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Can the elderly take the action? – The influence of unitization induced by action relationships on the associative memory deficit☆

Véronique Huffer *, Regine Bader, Axel Mecklinger

Experimental Neuropsychological Unit, Department of Psychology, Saarland University, Saarbrücken, Germany

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ABSTRACT

Healthy aging is associated with intact familiarity, whereas recollection, usually supporting associative memory, is attenuated. Accordingly, associative memory shows a stronger age-related decline than item memory. One approach to alleviate age-related associative memory deficits is to increase the contribution of familiarity to associative memory by creating encoding conditions that allow to integrate separate stimuli to an entity (unitization). The current study investigated whether bottom-up unitization can reduce age-related differences in associative memory. Younger (YA) and older adults (OA) studied associations between semantically unrelated objects, spatially arranged in a way that an action between these two objects is possible (unitized, e.g., emptying a bottle into a sneaker) or not (non-unitized). At test, participants distinguished intact from recombined and new object pairs. As expected, we found larger age differences for associative memory than for item memory. Additionally, the presence of action relationships supports memory performance in both age groups. In the event-related potentials (ERP) of the test phase, we observed an age-related attenuation of recollection and preserved familiarity independent of the action relationship condition. Considering comparisons including the recombined pairs, the ERP correlate of associative familiarity (i.e., intact vs. recombined) was present in OA for action-related pairs, whereas for YA, there was no evidence for enhanced familiarity for action-related pairs. In the late time window, ERP evidence for recollection for intact action-related object pairs was obtained independent of age group. In conclusion, both age groups benefited from unitization by action relationships but by different mechanisms. While YA show no associative familiarity for action-related object pairs but a general reliance on recollection for associations in action-related and –unrelated pairs, OA seem to rely more on familiarity for the specific arrangement of action-related pairs.

1. Introduction

The process of healthy aging impacts different aspects of episodic memory in different ways, which is reflected in the associative memory deficit. According to the associative deficit hypothesis (ADH) proposed by Naveh-Benjamin (2000), the associative memory deficit is defined as the older adults' reduced ability of encoding and retrieving associations among separate components, while memory for each of the separate components is retained. This leads to stronger age-related differences in associative memory compared to item memory (Naveh-Benjamin, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003, 2004).

According to dual-process theories, recognition memory can be supported by two functionally distinct processes: familiarity and recollection (Yonelinas et al., 2010). Familiarity, a fast and automatic process, is described as a feeling of knowing without the retrieval of specific details, while recollection, a more effortful and deliberate process, includes the processing of relations (i.e., remembering when and where an item was encountered before) and associations (e.g. were item A and item B studied together?) as well as the retrieval of qualitative information from the prior study phase. These two processes play different roles in the successful recognition of items and associations, depending on the critical discriminations that have to be made in the respective task. While familiarity is sufficient for successful item recognition (i.e., discrimination between old and new items), recollection is necessary when more detailed distinctions have to be made. More specifically, in associative recognition tasks, when the discrimination between intact (i.e., pairs that were presented exactly in the same constellation during the study phase) and recombined pairs (i.e., pairs

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* Corresponding author at: Experimental Neuropsychology Unit, Department of Psychology, Saarland University, 66123 Saarbrücken, Germany.
E-mail address: veronique.huffer@uni-saarland.de (V. Huffer).

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that consist of components that were presented in the study phase but with another partner) is required, all components of intact as well as recombined pairs possess a similar memory strength (familiarity) due to their prior exposure in the study phase. Therefore, recollection is necessary in order to retrieve the specific association so that intact pairs can be distinguished from recombined pairs. Healthy aging is associated with impaired recollection whereas familiarity is relatively unaffected (Friedman, 2013). Hence, dual-process theories of recognition memory can account for the age-related associative memory deficit with higher importance of recollection for associative compared to item memory tasks.

Familiarity and recollection can be mapped onto qualitatively distinct event-related potential (ERP) measures. In recognition memory tasks, ERP differences between waveforms elicited by correctly classified old and new pairs can be taken as correlate of general retrieval success (for a review, see Rugg & Curran, 2007). Familiarity is associated with an early mid-frontal old/new effect that appears between 300 and 500 ms post-stimulus, whereas recollection is reflected in a later (500–800 ms) and parietally distributed old/new effect (Mecklinger, 2000; for reviews, see Friedman & Johnson, 2000; Mecklinger, 2006; Mecklinger & Bader, 2020; Rugg & Curran, 2007; but see Paller, Voss, & Boehm, 2007, for an alternative view).

The pattern of relatively intact familiarity but attenuated recollection in older age is supported by behavioral (e.g. Koen & Yonelinas, 2016) and ERP evidence (Friedman, 2013; Scheuplein, Bridger, & Mecklinger, 2014). In some studies, the early mid-frontal old/new effect was not observed in older adults despite successful familiarity-driven recognition memory (e.g., Duarte, Ranganath, Trujillo, & Knight, 2006; Trott, Friedman, Ritter, Fabiani, & Snodgrass, 1999; Wang, de Chastelaine, Minton, & Rugg, 2012). However, the early mid-frontal old/new effect is consistently present in older adults when pictorial materials are employed as stimulus materials, for which detailed and distinctive memory representations can be formed. In an illustrative study, Ally et al. (2008) investigated the impact of aging on the so-called picture superiority effect. The picture superiority effect describes the phenomenon that items are more easily remembered when they are presented as pictures compared to words (Nelson, Reed, & Walling, 1976). As pictures provide distinctive visual information and features, more unique memory representations can be created (Ally & Budson, 2007; Nelson et al., 1976). Ally et al. (2008) showed that older adults could benefit from this picture superiority effect given that they achieved similar memory performance to younger adults in a picture-picture study-test condition, while their memory in a word-word study-test condition was impaired. Furthermore, in the picture-picture study-test condition no age-related differences in the early mid-frontal old/new effect were observed, whereas in the word-word study-test condition the ERP familiarity effect was only present in younger adults. Hence, Ally et al. (2008) could show that for pictures, familiarity-driven memory in older age participants is accompanied by a mid-frontal old/new effect.

Several recent studies (e.g., Ahmad, Fernandes, & Hockley, 2015; Bastin et al., 2013; Bridger et al., 2017) that investigated the associative memory deficit in older adults explored environmental conditions that increase the contribution of familiarity to associative recognition in order to compensate for impaired recollection. In this context, unitization might be an efficient way of encoding to minimize the age-related associative memory deficit. Unitization is defined as the process of integrating previously separate stimulus components into a single unitized representation of the association (Graf & Schacter, 1989). When a pair is treated as a single item rather than as two separate items as a consequence of unitization, then familiarity should support associative recognition (Parks & Yonelinas, 2015).

According to Tibon, Gronau, Scheuplein, Mecklinger, and Levy (2014), models of unitization can be categorized in bottom-up and top-down approaches. Top-down approaches represent active encoding strategies that have to be initiated by the participants themselves in order to encourage unitization (e.g., using fictional definitions, Bader, Mecklinger, Hoppstädter, & Meyer, 2010 and using imagery instructions for word pairs, Rhodes & Donaldson, 2008). Conversely, in bottom-up approaches, the stimulus material per se induces a more or less unitized processing of the association without the necessity to actively adapt encoding strategies (Tibon et al., 2014). Bottom-up unitization can be implemented by manipulating different characteristics for the associations between the to-be-remembered components (e.g., Rhodes & Donaldson, 2007; Bridger et al., 2017). For example, Rhodes and Donaldson (2007) showed that the presence of an associative relationship between two words increased associative recognition performance and enhanced the reliance on familiarity (see Ahmad & Hockley, 2014 for similar results with pre-experimentally unitized compound word pairs).

Notably, several studies have shown that both top-down and bottom-up unitization strategies provide an opportunity to alleviate the age-related associative memory deficit, and are often accompanied by elevated familiarity in conditions supporting unitization. For instance, Bastin et al. (2013) report a reduction of the age-related associative memory deficit and higher familiarity estimates in a source memory task when older adults were instructed to encode the presented object in the color of the background. Ahmad et al. (2015) applied a bottom-up unitization approach by using pre-experimentally unitized compound word pairs. They showed a discrimination advantage for these unitized representations compared to noncompound word pairs, while younger and older adults relied more on familiarity for successful recognition of compound word pairs. Employing a bottom-up unitization approach with Chinese lexical materials, Zheng et al. (2015) showed a reduction of age-related differences in associative memory for compound words. Furthermore, older adults revealed the early mid-frontal old/new effect for compound words, suggesting that compound words were unitized and older adults were able to rely on associative familiarity when remembering these words. Thus, the aforementioned studies suggest that age-related deficits in associative memory cannot only be alleviated by actively adapting encoding instructions but instead can also be achieved by manipulating the stimulus material. Compared to top-down self-initiated processing, bottom-up unitization has the advantage of being less effortful. As self-initiated processing is also often more difficult and effortful for older adults, bottom-up unitization approaches are an ideal procedure for minimizing the age-related associative deficit (Old & Naveh-Benjamin, 2008).

In a recent ERP study, Bridger et al. (2017) implemented bottom-up unitization using pictorial stimulus materials. Presenting pairs of two semantically unrelated objects, the critical manipulation concerned the plausibility of the spatial relation between the two objects. Object pairs that were positioned to each other in a spatially plausible way (e.g., a can opener over a schnitzel) – intended to induce unitization - were remembered better than object pairs arranged in a spatially implausible manner. From a memory perspective, this spatial plausibility effect was comparable for associative and item memory and, interestingly, the performance benefit for spatially plausible arrangements was greater for younger than older adults. In addition, the ERP effects in younger and older adults did not differ between spatially plausible and implausible object pairs, suggesting that there was no electrophysiological evidence for enhanced familiarity-based remembering for spatially plausible object pairs (i.e., in the unitization condition). It is thus conceivable that the spatial plausibility manipulation was too weak to support unitization encoding and familiarity-based recognition.

Therefore, it could be asked how conditions can be created that increase the probability of bottom-up unitization and familiarity-based recognition of unitized pairs in order to attenuate the age-related associative memory deficit. These unitization conditions should not only lead to a boost in associative memory in both age groups, but also to a greater benefit for older adults compared to younger adults; this is because increasing the contribution of familiarity for associations should compensate for older adults' impaired recollection, whereas for younger adults the benefit should be smaller because they can rely on their intact recollection in both conditions.

