal vision and no signs of color-blindness. All participants gave informed consent prior to participation and were reimbursed at a rate of 8€ per hour.

4.2. Stimuli

The current experiment required a sufficient number of semantically unrelated pictures that could be arranged in either a plausible or an implausible spatial configuration and recombined with another pairing in such a manner that intact and recombined stimuli did not differ in their relatedness and associative strength (see Fig. 1 for examples of such stimulus quadruplets). Stimuli consisted of pictures of object including vegetables, fruits, various foods, beverages, animals, insects, clothing, tools, furniture and appliances, selected from the Hemera Photo-Objects Collection (Hemera Technologies Inc) as well as diverse free internet sources, before being edited with Adobe® Photoshop® CS6. 278 stimulus quadruplets were created and were rated for semantic relatedness ("How meaningfully are the two objects related with each other, disregarding their spatial plausibility? i.e., dog-cat are both animals; table-chair are kinds of furniture.") and spatial plausibility ("How plausible is the arrangement of two objects, disregarding their semantic relatedness? i.e., a kangaroo on top of a bicycle is plausible because it is suggestive of a performed action.") on a scale from 0 ("very low") to 5 ("very high"). Pairings were also screened for nameability of the single components by asking respondents to "Please mark all individual objects that you cannot identify." We built four versions of the rating questionnaire. Each version was built upon half of the stimulus materials and included two pairings (intact and recombined) of one quadruplet (either plausible or implausible) and thus contained 278 pictures pairings in total, with half of the questionnaire pictures belonging to the plausible or implausible category.

This pilot rating was performed by 42 participants, psychology students at Saarland University or adults from the local community (*mean age* = 25.0, *range* = 19–60). We removed all pairs for which one component was not identifiable by five or more of the 21 raters per picture pairing, and those pairs for which the majority of participants did not confirm the attribution of spatial plausibility and/or lack of relatedness (e.g. that received a mean score of <3 on the plausibility scale and/or >3 on the relatedness scale), leaving 154 quadruplets. Since this number was insufficient, we conducted the same procedure with a second rating questionnaire containing 148 quadruplets (built from different pictures of the same sources) rated by an additional 22 participants, leaving 110 quadruplets. Thus, in total 264 quadruplets were employed in the associative memory test. All confirmed objects were then fully counterbalanced across experimental conditions (plausible/implausible and old/recombined/new), with each stimulus pair of one quadruplet associated with one plausible and one implausible pair and with one intact and one recombined test response condition. Each participant saw the two corresponding stimuli of each quadruplet in only one of these conditions. Those items that were not seen during study served as new items.

4.3. Procedure

Participants were seated comfortably in a sound- and electrically-shielded room at a distance of approximately 65 cm from a 17″ display monitor. On-screen size of the stimulus pairings varied from 3 to 7 cm in length and from 4 to 8 cm in height, with a distance of approximately 1 cm between stimuli. Thus, horizontal and vertical visual angles ranged from approximately 2.6° to 6.2° and 3.5° to 7.0°, respectively. All objects were presented against a gray background.

A total of 176 stimulus pairs served as pictures in the study phase. Half of the stimuli were presented in a plausible and half in an implausible spatial configuration. The plausibility factor was kept constant from study to test. During the recognition test phase, half of the encoded stimuli (88) were presented as old (intact) and half as recombined pairs, and 88 additional picture pairs (half plausible, half implausible) served as new items. Thus, at test, stimuli could appear as one of 44 items in each of the following six conditions: plausible-old, implausible-old, plausible-recombined, implausible-recombined, plausible-new, implausible-new. Stimulus assignment to these conditions was completely counterbalanced across participants.