One possibility to improve unitization of two objects could be to induce an action relationship between these two objects (Humphreys, Riddoch, & Fortt, 2006). Empirical support for the importance of action relationships during visual perception comes from a series of studies on a patient with Balint's syndrome, which is characterized by a variety of visual perception deficits. Crucially, patients with Balint's syndrome are not able to perceive two objects simultaneously. In an illustrative study by Humphreys et al. (2006), object pairs with a semantic relationship, an action relationship or both were presented. The identification performance of the patient with Balint's syndrome was not only better for objects presented with an action relationship, but it was also better for action-related objects even when no semantic relationship existed, suggesting that the sole presence of an action relationship supports the perception of the object pair as a single unit. It is assumed that an action relationship between two objects can be created by familiar visual units (e.g., a corkscrew and a wine bottle) or by "affordance" of the objects themselves. "Affordance" means that objects have structural properties that afford a certain action. When presented together with another object, this affordance can cue attention to both objects of an object pair at a time leading to the perception of a single unit. In other words, the affordance of the objects for the action, and not the presence of a semantic relationship, is critical in order to enhance integration. Affordance cues the attention towards both objects of an object pair enabling a recovery of the patient's visual extinction (Humphreys et al., 2006).

In line with the reasoning by Humphreys and colleagues, we assume that action relationships between two objects without a semantic relationship can create a perceptual unit and encourage bottom-up unitization. The goal of the present study was to investigate whether bottom-up unitization through action relationships between two semantically unrelated objects fosters familiarity-based remembering and can reduce the age-related associative memory deficit. Therefore, object pairs including two semantically unrelated single objects were presented in a way that an action could be conducted or not. Assuming that the presence of an action relationship can support unitization, associative memory performance should be enhanced for action-related object pairs (i.e., unitized object pairs) compared to action-unrelated object pairs (i.e., not unitized object pairs). Furthermore, under the assumption that bottom-up unitization by action relationships boosts associative memory mainly by increasing familiarity, which as opposed to recollection is largely preserved in old age, we expect the age-related associative memory deficit to be attenuated for action-related object pairs compared to action-unrelated pairs. ERP measures were used to further index the contribution of familiarity and recollection to memory performance: Familiarity should be reflected in differences between ERPs elicited by correctly identified intact and new object pairs in the early time window, whereas recollection should be reflected in the same contrast in the late time window (Bridger et al., 2017; Tibon et al., 2014). Since the current study used pictorial stimuli in the form of object pairs, we expected comparable familiarity effects in older and younger adults. If the condition with action-related object pairs encourages unitization and if this leads to an enhanced reliance on familiarity, then the early familiarity effect (i.e., intact vs. new) should be larger for action-related object pairs compared to action-unrelated pairs (i.e., no unitization) in both age groups. In addition, given that recollection is attenuated in old age, the late parietal old/new effect should be attenuated in older adults compared to younger adults in both action relationship conditions, while the early familiarity effect should be preserved for action-related object pairs in older adults.

The ERP differences between correctly responded to intact and new object pairs serve as an index of general retrieval success and enable to establish a correspondence between the results of the current study and widely reported ERP recognition memory studies of this kind (see Friedman, 2013, for a review). A drawback of the general old/new contrast in associative memory studies is that in this comparison familiarity of the individual components of an association in intact pairs cannot be controlled for. Therefore, we will complement the index of general retrieval success with two additional contrasts including recombined object pairs: First, ERPs elicited by correctly identified intact and recombined object pairs will be compared as an index of associative memory processes that controls for familiarity of the individual components of the object pairs, as these should be highly similar for old and recombined pairs (Kamp, Bader, & Mecklinger, 2016). Second, differences between ERPs elicited by correctly responded to recombined and new object pairs will be considered as complementary measures of item memory processes because the individual components of the recombined pairs should be more familiar than the components of the new object pairs, whereas the associations should be equally unfamiliar for both object pair types (Bridger et al., 2017; Tibon et al., 2014).

2. Methods

2.1. Sample

Twenty-four younger adults (YA) were tested. To obtain the same sample size for older adults (OA), twenty-nine participants were invited to the first session (i.e., neuropsychological screening). After excluding older adults with severe cognitive deficits (see section about neuropsychological screening below), 24 OA were tested in the second session (i.e., EEG session). The YA were students from Saarland University. The OA were recruited from various internal databases and through an announcement in the daily newspaper. Data of one younger adult and five older adults was excluded from the analyses because of a technical error during the experiment (YA: $n = 1$) or due to an insufficient number of correctly responded to trials (i.e., less than eight) in one of the conditions for ERP averaging (OA: $n = 5$). The final sample for behavioral and ERP data included 23 younger adults (17 females, $M = 21$ years, $SD = 2.0$ years, range = 18–25 years) and 19 older adults (14 females, $M = 72.5$ years, $SD = 4.5$ years, range = 66–81 years). All participants were German native speakers, right-handed as confirmed by positive values on the Edinburgh Handedness Inventory (Oldfield, 1971), had no known neurological problems and had normal or corrected-to-normal vision and no signs of color-blindness. Informed consent was required, and the younger adults received a payment of 8€/hour or course credit for their participation. The older adults received a payment of €8/hour plus parking fees. All participants were debriefed after the experiment. The experiment was approved by the ethics committee of the Faculty for Human and Business Sciences, Saarland University.

2.2. Neuropsychological screening

After completing a screening on the telephone, in which general criteria such as age, native language, neurological and psychological diseases as well as visual problems were assessed, older adults were invited for a first session to conduct neuropsychological tests. This session lasted about 45 min and started with the neuropsychological test battery CERAD-Plus (Monsch, Thalmann, & Scheitter, 1997) that includes the following seven subtests: (1) verbal fluency, (2) Boston Naming Test, (3) Mini-Mental Status, (4) word-list memory (recall, recognition), (5) figural memory (copy and recall), (6) Trail-Making Test A and B and (7) phonemic fluency. Afterwards, an adapted version of the Wechsler Digit-Symbol Substitution Test (Wechsler, 2009) consisting of nine digit-symbol mappings and a total of 93 digits was administered. The session concluded with the Edinburgh Handedness Inventory (Oldfield, 1971). Twenty-nine older adults were tested and only those participants who showed no severe deficits in all subtests of the CERAD (i.e., min. −1.5 SD) were invited to the second session ($n = 24$), in which the EEG experiment was conducted. Table 1 shows the demographic information as well as some neuropsychological data for the final sample that was included into all analyses. The two age groups did neither differ significantly regarding the years of education, $t(40) = 0.78$, $p = .43$, nor

Table 1
Demographic information and neuropsychological data of the sample.

	Younger adults	Older adults
N	23	19
Gender distribution (female/male)	17/ 6	14/ 5
Mean age (years)	21 (2.08)	72.52 (4.50)
Age range (years)	18–25	66–81
Education (years)	15.08 (1.97)	14.53 (2.63)
Neuropsychological data		
Mini-Mental State Examination		29.10 (0.80)
Digit-Symbol-Test		44.10 (8.61)

Note. Standard deviations are given in parentheses.

regarding their gender distribution, $x^2(1) = 0.00$, $p = .98$. The older adults' performance in the Wechsler Digit-Symbol Substitution Test ($M = 44.10$, $SD = 8.61$), representing their perceptual speed of processing, corresponds to the normal range for this age group as indicated by results of previous studies (e.g. Ferdinand & Kray, 2013; Kray, Eber, & Karbach, 2008). The Mini-Mental State Examination (MMSE, Folstein, Folstein, & McHugh, 1975) is used as a short standardized test in order to investigate one's cognitive state and indicate severe cognitive impairments. All older adults had a normal MMSE score ($M = 29.10$, $SD = 0.80$, range = 28–30).

2.3. EEG session

2.3.1. Stimulus material

The stimulus material consisted of 640 single objects that were collected from various picture databases and internet sources and then edited with Photoshop CS6. These objects were used to build 320 object pairs without a semantic relationship. To evaluate the stimulus material, a rating study was conducted. For this purpose, 412 object pairs and their 206 corresponding recombined pairs were created by using 824 single objects. Every recombined pair was built on the basis of two intact pairs. All action-related object pairs included actions that could be conducted from a right-handed perspective. For the action-unrelated object pairs, the positions of the two objects were swapped so that the previous upper object was at the bottom and vice versa for the previous bottom object (see Fig. 1 for examples of the object pairs). Size relations between the two objects building an object pair were approximately realistic. The object pairs had a height of 4 to 10 cm and a width of 3 to 7 cm. In order to facilitate the processing of the object pair as one unit, the distance between the two single objects of an object pair was 0.5 cm. The material was rated by 36 older ($M = 69.36$ years, range = 65–80) and 36 younger ($M = 23.22$ years, range = 19–30) adults, who did not participate in the EEG experiment. First, participants were familiarized with all single objects by presenting them in a booklet in the same size as their presentation shown later on the computer screen. Participants were instructed to indicate those objects they could not recognize. Afterwards, 24 subjects of each age group rated the action relationship of the object pairs by answering the question how easy it is to name one action that could be executed with the two presented objects (in German: "Wie leicht fällt es Ihnen, eine Handlung zu benennen, die mit den beiden dargestellten Objekten ausgeführt werden könnte?" 0 = not easy at all („gar nicht leicht") – 5 = very easy („sehr leicht")). Each object pair and the corresponding recombined pair were evaluated by half of the

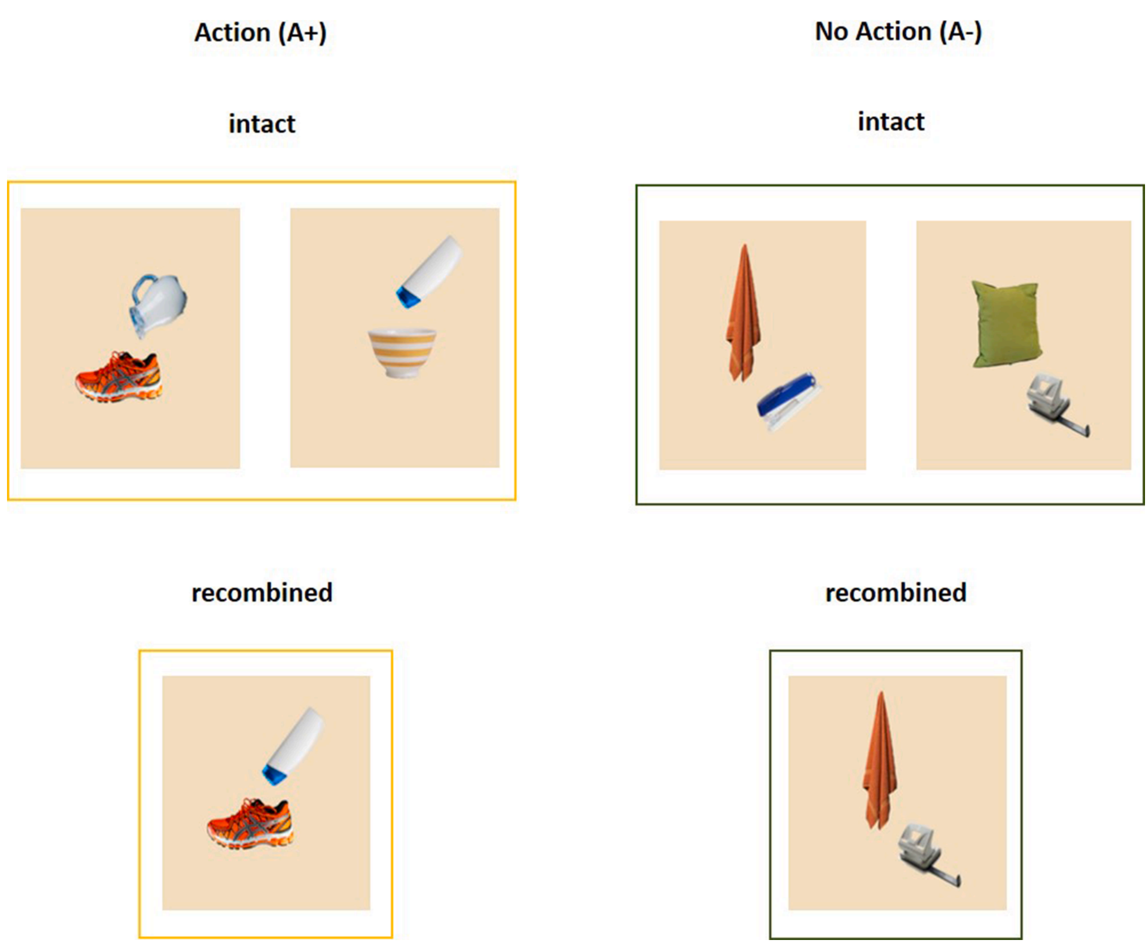

Fig. 1. *Examples for intact and recombined object pairs with and without action relationship. Note.* One recombined object pair was always built on the basis of two intact object pairs. A+ intact: A milk bottle above a sports shoe (left side), a body lotion above a bowl (right side), A+ recombined: a body lotion above a sports shoe; A– intact: A towel above a stapler (left side), a cushion above a punch (right side), A– recombined: A towel above a punch.

subjects in an arrangement with (A +) and by the other half without action relationship (A−). Furthermore, the same object pairs were rated with regard to their (associative) semantic relationship by 12 additional subjects of each age group, asking the participants to rate the likelihood of the two objects to appear together in real life as currently presented (in German: "Wie wahrscheinlich ist es, dass diese beiden Objekte zusammen in der Umwelt so auftreten, wie sie hier dargestellt werden?" 0 = very unlikely ("sehr unwahrscheinlich") – 5 = very likely ("sehr wahrscheinlich")). Participants saw all semantically unrelated pairs (intact and recombined) as well as 412 semantically related intact pairs and their 206 corresponding recombined pairs (the latter were not used in this study). The pictures of the two single objects contributing to each object pair were presented side by side to reduce the possibility of participants perceiving an action relationship because of a vertically presentation mode.

Prior to the selection of the object pairs with and without action relationship, only single objects that were recognized by at least 80 percent of the participants of both age groups were included into the material set. Then, the best 320 object pairs based on older adults' action relationship rating were chosen assuming that especially the older adults would be stricter in their rating of an action relationship for a pair of objects that is usually not used together. Afterwards, it was verified that these object pairs were not rated as highly semantically related (i.e., semantic relatedness <= 4). For younger adults, the same object pairs were selected, and Table 2 shows the total means regarding action relationship and semantic relationship for the intact and recombined pairs in both age groups. For both age groups, the rating of the action relationship did not differ significantly between the intact pairs and the recombined pairs, YA: A+: $t(478) = 1.29$, $p = .19$, $g_s = 0.12$, A−: $t(478) = -0.03$, $p = .97$, $g_s = 0.01$; OA: A+: $t(478) = 1.23$, $p = .21$, $g_s = 0.12$, A−: $t(478) = 0.64$, $p = .52$, $g_s = 0.06$. As expected, the object pairs with action relationship achieved significantly higher action ratings than the object pairs without action relationship, YA: intact: $t(638) = 43.41$, $p < .001$, $g_s = 3.43$, recombined: $t(318) = 28.98$, $p < .001$, $g_s = 3.22$; OA: intact: $t(638) = 30.06$, $p < .001$, $g_s = 2.37$, recombined: $t(318) = 21.14$, $p < .001$, $g_s = 2.36$. Although the rating differences between action-related and action-unrelated object pairs were larger for younger adults compared to older adults, the results show that the manipulation of the action relationships was effective in both age groups.

Study lists consisted of 240 object pairs (120 pairs with action relationship, 120 pairs without action relationship). Test lists consisted of 120 object pairs with action relationship and 120 object pairs without action relationship with 40 intact pairs, 40 recombined pairs and 40 new pairs (in each condition). Within the stimulus set, each object pair appeared once as a new and intact pair and twice as a recombined pair in each action condition. The assignment of the object pairs to the conditions was counterbalanced across subjects.

Table 2
Means for action relationship as well as semantic relationship of selected intact and recombined pairs for both age groups.

		Action Relationship		Semantic Relationship
		Action	No Action	
Younger adults				
	Intact	3.97 (0.65)	1.48 (0.79)	0.51 (0.52)
	Recombined	3.89 (0.69)	1.49 (0.79)	0.48 (0.60)
Older adults				
	Intact	3.80 (0.79)	1.64 (1.01)	0.65 (0.63)
	Recombined	3.70 (0.87)	1.58 (0.92)	0.58 (0.63)

Note. Standard deviations are given in parentheses.

2.3.2. Procedure

The EEG session lasted about 3 h. At the beginning, participants gave informed consent and filled out a questionnaire about general health aspects. The younger adults additionally completed the Edinburgh Handedness Inventory (Oldfield, 1971). During the following preparation of the EEG, participants were familiarized with all single objects used later in the experiment by looking through a booklet containing the single objects. Afterwards, subjects were seated comfortably in a sound- and electrically-shielded room with a distance of approximately 80 cm from a 19''-display monitor with a resolution of 1280 × 1024 pixels. The experiment was programmed and presented with E-Prime 2 software (Psychology Software Tools, Inc., Pittsburgh, PA). All object pairs were presented against a beige background with a size of 500 × 500 pixels.

Before the actual experiment started, a practice block including a study and a test phase was conducted. Therefore, 30 additional object pairs were used that were not selected for the actual experiment. The practice study phase consisted of 18 object pairs (nine pairs with action relationship, nine pairs without action relationship). The practice test phase included 18 object pairs, with half of them possessing an action relationship (three pairs per condition intact/recombined/new) and the other half possessing no action relationship (again three pairs per condition intact/recombined/new). The practice block followed the procedure from the actual experiment. The only exception was that feedback was provided after each trial, indicating whether the answer was correct or, if not, which answer would have been correct. The actual experiment was divided into four study-test cycles leading to 60 trials (30 object pairs with action relationship, 30 pairs without action relationship) per study block and test block, respectively. The order of the four blocks was randomized and the order of the trials within each block was pseudorandomized for each participant with the constraint that in the study phase, no more than three object pairs of the same action relationship were presented in a row and in the test phase, each combination of action relationship (A+ or A−) and status condition (intact, recombined or new) appeared not more than three times in a row. Each study and test block began with additional four stimulus examples in order to ensure that the subjects knew which task is relevant for the following part. During the study phase, participants had to judge how appropriate the arrangement was in order to conduct an action with the two presented objects (0 = not at all appropriate ("gar nicht richtig"), 5 = absolutely appropriate ("absolut richtig")) using a response box with six buttons. The assignment of the buttons to the response options was counterbalanced across subjects. Furthermore, they were instructed to memorize the presented object pairs for the next part of the experiment. A study trial started with a fixation cross for 1000 ms (randomly jittered between 975 and 1025 ms), and then the object pair was presented for 2500 ms. If no response was given during the presentation of the object pair, a blank screen was presented for 2000 ms during which participants were still able to provide their answers. A response finished the trial and led to a 700 ms blank screen concluding the study trial (see Fig. 2). After half of the trials within each study block, there was a self-paced break, in which subjects read again the instructions of the encoding task. After each study phase, a paper-pencil filler task was conducted for that lasted approximately three minutes. Here, the subjects had to indicate whether given arithmetic equations were correct or incorrect. In the test phase, participants had to judge if the presented object pair was old, recombined or new by pressing one of three buttons. Response assignments were counterbalanced across participants. Each test trial started with a fixation cross presented for 500 ms (randomly jittered between 475 and 525 ms), which was replaced by the object pair shown for 4000 ms. Participants had to respond as accurately as possible while the object pair was presented on the screen. As soon as an answer was given, a blank screen for 1250 ms finished the trial (see Fig. 2). After completing all four study-test blocks, the participants concluded the session with an unrelated active oddball task. This task is part of another study and will not be reported in this paper. At the end of the session, subjects filled out a follow-up survey, were debriefed and paid for their

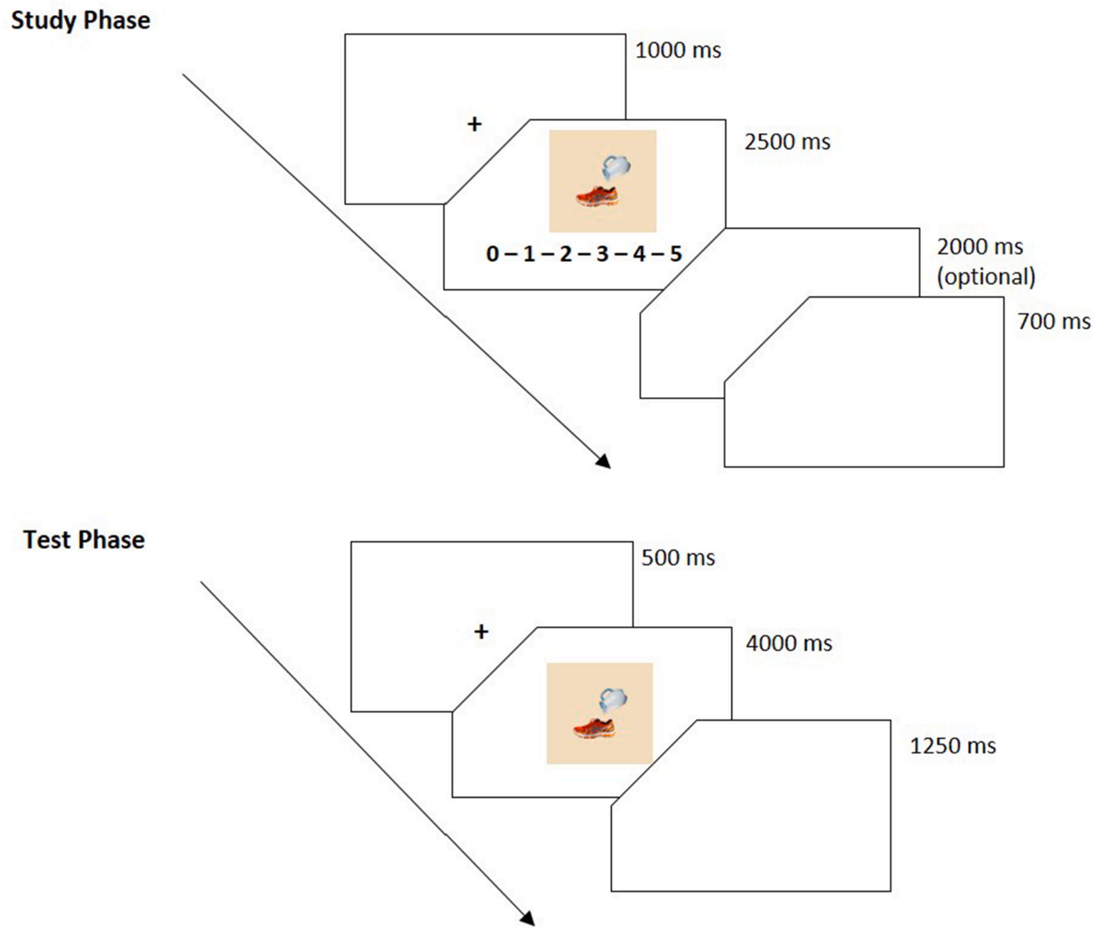

Fig. 2. *Trial procedure for the study and test phase.*

participation.