The experimental procedure was adapted from Tibon et al. (2014). Before the main phase of the experiment, instructions were read to participants by the experimenter and a practice session with both study and test phases was completed, to ensure participants understood the procedure correctly. The instructions explained to participants that they were going to see pairs of pictures that generally do not tend to appear together. Participants were asked to decide whether the picture pairs were arranged so as to represent a possible interaction or not. An initial example involving a kangaroo and bicycle was presented in order to specify this distinction. When the kangaroo was shown above the bicycle, it was explained that the arrangement allowed for a potential interaction because the kangaroo appeared to sit on or towards the bicycle, whereas the reversed spatial arrangement did not allow this. Participants were given further examples to emphasize the distinction before being asked to rate a series of pairs on a response pad, according to whether "the stimulus array represented a possible interaction or not" ("ob die räumliche Anordnung der beiden Objekte eine mögliche Interaktion darstellt") (from 0 "absolut unmöglich"/"absolutely impossible" to 5 "sehr gut mögli ch"/"entirely possible").[2] Participants practiced making categorization judgments of this kind on a further 44 additional picture pairings.[3] During the practice test phase, participants were shown old, recombined and new pairs and had to indicate for each by pressing a corresponding key on a response pad. Feedback was given after test responses during the practice phase: In the case of a correct response, feedback took the form of a smiley and the word "correct!", and in case of an incorrect response, a frown and the sentence "old/recombined/new would have been the correct response!" was presented for 1500 ms. No such feedback was provided during the actual test phase (or during the encoding phase at any point). Participants were able to repeat the practice phase if they remained uncertain about any of the task instructions.

Once ready, participants began the study phase proper, in which they saw unique picture pairs and were asked to rate on a response pad whether "the stimulus array represented a possible interaction or not". Participants were also instructed to memorize the pairings but no feedback was given. A study trial consisted of a 1000 ms fixation cross followed by the study picture pairs that were presented for 2500 ms on the screen. If no response was given during this time a blank screen appeared for 2000 ms, during which a response could also be provided. A subsequent 700 ms blank screen ended the trial. Every 44 trials participants were given self-paced breaks. The interval between study and test phase lasted approximately five minutes in which subjects performed an arithmetic distractor task (counting aloud backwards for 60 s in steps of three from a random number between 300 and 900).

In the test phase, each trial began with a 500 ms fixation cross, after which picture pairs (each belonging to one of the six described test conditions) were shown until a response was made. Participants had to indicate for each pair whether it was old, recombined, or new by pressing a corresponding key on a response pad. Response assignments were counterbalanced across participants. After a response was provided, a blank screen appeared for 1000 ms. During the test phase, participants were given self-paced breaks every 88 trials.

4.4. EEG recording

EEG activity was recorded with the BrainVision Recorder V1.02 (Brain Products) from 27 Ag/AgCl scalp electrodes in an elastic cap, arranged according to the extended international 10–20 system (American Clinical Neurophysiology, 1994). The reference was placed at the left mastoid and data was re-referenced off-line to the average of both mastoids. Electrooculograms (EOGs) were recorded with four additional electrodes that were placed above and below the right eye and at the outer canthi of both eyes. Electrode impedance was kept below 7 kΩ. EEG preprocessing was then conducted with EEProbe (A.N.T. Software). EEG data was low-pass filtered online (250 Hz), analog-to-digital converted at a sampling rate of 500 Hz and offline a band-pass filter from 0.03 to 30 Hz was applied. Trials were then epoched with a 200 ms pre-stimulus baseline and up to 1000 ms post-stimulus. Eye movement artifacts of epoched trials were corrected following a linear regression approach (Gratton et al., 1983) and trials with artifacts exceeding a 30 μV standard deviation within a 200 ms time interval were rejected from analysis. Averages were built from trials with correct responses only. Moreover, trials contributing to ERPs to old items were limited to those trials for which a correct plausibility response was given at study. To retain a sufficient signal-to-noise ratio, the minimum number of trials contributing to each average ERP was 10. The mean trial number and range of each condition that entered analysis were as follows: plausible-old (YA: 33.9 [25–42]; OA: 23.6 [11–37]), implausible-old (YA: 20.5 [12–33]; OA: 18.1 [10–30]), plausible-recombined (YA: 25.1 [17–37]); OA: 19.1 [10–33]), implausible-recombined (YA: 21.1 [13–33]); OA: 19.4 [12–38]), plausible-new (YA: 31 (21–41); OA: 25.9 (15–39)), implausible-new (YA: 30.9 (19–39); OA: 27.1 (15–42)).

4.5. Data analysis

Main analyses comprised repeated measures analysis of variance (ANOVA) on behavioral and ERP data and univariate ANOVAs or *t*-tests were conducted for subsequent contrasts. To account for violations of homogeneity, *p*-values were corrected using the Greenhouse-Geisser method (Greenhouse and Geisser, 1959). In such cases, uncorrected degrees of freedom are reported. To draw comparisons on significant effects in ANOVAs, partial eta squared (η_p^2) is provided for subsequent simple effects whenever required (Tabachnik and Fidell, 2007).