2.3.3. EEG recording and analysis

The EEG was recorded using BrainVision Recorder V1.02 (Brain Products) from 28 Ag/AgCl-electrodes embedded in an elastic cap according to the international 10–20 electrode system (Fp1, Fp2, F7, F3, Fz, F4, F8, FC5, FC3, FCz, FC4, FC6, T7, C3, Cz, C4, T8, CP3, CPz, CP4, P7, P3, Pz, P4, P8, O1, O2, and A2) during the study and the test phase. Four additional electrodes were placed around the eyes (two electrodes above and below the right eye, two electrodes at the outer canthi of both eyes) to measure the vertical and horizontal Electrooculogramm (EOG). An electrode placed on the left mastoid (A1) served as online reference and AFz was used as ground electrode. Electrode impedances were kept below 5 kΩ. The EEG was amplified with a BrainAmp DC amplifier (Brain Products GmbH) from 0.016 Hz to 250 Hz and digitized at a sampling rate of 500 Hz. For offline processing of the EEG data, BrainVision Analyzer 2.1 software (Brain Products GmbH) was used. Offline processing applied to EEG data was identical for both age groups. The data were filtered with a fourth order bandpass-filter at 0.1–30 Hz and a notch filter at 50 Hz. In order to identify and correct blinks and horizontal eye movements, the semi-automatic algorithm implemented in BrainVision Analyzer 2.1 was applied to the continuous EEG data (Ocular Correction ICA). After re-referencing to the left and right mastoid electrodes, the continuous EEG was divided into segments that started 200 ms before stimulus presentation and ended 2000 ms after stimulus onset. Baseline correction was applied using the 200 ms time interval pre-stimulus onset. Thereafter, averaging was conducted for each condition with a minimum of eight trials per condition. Even though this is a rather small number of trials for subject averages, this procedure is consistent with a variety of previous studies investigating memory-related ERPs (e.g., Höltje & Mecklinger, 2020; Kamp, Bader, & Mecklinger, 2018; Otten & Donchin, 2000; Trott et al., 1999). No further artifact rejection was applied in order to avoid loss of further trials and consequently exclusion of participants due to too small trial numbers for subject averages (see Trott et al., 1999 for a similar procedure). The mean trial numbers and ranges were: intact pairs with action relationship (YA: 33.3 (23–38), OA: 31.5 (22–37)), recombined pairs with action relationship (YA: 24.2 (11–38), OA: 16.7 (10–28)), new pairs with action relationship (YA: 31.8 (18–38), OA: 30.2 (18–37)), intact pairs without action relationship (YA: 27.5 (15–36), OA: 25.3 (8–37)), recombined pairs without relationship (YA: 22.7 (12–33), OA: 15.6 (9–23)), new pairs without relationship (YA: 32.9 (21–39), OA: 29.8 (15–37)). Grand averages were calculated for each condition and filtered with a second order low-pass filter at 12 Hz for illustration purposes only.

2.4. Analyses

All statistical analyses were conducted with R, version 3.6.1 and R studio (RStudio Team, 2019). The package “ez” (Lawrence, 2016) was used for the computation of mixed-model Analysis of Variance (ANOVA). In case of violation of sphericity, the Greenhouse-Geisser correction was applied, and uncorrected degrees of freedom are reported. The package “stats” (R Core Team, 2019) was used for computing *t*-tests for independent and dependent samples in order to disentangle significant interactions. The package “DescTools” (Signorell et al., 2020) was used to compute the effect size partial eta squared (η_p^2). The effect size Hedges’ g for the between-subjects and within-subjects comparisons was conducted based on the formula by Lakens (2013). The alpha level was set to 0.05.

2.4.1. Behavioral analyses

Study phase. For the analysis of the judgement task during the study phase, the mean rating of the action relationship based on the given ratings during encoding was calculated for action-related and action-unrelated object pairs, respectively. These ratings were included in a mixed-model ANOVA with Age Group (young/old) as between-subjects factor and Action Relationship (A+/A−) as within-subjects factor.

Test phase. To quantify associative memory performance, an associative memory index for each action relationship was calculated. In the equation for associative memory (1), the false alarm rate includes recombined object pairs mistakenly recognized as old relative to all recombined pairs with at least correct item memory (recombined pairs as recombined and recombined pairs as old). This false alarm rate is subtracted from the hit rate containing the proportion of object pairs correctly recognized as old (i.e., correct associative memory) relative to all intact object pairs with at least correct item memory (old object pairs as old and old object pairs as recombined).

$$PR - Association = \frac{old|\mathrm{old}}{old|\mathrm{old} + rec|\mathrm{old}} - \frac{old|\mathrm{rec}}{rec|\mathrm{rec} + old|\mathrm{rec}} \quad (1)$$

In addition, an item memory index was computed in order to establish a correspondence with other aging studies on memory. This allowed us to test whether the frequently reported associative memory deficit (i.e., larger age-related differences in associative than in item memory tasks) (Bastin et al 2013; Old & Naveh-Benjamin, 2008) is also present in this study. The equation for item memory (2) consists of the difference between the hit rate including the proportion of object pairs with correct item memory (old object pairs as old, old object pairs as recombined, recombined object pairs as recombined, recombined object pairs as old) relative to all object pairs that could be known from the study phase (old and recombined object pairs). The corresponding false alarm rate comprises new object pairs that are mistakenly recognized as known on an item basis (new object pairs as old and new object pairs as recombined) relative to all new object pairs.

$$PR - Item = \frac{old|\mathrm{old} + rec|\mathrm{old} + rec|\mathrm{rec} + old|\mathrm{rec}}{\mathrm{old} + \mathrm{rec}} - \frac{old|\mathrm{new} + rec|\mathrm{new}}{\mathrm{new}} \quad (2)$$

The indices were included in a 3-factorial mixed-model ANOVA with the between-subjects factor age group (young/old) and the two within-subjects factors action relationship (A+/A−) and memory type (item/associative). In addition, reaction times (RT) to correct responses were analyzed with a 3-factorial mixed-model ANOVA including the between-subjects factor age group (young/old) and the two within-subjects factors action relationship (A+/A−) and status (intact/recombined/new).

2.4.2. Electrophysiological analyses

Here, we only report EEG data from the test phase. Analyses of the ERPs were limited to correct responses. Nine representative electrodes were selected: F3, Fz, F4 for frontal, C3, Cz, C4 for central, and P3, Pz, P4 for parietal scalp distribution of the ERP effects (see Bridger et al., 2017; Bridger & Mecklinger, 2012; Zheng, Li, Xiao, Ren, & He, 2016, for similar configurations). For both age groups, an early and a late time window were analyzed, which are associated with familiarity and recollection, respectively. For younger adults, the early time window was set from 300 to 500 ms post-stimulus onset and the late time window was set from 500 to 700 ms post-stimulus onset. The selection of the time windows for older adults followed previous studies showing an age-related delay of the early familiarity effect by about 100 ms (Nessler, Friedman, Johnson, & Bersick, 2007; Wegesin, Friedman, Varughese, & Stern, 2002). Therefore, the time window from 400 to 600 ms was selected for the early old/new effects in older adults. The time window for the late effects was adjusted accordingly (600 to 800 ms) to avoid overlapping time windows.

First, a global ANOVA was conducted separately for each time window including the between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−), retrieval category (intact/recombined/new), laterality (left/middle/right) and location (frontal/central/parietal). Further ANOVAs were conducted with pooled electrodes data, anticipating the lack of significant interactions between action relationship, retrieval category and laterality. In case of significant interactions, these were further unraveled by 2-factorial ANOVAs and pairwise *t*-tests so that for the investigation of old/new effect as well as associative and item memory contrasts the following critical comparisons were conducted for both action relationship conditions: intact vs. new object pairs (familiarity in early time window, recollection in late time window), intact vs. recombined object pairs (associative familiarity in early time window, associative recollection in late time window) and recombined vs. new object pairs (item familiarity in early time window, item recollection in late time window).

3. Results

3.1. Behavioral results

3.1.1. Study phase

Table 3 shows the mean ratings for action-related and action-unrelated object pairs within each age group. The mixed-model ANOVA of the mean ratings yielded a significant main effect of Action Relationship, $F(1,40) = 672.20$, $p < .001$, $\eta_p^2 = 0.94$, indicating that, as expected, action-related object pairs were rated significantly higher than action-unrelated object pairs. Neither the main effect of age group nor the Age Group × Action Relationship interaction reached significance. Age differences were neither present in ratings of action-related object pairs, $t(40) = 0.98$, $p = .33$, $g_s = 0.30$, nor in ratings of action-unrelated object pairs, $t(40) = -1.74$, $p = .08$, $g_s = 0.53$.

3.1.2. Test phase

Fig. 3 shows the means for the two calculated performance measures. Table 4 includes the indices and RTs for the correct responses in the test phase.

There were main effects of age group, $F(1,40) = 16.84$, $p < .001$, $\eta_p^2 = 0.29$, action relationship, $F(1,40) = 28.90$, $p < .001$, $\eta_p^2 = 0.41$, and memory type, $F(1,40) = 167.99$, $p < .001$, $\eta_p^2 = 0.80$. In addition, an interaction between age group and memory type, $F(1,40) = 7.91$, $p = .007$, $\eta_p^2 = 0.16$, was revealed. This interaction was dissolved by memory type specific analyses. There were age-related differences for both item, $t(40) = 2.10$, $p = .041$, $g_s = 0.63$, and associative memory, $t(40) = 4.98$, $p < .001$, $g_s = 1.23$, revealing better memory for younger adults than older adults with larger effect sizes for associative memory, indicating the frequently reported larger age-related difference in tests of associative memory than item memory (e.g. Naveh-Benjamin, 2000) None of the other interactions reached significance ($ps > 0.25$).

The analysis of RTs to correct responses yielded main effects of age group, $F(1,40) = 26.83$, $p < .001$, $\eta_p^2 = 0.40$, action relationship, $F(1,40) = 42.49$, $p < .001$, $\eta_p^2 = 0.51$, and status, $F(2,80) = 81.62$, $p < .001$, $\eta_p^2 = 0.67$. Furthermore, interactions between age group and status, $F(2,80) = 5.77$, $p = .004$, $\eta_p^2 = 0.12$, and between action relationship and status, $F(2,80) = 25.23$, $p < .001$, $\eta_p^2 = 0.38$, were obtained. Concerning the Age Group × Status interaction, response times were faster for younger

Table 3
Mean ratings during the study phase for action-related and action-unrelated object pairs within each age group.

	Action Relationship	
	Action	No Action
Younger adults	4.43 (0.34)	0.93 (0.50)
Older adults	4.31 (0.49)	1.27 (0.78)

Note. Standard deviations are given in parentheses.

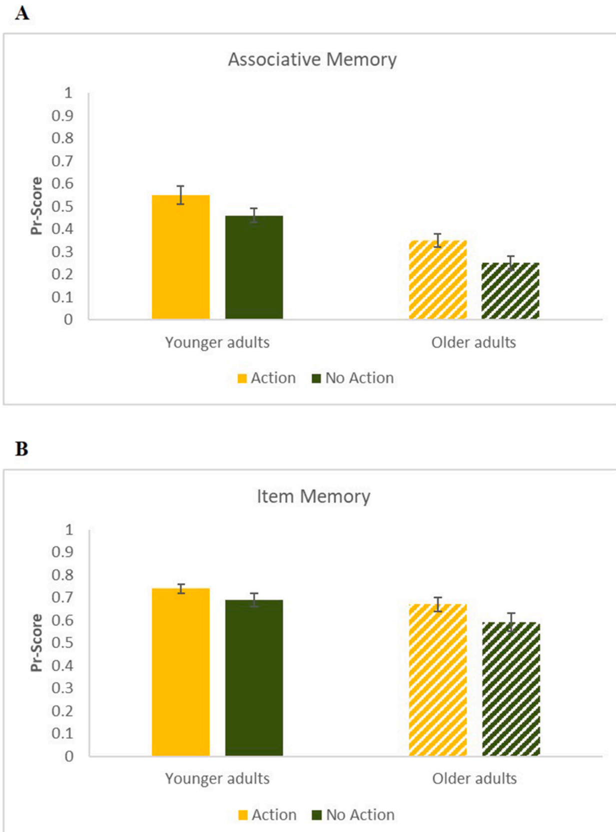

Fig. 3. *Means of the Pr-Scores for Association and Item Memory, separated for Action Relationship Condition and Age Group. Note.* **A** shows the mean of the PR-Score for Associative Memory, separated for Action Relationship condition and Age Group; **B** shows the Mean of the PR-Score for Item Memory, separated for Action Relationship condition and Age Group. Error bars show ± 1 SEM.

Table 4
PR-Scores and RTs to correct responses of the test phase.

	Younger Adults		Older Adults	
	Action	No Action	Action	No Action
Pr-Score				
Item	0.74 (0.12)	0.69 (0.14)	0.67 (0.15)	0.59 (0.16)
Association	0.55 (0.19)	0.46 (0.17)	0.35 (0.12)	0.25 (0.13)
RT				
Intact	1357 (260)	1540 (282)	1753 (316)	1982 (339)
Recombined	1748 (270)	1821 (308)	2361 (423)	2408 (444)
New	1483 (255)	1473 (258)	1847 (370)	1808 (373)

Note. Standard deviations are given in parentheses.

adults for intact, $t(40) = -4.63$, $p < .001$, $g_s = 1.31$, recombined, $t(40) = -5.50$, $p < .001$, $g_s = 1.64$, and new object pairs, $t(40) = -3.68$, $p < .001$, $g_s = 1.10$, with these age differences in response speed being largest for recombined object pairs. Following up the Action Relationship × Status interaction, comparisons between the action relationship conditions for each status condition revealed faster responses for action-related intact, $t(41) = -10.30$, $p < .001$, $g_{av} = 0.55$, and recombined pairs, $t(41) = -2.40$, $p = .020$, $g_{av} = 0.12$, compared to action-unrelated intact and recombined pairs, respectively. The corresponding effect sizes indicate that these differences were larger for intact than for recombined pairs. There was no significant difference between the action relationship conditions for the new object pairs, $t(41) = 1.10$, $p = .27$, $g_{av} = 0.06$.

3.2. Electrophysiological results

Figs. 4 and 5 show the averaged ERP waveforms for correct responses to intact, recombined, and new object pairs in the condition with action relationship (Fig. 4a/5a) and without action relationship (Fig. 4b/5b) for younger adults and older adults respectively.

A comparison of Figs. 4 and 5 reveals pronounced between-group differences in the ERP waveforms. In the early time window, the ERPs of the older adults are positive going and of negative polarity for the younger adults. Morphological differences in the ERPs of young and old adults of this kind are not atypical. See for example in the ERP results from Bridger et al. (2017) or Mark and Rugg (1998). Mark and Rugg (1998) discuss these age-related morphological differences as reflecting consequences of structural brain aging such as changed generator orientation due to brain atrophy.

Fig. 6 presents the topographical maps for the early and late old/new effects in both age groups.

3.2.1. Early time window (YA: 300–500 ms, OA: 400–600 ms)

As a first step, a global 5-factorial ANOVA with the between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−), retrieval category (intact/recombined/new), laterality (left/middle/right) and location (frontal/central/parietal) was conducted for the early time window. Table 5 provides an overview of the results of this ANOVA, depicting only the significant effects and interactions that include retrieval category or action relationship. There was an interaction between age group, action relationship, retrieval category and location in the early time window. As there were no significant interactions between action relationship, retrieval category and laterality (all $ps > 0.27$), all follow-up analyses were pooled across the laterality factor (i.e., frontally combining F3, Fz, F4).

Old/New effects. In order to investigate age-related old/new effects depending on the action relationship in the early time window, a 2 × 2 × 2 ANOVA with the between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−) and retrieval category (intact/new) was conducted for the pooled mean amplitudes at frontal electrodes in the early time window.

This analysis revealed main effects of age group, $F(1,40) = 11.58$, $p = .001$, $\eta_p^2 = 0.22$, action relationship, $F(1,40) = 15.39$, $p < .001$, $\eta_p^2 = 0.28$, and retrieval category, $F(1,40) = 29.64$, $p < .001$, $\eta_p^2 = 0.42$. None of the interactions reached significance (all $ps > 0.39$). Thus, the waveforms were more positive-going for older than younger adults, and in the A+ than in the A− condition. Reliable ERP correlates of familiarity were present in both age groups and were not modulated by action relationship.

Contrast between intact and recombined object pairs. In order to investigate age-related differences regarding associative memory and their modulation by action relationship, a 2 × 2 × 2 ANOVA with the between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−) and retrieval category (intact/recombined) was conducted with the pooled frontal electrodes in the early time window.

There were main effects of age group, $F(1,40) = 11.57$, $p = .001$, $\eta_p^2 = 0.22$, and action relationship, $F(1,40) = 6.37$, $p = .015$, $\eta_p^2 = 0.13$. There were also significant interactions between age group and action relationship, $F(1,40) = 5.48$, $p = .024$, $\eta_p^2 = 0.12$, and between age group, action relationship and retrieval category, $F(1,40) = 10.54$, $p = .002$, $\eta_p^2 = 0.21$. Following-up the significant three-way interaction, 2-factorial ANOVAs were conducted to investigate differences between action relationship conditions for each age group.

For younger adults, there was a main effect of action relationship, $F(1,22) = 18.05$, $p < .001$, $\eta_p^2 = 0.45$, reflecting the generally more positive-going waveforms in the A+ when compared to the A− condition. The interaction between action relationship and retrieval category did not reach significance ($p = .16$).