4.5.1. Behavioral data analysis

Recognition accuracy rates and reaction times to correct responses (RTs) were subjected to a 2 × 3 × 2 ANOVA with the between-subject factor of Age Group (YA, OA) and the within-subject factors of Plausibility (plausible, implausible) and Memory Status (old, recombined, new). Performance scores for item memory [PrI = hit rate (old/″old″) – false alarm rate (new/″old″)] and associative memory [PrA = hit rate (old/″old″) – false alarm rate (recombined/″old″)] (Snodgrass and Corwin, 1988), were computed to analyze age-related performance differences on item and associative memory. Towards that end, Pr-scores were subjected to a 2 × 2 × 2 ANOVA with the within-subject factors Plausibility (plausible, implausible) and Pr Type (PrI, PrA), and the between-subject factor Age Group (YA, OA).

We also analyzed plausibility judgments in the study phase, to test whether age groups gave the same proportions of congruent (i.e., judging a plausible configuration with 3, 4 or 5) and incongruent judgments (i.e., judging an implausible configuration with 0, 1 or 2). Study responses were subjected to a 2 × 2 × 2 ANOVA with the between-subject factor Age Group (YA, OA) and the within-subject factors Plausibility and Judgment (congruent, incongruent).

4.5.2. ERP data analysis

ERP contrasts were restricted to trials elicited by correct responses to old, recombined and new items. Specifically, ERPs to old items were limited to those for which a correct plausibility judgment was given at study. For statistical analysis, mean amplitudes from 9 representative electrodes covering frontal (F3/Fz/F4), central (C3/Cz/C4) and parietal (P3/Pz/P4) scalp regions in two

[2] We used the term "interaction possible or not" instead of "plausible or implausible configuration", because during piloting older adults had problems understanding the plausible-instructions, and tended to confuse "plausibility" with "possibility in reality" despite instructing them profoundly otherwise, and thus rated the majority of pictures as "implausible".

[3] These items were taken from those excluded in the pre-experimental rating because of problems with nameability (in this case improved pictures were substituted) or high rankings on semantic relatedness. The assignment to conditions was not counterbalanced in the practice session; 22 were assigned to old, 12 to recombined and 10 to the new condition (with half of the stimuli corresponding to the plausible and half to the implausible array in each condition). There were twice as many old items than new and recombined, because piloting revealed that participants were less likely to give an old response when they were unsure. We assumed that this "response bias" would diminish with unbalanced conditions, because participants received specific feedback on each response in the practice session, and would have been advised more often that they should have pressed the "old" button.

time windows (early: 300–500 ms, late: 500–700 ms) associated with familiarity and recollection respectively were used. Selection of time windows was based on previous studies with old adults (Ally et al., 2008; Scheuplein et al., 2014) and confirmed by visual inspection of the grand average waveforms.

The analysis strategy began with a global six-way ANOVA with the between-subject factor of Age Group (YA, OA) and within-subject factors of Plausibility (plausible, implausible), Memory Status (old, recombined, new), Location (frontal, central, parietal), Laterality (left, midline, right) and Time Window (early, late). As reported above, this initial analysis revealed two notable observations: (i) both Plausibility and Memory Status effects were present, and changed over time but (ii) did not interact with each other. Further analyses were therefore conducted within each time window and separately for Memory Status and Plausibility in order to individually characterize old/new and plausibility manipulation effects. For old/new analyses, an initial four-way $2 \times 3 \times 3 \times 3$ ANOVA with factors of Age Group, Memory Status, Laterality and Location was followed up with three comparable pairwise analyses with only two levels of Memory Status in each (Old vs. Recombined, Recombined vs. New, Old vs. New), in order to properly index associative (Old vs. Recombined) and item memory (Recombined vs. New) contrasts. Where these contrasts revealed interactions with Age Group, separate analyses were conducted for each group, and the outcomes of these group-specific analyses were used to determine the distribution of the effects in each time window. Interactions with electrode location factors (Laterality and/or Location) were deconstructed by taking the highest level interaction and running separate Bonferroni-corrected pairwise contrasts at each level. A comparable strategy was used to characterize the Plausibility effects.

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