For older adults, there was a significant interaction between action

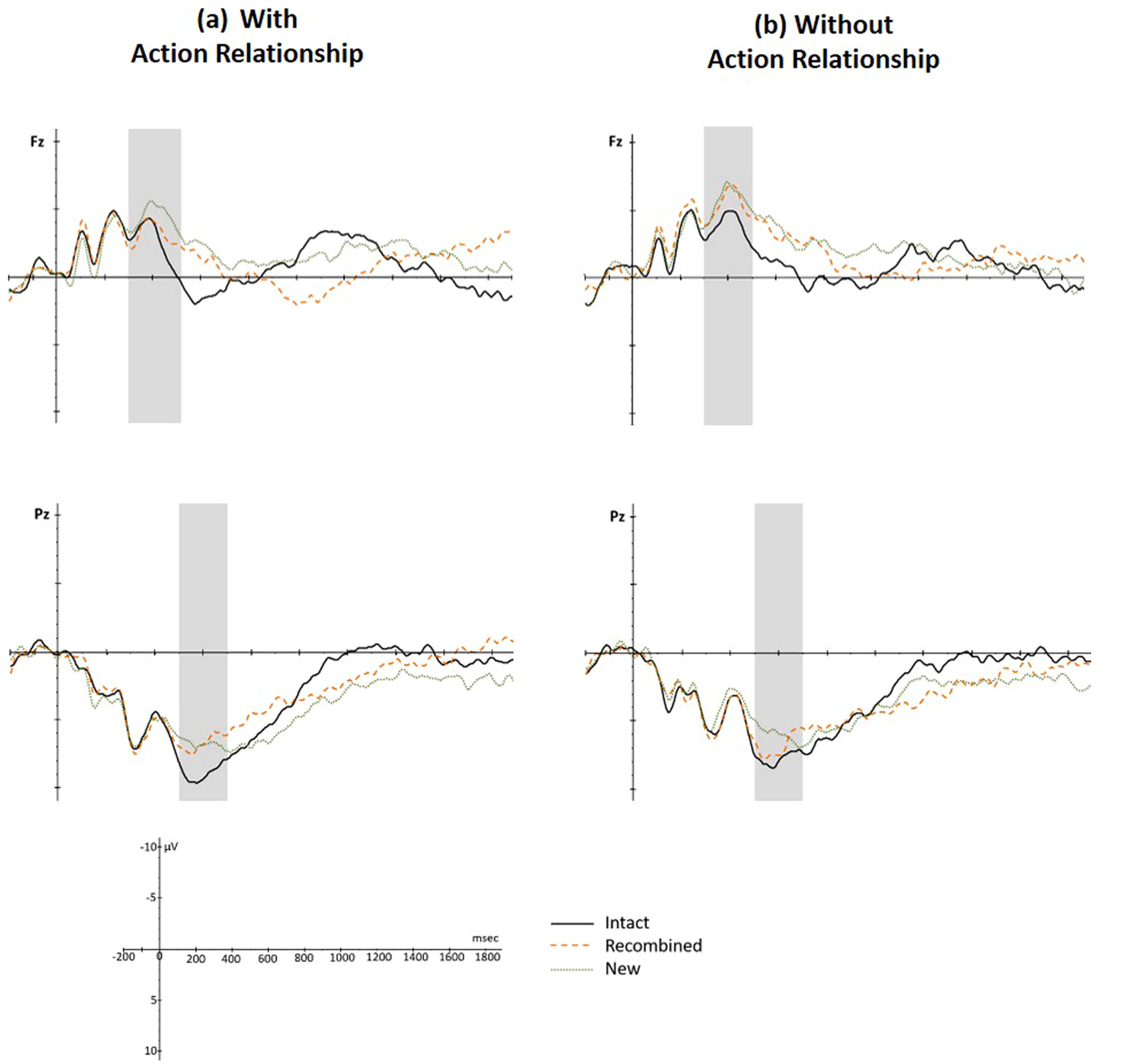

Fig. 4. *ERP waveforms associated with correct responses to intact, recombined and new object pairs for both Action Relationship conditions for Younger Adults. Note.* (a) condition with action relationship and (b) condition without action relationship for Younger adults. Data are depicted at the Fz and Pz electrode.

relationship and retrieval category, $F(1,18) = 8.07$, $p = .01$, $\eta_p^2 = 0.31$. In order to disentangle this interaction, follow-up contrasts between intact and recombined pairs were conducted for each action relationship condition. There was a significant difference between the action-related intact and recombined pairs, $t(18) = 2.66$, $p = .016$, $g_{av} = 0.25$. For the action-unrelated condition, the difference between intact and recombined pairs did not reach significance, $t(18) = -1.39$, $p = .18$, $g_{av} = 0.22$). In sum, for older adults, reliable ERP differences between intact and recombined object pairs (i.e., reflecting associative familiarity processes) are observable only for action-related object pairs, whereas for younger adults, action relationship and retrieval category did not interact.

Contrast between recombined and new object pairs. In order to investigate age-related differences regarding item memory and their modulation by action relationship, a 2 × 2 × 2 ANOVA with between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−) and retrieval category (recombined/new) was conducted with the pooled frontal electrodes in the early time window.

There were main effects of age group, $F(1,40) = 12.63$, $p < .001$, $\eta_p^2 = 0.24$, action relationship, $F(1,40) = 4.81$, $p = .034$, $\eta_p^2 = 0.11$, and retrieval category, $F(1,40) = 7.39$, $p = .009$, $\eta_p^2 = 0.16$. Also, there were significant interactions between age group and action relationship, $F(1,40) = 9.77$, $p = .003$, $\eta_p^2 = 0.19$, and between age group, action relationship and retrieval category, $F(1,40) = 8.15$, $p = .007$, $\eta_p^2 = 0.17$. Following-up the significant three-way interaction, 2-factorial ANOVAs were conducted in order to investigate differences between action relationship conditions for each age group.

For younger adults, there was a main effect of action relationship, $F(1,22) = 12.84$, $p = .002$, $\eta_p^2 = 0.37$, again reflecting the generally more positive-going waveforms in the A+ condition. The interaction between action relationship and retrieval category did not reach significance ($p = .25$).

For older adults, there was a significant interaction between action relationship and retrieval category, $F(1,18) = 8.44$, $p = .009$, $\eta_p^2 = 0.32$. Follow-up contrasts between recombined and new pairs revealed no significant difference for action-related pairs, $t(18) = 0.03$, $p = .97$, $g_{av} = 0.00$. However, for action-unrelated object pairs, ERPs were more positive for recombined than new pairs, $t(18) = 2.95$, $p = .009$, $g_{av} = 0.36$.

To sum up the results for the early time window, there were neither

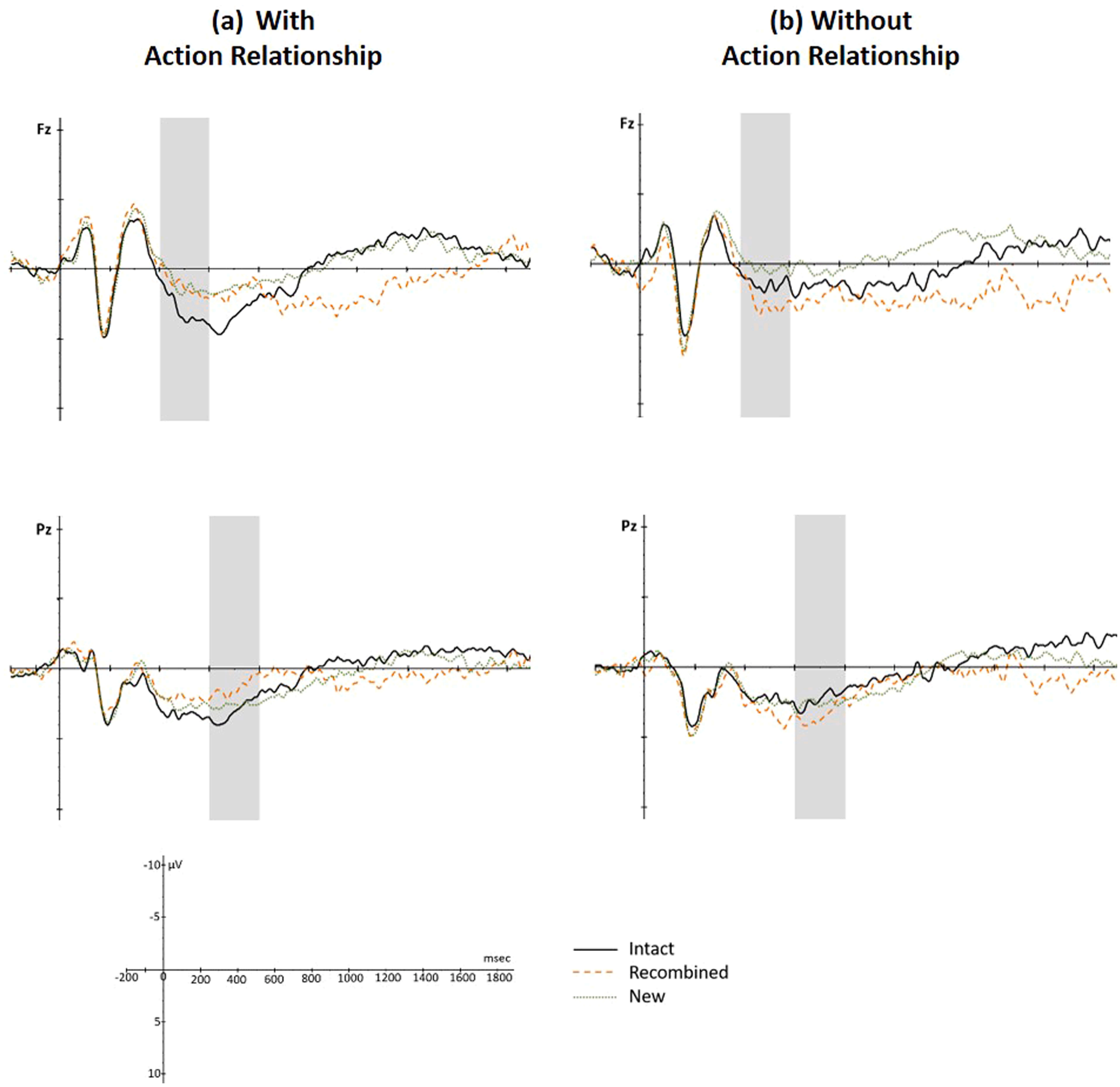

Fig. 5. *ERP waveforms associated with correct responses to intact, recombined and new object pairs for both Action Relationship conditions for Older Adults. Note.* (a) condition with action relationship and (b) condition without action relationship for Older adults. Data are depicted at the Fz and Pz electrode.

age-related differences nor differences between the action relationship conditions for the ERP correlate of familiarity (i.e., intact vs. new). Regarding the additional ERP contrast for associative familiarity (intact vs. recombined), effects were only found for action-related pairs in older adults. In contrast, no modulation of this contrast by action relationship was found in younger adults. For the ERP contrast relating to item familiarity (recombined vs. new), older but not younger adults showed a significant difference between recombined and new object pairs that was only found for action-unrelated object pairs.

3.2.2. Late time window (YA: 500–700 ms, OA: 600–800 ms)

As for the early time window, a global 5-factorial ANOVA with the between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−), retrieval category (intact/recombined/new), laterality (left/middle/right) and location (frontal/central/parietal) was conducted also for the late time window. Table 5 provides an overview of the results of this ANOVA, depicting only the significant effects and interactions that include retrieval category or action relationship. All two-way interactions between the four factors age group, action relationship, retrieval category and location were significant (all *ps* < 0.016) so that the follow-up 3-factorial ANOVA was conducted for the parietal electrodes. Since there were no significant interactions including action relationship, status and laterality (all *ps* > 0.16), all follow-up analyses were pooled across the laterality factor (i.e., parietally combining P3, Pz, P4).

Old/new effects. As in the early time window a 2 × 2 × 2 ANOVA with the between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−) and retrieval category (intact/new) was conducted in the late time window but with pooled parietal electrodes.

As in the early time window, there were main effects of age group, $F(1,40) = 7.94$, $p = .007$, $\eta_p^2 = 0.16$, action relationship, $F(1,40) = 5.54$, $p = .024$, $\eta_p^2 = 0.12$, and retrieval category, $F(1,40) = 19.38$, $p < .001$, $\eta_p^2 = 0.33$. Notably, there was a significant interaction between age group and retrieval category, $F(1,40) = 11.76$, $p = .001$, $\eta_p^2 = 0.23$. In order to disentangle this interaction, follow-up comparisons between both levels of the retrieval category factor (intact vs. new) were conducted for younger and older adults collapsed across action-related and action-unrelated pairs. For younger adults, there was a significant old/new effect, $t(22) = 5.04$, $p < .001$, $g_{av} = 0.42$, whereas for older adults the late

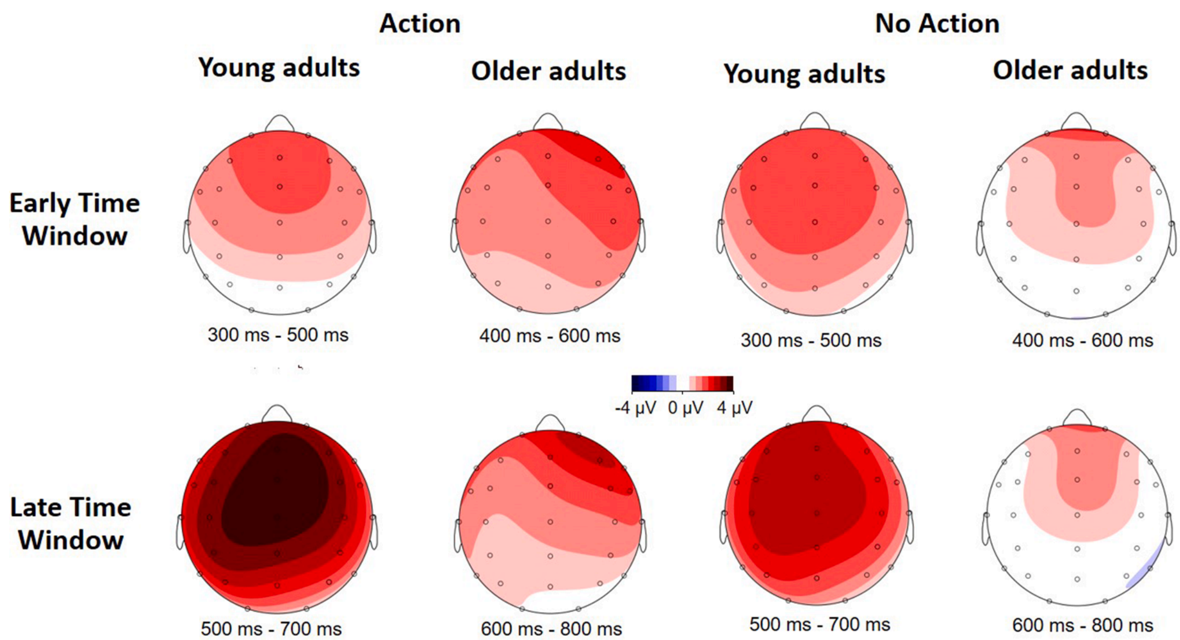

Fig. 6. *Topographical maps for the old/new effects for Younger and Older Adults. Note.* Topographical maps for the early and late old/new effects are presented for both age groups.

Table 5
Outcomes of global ANOVA in each time window.

	Early Time Window	Late Time Window
	(YA: 300–500 ms, OA: 400–600 ms)	(YA: 500–700 ms, OA: 600–800 ms)
ActionRel F(1,40)	14.09***	10.84**
ActionRel × Age (F(1,40)	8.36**	6.44*
ActionRel × Laterality F(2,80)	17.11***	4.95**
ActionRel × Location F(2,80)	–	17.32***
ActionRel × Laterality × Location F(4,160)	2.80*	2.87*
Retrieval Category F(2,80)	7.25**	18.52***
Retrieval Category × Age F(2,80)	–	5.09*
Retrieval Category × Location F(4,160)	7.47***	7.30***
Retrieval Category × Laterality × Age F (4,160)	–	4.05**
Retrieval Category × Laterality × Location F (8,320)	–	6.75***
Retrieval Category × ActionRel F(2,80)	–	5.13**
Age × ActionRel × Retrieval Category F (2,80)	5.64**	–
Age × ActionRel × Retrieval Category × Location F(4,160)	3.45*	–

Note. Shown are only significant effects and interactions including the factors Status or Action Relationship in the global ANOVA in each time window.
ActionRel = Action Relationship.
*p <.05. **p <.01. ***p <.001.

old/new effect did not reach the significance level, $t(18) = 0.49$, $p = .63$, $g_{av} = 0.04$.

Contrast between intact and recombined object pairs. In order to investigate age-related differences regarding late associative memory processes and their modulation by action relationship, a 2 × 2 × 2 ANOVA with between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−) and retrieval category (intact/recombined) was conducted with the pooled parietal electrodes in the late time window.

There were main effects of age group, $F(1,40) = 9.21$, $p = .004$, $\eta_p^2 = 0.19$, and retrieval category, $F(1,40) = 7.74$, $p = .008$, $\eta_p^2 = 0.16$. Furthermore, there were significant interactions between age group and action relationship, $F(1,40) = 4.22$, $p = .046$, $\eta_p^2 = 0.09$, and between action relationship and retrieval category, $F(1,40) = 13.39$, $p < .001$, $\eta_p^2 = 0.25$.

In order to disentangle the latter interaction, intact and recombined pairs were directly contrasted in each action relationship condition collapsed across both age groups. There was a significant difference between action-related intact and recombined object pairs, $t(41) = 5.07$, $p < .001$, $g_{av} = 0.39$. For action-unrelated object pairs, intact pairs did not differ significantly from recombined pairs, $t(41) = 0.08$, $p = .94$, $g_{av} = 0.00$. The interaction between age group and action relationship reflects larger age-related differences for action-related object pairs, $t(40) = 3.50$, $p = .001$, $g_s = 1.06$, than for action-unrelated object pairs, $t(40) = 2.45$, $p = .01$, $g_s = 0.74$.

Contrast between recombined and new object pairs. In order to investigate age-related differences regarding item memory processes and their modulation by action relationship, a 2 × 2 × 2 ANOVA with between-subjects factor age group (young/old) and the within-subjects factors action relationship (A+/A−) and retrieval category (recombined/new) was conducted with mean amplitudes at pooled parietal electrodes in the late time window as dependent variable.

This analysis revealed a main effect of age group, $F(1,40) = 5.55$, $p = .023$, $\eta_p^2 = 0.12$, and significant interactions between age group and action relationship, $F(1,40) = 7.19$, $p = .011$, $\eta_p^2 = 0.15$, and between action relationship and retrieval category, $F(1,40) = 5.65$, $p = .022$, $\eta_p^2 = 0.12$. Contrasts between recombined and new pairs revealed a marginally significant difference (rec > new) for action-unrelated pairs, $t(41) = -1.95$, $p = .058$, $g_{av} = 0.17$, but no significant difference for action-related pairs, $t(41) = 1.26$, $p = .22$, $g_{av} = 0.09$. The interaction between age group and action relationship reflects age-related differences for action-related object pairs, $t(40) = 2.97$, $p = .004$, $g_s = 0.90$, whereas there were no age-related differences for action-unrelated object pairs, $t(40) = 1.71$, $p = .09$, $g_s = 0.74$.

To sum up, in the late time window, age-related differences were observed in the ERP correlate of recollection (i.e., the late parietal old/new effect) with smaller old/new effects in older adults than younger adults. For the ERP differences between intact and recombined object pairs, which are assumed to reflect associative memory processes, there were differences between the action relationship conditions regardless of age group, showing a significant difference between intact and recombined object pairs only for object pairs with action relationships (i.e., unitized object pairs). In contrast, regarding the ERP differences between recombined and new object pairs, presumably reflecting item memory processes, there were differences between the action relationship conditions regardless of age group, showing a marginally significant difference between recombined and new object pairs only for object pairs without action relationships (i.e., non-unitized object pairs).

4. Discussion

The goal of the present study was to investigate whether bottom-up unitization through action relationships between two semantically unrelated objects fosters familiarity-based remembering and can reduce the age-related associative memory deficit. Assuming that bottom-up unitization by action relations boosts associative memory mainly by increasing familiarity, which is relatively unaffected by age, we expected the associative memory deficit to be alleviated for action-related object pairs compared to action-unrelated object pairs. The behavioral results revealed main effects of age and action relationship on memory performance. As expected, and consistent with a large number of prior studies (e.g., Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003, Naveh-Benjamin, Guez, Kilb, & Reedy, 2004), we found an age-related associative memory deficit, i.e. larger age differences in measures of associative memory than item memory. Contrary to our prediction that bottom-up unitization by action relationships boosts associative memory, in particular in older adults (i.e., compensates for compromised recollection), the associative memory deficit in the elderly was not attenuated for action-related object pairs. Instead, both age groups showed a comparable memory boost for action-related object pairs. Interestingly, age-related differences between the ERP indices of memory processes suggest that the memory advantage for action-related object pairs in both age groups results from different underlying mechanisms.

4.1. Comparable memory boost in younger and older adults

Contrary to our expectations we found a similar boost in memory performance for action-related object pairs in younger and older adults, as well as for both, associative and item memory. However, our behavioral measure of item memory is only an indirect measure as it was extracted from the associative memory task by pooling old and recombined responses. Therefore, the effect of action relationship on item memory should be interpreted with caution. Future studies which assess associative and item recognition in separate recognition tasks as has been done for example in Naveh-Benjamin (2000) should shed further light on this issue.

In order to explain that both age groups showed a comparable memory boost in associative memory performance, it is worth comparing our manipulation of action-relatedness with another action-related manipulation, the so-called subject-performed task (SPT) effect. The classical SPT includes an enactment component during encoding of object-action associations. Participants are instructed to conduct an action that is described in a phrase with and physically present external object. This leads to enhanced episodic memory performance (for reviews, see Engelkamp & Cohen, 1991; Nyberg, Persson, & Nilsson, 2002). Investigating the crucial components for the enactment effect, Kormi-Nouri (2000) showed that neither physical movement nor the presence of a real object is necessary for the enactment effect because the increase in memory performance was similar for the classical SPT (i.e., real movement and real object) and for visual imagination of both the action and the object. Furthermore, Zhao et al. (2016) showed that the SPT improved associative memory performance and enhanced familiarity-based remembering of the associations between action and object. This is consistent with the view that the components of an action can be unitized by enactment. As unitization is considered as one potential mechanism for the observed enhanced familiarity-based remembering of the action-related associations in the SPT, unitization and enactment are not mutually exclusive explanations for the action effect observed in our study. Rather, enactment can be seen as another encoding manipulation that fosters the creation of unitized representations that support familiarity-based remembering. Recent brain imaging studies suggest that such representations enable a bypassing of hippocampal encoding while learning new associations (see for a review, Gilboa & Marlatte, 2017). Thus, these two circumstances (i.e., enactment and unitization) expand conditions supporting encoding of new associations without hippocampal involvement (see Sharon, Moscovitch, & Gilboa, 2011; van Kesteren, Ruiter, Fernández, & Henson, 2012). Thus, it is conceivable that the applied action relationships in the current study enabled unitization similar to enactment because objects in each action-related object pair in the current study are arranged in a manner to convey an action that can easily be imagined (i.e., constructed for right-handed persons and positioned close to each other, see Fig. 2).

If enactment is the driving factor of the action effect on associative memory in the current study, it might be less surprising that we did not find this effect to be moderated by age. Research about the effects of encoding enactment in healthy aging has found that older and younger adults showed a similar memory benefit from an SPT manipulation (e.g., Silva, Pinho, Souchay, & Moulin, 2015) but that different mechanisms contribute to this effect in both age groups. For example, Mangels and Heinberg (2006) investigated whether the associative memory deficit in older adults can be reduced by enactment. Compared to verbal encoding, enactment improved memory performance for episodic associations, even when object-action associations were semantically unrelated. Interestingly, however, both age groups benefitted similarly from the enactment. To account for these results, Mangels and Heinberg (2006) proposed that there are multiple routes to successful associative retrieval. On the one hand, enactment can facilitate conscious recollection, which may be especially beneficial for younger adults but a rather unlikely route for older adults for which recollection is attenuated. On the other hand, older adults' associative memory benefits from enactment because familiarity is preserved for the unitized object action relation. In line with Mangels and Heinberg (2006), we assume that in the current study both age groups use different routes to successful associative retrieval: Older adults seem to rely more on associative familiarity, whereas younger adults rely more on recollection. This will be discussed in more detail below.

4.2. ERP results in the early time window

4.2.1. Familiarity effect (intact vs. new)

No significant age-related differences were obtained for the frontal old/new effect, the ERP correlate of familiarity, suggesting that both younger and older adults relied on familiarity during successful recognition. This result is in line with aging studies showing that familiarity and its ERP correlate is mostly preserved in old age (Friedman, 2013; Koen & Yonelinas, 2016; Scheuplein et al., 2014). In addition, by showing a topographically similar early old/new effect in both age groups, our study adds to the increasing number of memory studies revealing that a reliable ERP correlate of familiarity can be obtained with perceptually rich pictorial stimuli for which detailed and distinctive memory representations can be created (e.g., Ally et al., 2008; Scheuplein et al., 2014). Unexpectedly, there were no differences in the frontal old/new effect for object pairs with and without action relationships. At first glance, this challenges the idea that action-related object pairs are unitized and enhance familiarity-based remembering. However, as outlined before, in the comparison between intact and new object pairs familiarity of the individual components cannot be completely controlled for (Kamp et al., 2016), and thus, additional contrasts including recombined object pairs were considered as complementary ERP measures for associative and item memory processes that control for confounding factors (Bridger et al., 2017). Referring to these contrasts, differences between action relationship conditions were observed, suggesting that the implemented unitization approach differentially influenced early memory processes. These observations will be discussed in the following.

4.2.2. Associative and item familiarity (intact vs. recombined & recombined vs. new)

Whereas younger adults showed no significant differences between action-related and action-unrelated object pairs in terms of associative and item memory processes, older adults revealed an early associative familiarity effect (i.e., intact vs. recombined) that was present for action-related object pairs only, i.e., in the condition assumed to support unitization and to enhance familiarity-based remembering. This result supports the view that older adults indeed benefitted from the bottom-up unitization via enhanced familiarity-based remembering of the action-related intact object pairs. However, for action-unrelated object pairs, older adults showed a significant difference between recombined and new object pairs with recombined pairs being more positive-going than new object pairs. It should be noted that an interpretation of this effect in terms of item familiarity might not be straightforward because only recombined but not intact object pairs seem to be processed differentially depending on the action relationship. In addition, we would have expected to observe item familiarity (i.e., recombined vs. new) also for action-related object pairs. Notably, the frontal positivity to action-unrelated recombined pairs bears similarities with the P3a, an ERP component that is assumed to reflect a stimulus driven attention mechanism to salient and rare events (Polich, 2007). Fonken, Kam, and Knight (2020) describe the fronto-centrally distributed P3a as an electrophysiological manifestation of involuntarily attentional shifts to distractors and infrequent stimuli. Given that, for older adults, correctly recognized recombined action-unrelated object pairs are the most difficult to process (i.e., showing the smallest proportion of correct responses), it is possible that these object pairs are perceived as a category of salient events presented with low frequency by older adults and give rise to a frontally distributed P3a that overlaps with memory-related effects in this time interval.

Of note, in all analyses, we found a main effect of action relationship, representing generally more positive-going waveforms for action-related compared to action-unrelated object pairs. This might represent an N400 effect for action-unrelated compared to action-related pairs, suggesting a similar processing of actions conveyed by pictures and linguistic stimuli (for a review, see Amoruso et al., 2013). Thus, it seems that in the current study, the depicted action-related object pairs were integrated and processed more easily than the object pairs without action relationships.

Unlike Bridger et al. (2017), the current revealed significant interactions between action relationship and retrieval category in older adults. As expected, we found enhanced associative familiarity-based remembering (i.e., intact vs. recombined) for action-related intact object pairs in older adults. This suggests that the implemented unitization approach (i.e., object pairs with action relationships) may have been more effective than the plausibility manipulation employed by Bridger et al. (2017). However, regarding the contrast between recombined and new object pairs in older adults, the findings were unexpected and cannot be interpreted unambiguously in terms of item familiarity. Given that these interactions were only observed in older adults, younger adults' associative memory boost for action-related pairs seems to be less reliant on enhanced associative familiarity for the unitized associations (i.e., action-related intact object pairs). Thus, the question arises in which way action relationship improved younger adults' associative memory. Therefore, recollection-related processes and their possible contribution to the memory boost in younger adults will be discussed next.

4.3. ERP results in the late time window

4.3.1. Recollection effect (intact vs. new)

The analyses of the parietal old/new effect (i.e., the ERP correlate of recollection) revealed the frequently reported general attenuation of recollective processing in older age (e.g., Friedman, 2013; Scheuplein et al., 2014). Thus, the correspondence between the results of the analysis of the typical old/new effects in the current study and similar ERP recognition memory studies emphasizes the importance of analyzing the old/new effects as index for general retrieval success. However, even if the ERP index of recollection did not differ between the action relationship conditions, a closer look at the complementary contrasts including recombined object pairs revealed differences between the action relationship conditions.

4.3.2. Associative and item memory processes (intact vs. recombined & recombined vs. new)

Interestingly, associative (i.e., intact vs. recombined) and item (i.e., recombined vs. new) memory processes in the late time window were not modulated by age. The associative memory contrast revealed clear evidence for recollection for action-related object pairs (independent of age group). In the item memory contrast (i.e., recombined vs. new), a marginal significant recombined > new effect was obtained for action-unrelated object pairs (independent of age group). Duarte et al. (2006) found an ERP correlate of recollection only in high performing older adults. Given that older adults of the current sample were very well screened, it is conceivable that memory performance in our sample of older adults was similar to that in Duarte et al. (2006). However, comparing the high performing older adults' memory performance (Old-high: accuracy source correct: 0.70, Duarte et al., 2006) with the older adults' associative memory performance for action-related object pairs in the current study (PR-Score Associative Memory: Action: 0.35), it is clear that our older adults performed lower, even though both memory indices are not completely comparable. Thus, it is unlikely that, in the current study, older adults showed recollection processes similar to the high-performing older adults in Duarte et al. (2006). We have no explanation for these putative recollection processes in older adults. In light of the frequently reported general attenuation of recollective processing and its ERP correlate in older adults, it is rather unlikely that older adults did not show the standard recollection effect in the intact vs. new contrast, while an ERP correlate of associative recollection (intact vs recombined) was observed.

In the late time window, an age-related decline of recollection (i.e., intact vs. new) independent of the action relationship condition was detected. In addition, differences between action-related and action-unrelated object pairs were shown for associative (i.e., intact vs. recombined) and item (i.e., recombined vs. new) memory processes, independent of age group. In order to be able to interpret associative and item recollection processes depending on action relationship and the influence of healthy aging, we would have expected clear interactions with age group. Nevertheless, the fact that older adults showed an attenuated ERP correlate of recollection for intact vs. new pairs and that younger adults showed no ERP evidence for enhanced familiarity (neither associative nor item familiarity) for action-related intact pairs, supports the view that both age groups relied on different underlying mechanisms for their associative memory boost by action relationships. While young adults may have more strongly relied on recollective processing (due to the absence of enhanced familiarity for action-related intact object pairs), older adults seemed to have depended more on familiarity (due to the general attenuation of recollection).

With respect to the multiple route account of the action-relation effect (Mangels & Heinberg, 2006), our results provide electrophysiological evidence for the view that there are multiple routes to successful associative retrieval (i.e., reliance on recollection for younger adults and on familiarity for older adults). While younger adults show no associative familiarity for action-related object pairs and rely on recollection for associations, older adults seem to be able to rely on enhanced familiarity-based remembering for the associations.

4.4. Caveats and conclusions

Even though our study unveiled a couple of age-specific mechanisms underlying successful associative recognition, there are some limitations. It could be argued that during the study phase a dual task situation was created because participants were explicitly instructed to learn the object pairs and had to judge the appropriateness of the arrangements at the same time. This could have been difficult, especially for older adults. However, the memory differences between younger and older adults were within the normal range of age-related changes and only a few older adults had to be excluded due to too poor memory performance (n = 5). Additionally, given that participants had to judge the fit of the arrangement during encoding, it could be criticized that attention was directed to the unitization manipulation (i.e., action relationship) and can therefore not be considered to be a purely bottom-up unitization manipulation. However, drawing participants' attention to the action relationships has likely increased the probability of unitization, which can also be seen as a strength of the current design.

In sum, the current study showed that associative memory in both age groups can be improved by creating action relationships between two semantically unrelated objects as a bottom-up unitization approach. Even though associative memory performance in both age groups benefitted from the presence of an action relationship, the corresponding ERP indices for familiarity and recollection differed qualitatively, suggesting age-related differences regarding the underlying mechanism: The combined behavioral and ERP findings are consistent with the view that younger adults rely generally more on recollection during associative recognition judgements. Conversely, older adults, seem to rely on associative familiarity, which is evidenced by an early frontal associative familiarity effect for action-related object pairs and indirectly supported by an attenuation of the ERP correlate of recollection. Thus, they seem to take advantage of the environmental support, delivered by the "automatically" (Craik, 1983) executed encoding due to the presence of action relationships, so that the object pairs are unitized and less self-initiated processing during encoding is needed. The current study showed that younger and older adults could increase their associative memory performance by a bottom-up unitization approach with action relationships. Enhanced familiarity-based remembering of action-related intact object pairs was particularly evident in older adults, suggesting that they benefitted from this bottom-up unitization approach, even in encoding situations in which they cannot profit from semantic relationships.

CRediT authorship contribution statement

Véronique Huffer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Regine Bader:** Conceptualization, Methodology, Resources, Supervision, Validation, Writing – review & editing. **Axel Mecklinger:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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