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# The Search for Meaning: Age-Related Differences in the Semantic N400 Effect for Picture Pairs Are Unrelated to Semantic Benefits in Episodic Memory

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Older age is characterized by attenuated episodic memory but intact semantic memory. At the same time, online semantic processing, particularly the prediction of lexical information, is attenuated, as reflected by a smaller event-related potential N400 effect for expected versus unexpected items. Previous research focused on semantic processing of verbal materials. However, we aimed at investigating not only age-related differences in the semantic processing of pictorial materials but also the relationship between such age-related differences and associative memory performance. Using picture pairs, we investigated whether age-related differences in online semantic processing, as manifested in the N400, are reflected in a behavioral measure of semantic processing (i.e., perceived semantic congruency) and, in addition, transfer to associative episodic memory. Younger and older adults studied sequentially presented object pairs with and without semantic relationships (e.g., a bathtub followed by a rubber duck, or a pillow followed by a punch, respectively). Their task was to judge the object pairs' semantic congruency. Thereafter, an associative memory test was conducted, in which participants had to discriminate between intact, recombined, and new object pairs. In the study phase, younger adults showed the expected N400 attenuation effect for semantically related pairs. For older adults, this effect was reduced, even though there was no difference between both age groups either in the magnitude of the semantic congruency judgments or in the behavioral congruency effect. Furthermore, both age groups showed highly similar benefits for semantically related pairs in the ensuing associative memory test. In conclusion, older adults seem to rely more on bottom-up stimulus-driven integrative processes instead of applying top-down predictive processes initiated by preactivated semantic knowledge. Furthermore, older adults' online semantic processing seems to be decoupled from the processing that results in associative memory benefit from semantic relations.

## Public Significance Statement

Episodic memory declines in older age, whereas semantic knowledge is still intact. However, our results suggest that older age affects two temporally distinct aspects of semantic processing differentially: Fast predictive processing, which happens concurrently with comprehension of semantic information, seems to be diminished in older adults. Nevertheless, when older adults have sufficient processing time, they are able to not only integrate semantic information into their semantic network. Their episodic memory also benefits from semantics in this situation.

**Keywords:** aging, semantic relationships, N400 effect, semantic processing, episodic memory

The process of healthy aging is characterized by an attenuation in episodic memory, especially associative memory. In older age, age-related differences are larger in associative memory tasks than in item memory tasks, which is reflected in the age-related associative memory deficit (Naveh-Benjamin, 2000). At the same time,

crystallized intelligence, which encompasses semantic knowledge besides vocabulary knowledge and knowledge about social situations, shows almost no age-related decline, whereas fluid intelligence decreases with older age (Horn & Cattell, 1967). We aim to investigate age-related differences in semantic processing of

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Data from this study were published as a conference abstract for the Cognitive Neuroscience Society Conference 2024 in Toronto, Canada. Data on which the study conclusions are based, as well as the analytical code of the reported analyses, are available in an Open Science Framework project ([https://osf.io/fpjbx/?view\\_only=4f3fb0b39cc64b2fa97aa0e49dfd8c3c](https://osf.io/fpjbx/?view_only=4f3fb0b39cc64b2fa97aa0e49dfd8c3c)). The present study was funded by Deutsche Forschungsgesellschaft (German Research Foundation) Grant ME1588/10-1. The author thank all volunteers who participated in this study.

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pictures and how such differences affect episodic memory for those pictures.

Access to semantic knowledge can be explored online using the event-related potential (ERP) N400 effect. The N400 effect is characterized by a centro-parietal scalp distribution and peaks approximately 400 ms after stimulus onset (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980). It reflects the ease of semantic integration of upcoming stimuli by showing a reduced amplitude for stimuli that are preceded by a semantically supporting context. In contrast, stimuli that are not preceded by a semantically related context show a more negative N400 amplitude (Federmeier et al., 2007, 2010).

### Age-Related Differences in the Online Semantic Processing of Verbal Materials

With respect to older age, the N400 effect is attenuated when investigated with verbal stimuli as, for example, sentences (Joyal et al., 2020; Payne & Federmeier, 2018; Wlotko et al., 2012), reflecting a less differentiated processing of contextually supported and unsupported stimuli. In a sentence-reading study, Wlotko et al. (2012) found similar N400 effects for older and younger adults when sentence contexts were highly predictive but reduced N400 effects for older adults when sentence contexts were less predictive. Thus, older adults seem to need stronger environmental support to initiate top-down predictive processing.

Further support for the claim of reduced capability for using top-down context-based predictive processing in older age is provided by Payne and Federmeier (2018). In a sentence comprehension task, younger adults showed that with increasing progress into a sentence, upcoming words could be more accurately predicted, reflected in a progressively reduced N400 (i.e., the word position effect). Furthermore, the word frequency effect (i.e., more negative N400 for less frequent words) was reduced in younger adults, suggesting that they were able to predict even less frequent words based on the preceding semantically related context. Older adults, however, did show a similar N400 word position effect but no attenuation of the N400 word frequency effect with increasing word position. Thus, older adults seem to rely more on bottom-up lexical features, such as word frequency, instead of contextual constraints in order to extract the meaning of sentences, supporting the view of attenuated top-down predictive processing during language comprehension in older adults.

### Age-Related Differences in the Online Semantic Processing of Pictorial Materials

The previously presented studies show a clear reduction in online semantic processing in older adults: There was no N400 effect for unexpected versus expected endings in weakly constraining contexts (Wlotko et al., 2012) and no attenuation of the N400 word frequency effect with increasing word position during sentence comprehension (Payne & Federmeier, 2018). This suggests that older adults are less able to make use of the available top-down information of the context in order to anticipate upcoming words. Strikingly, the majority of the studies investigating age-related differences in semantic processing used verbal materials. However, the N400 is assumed to reflect activity within a widespread domain-general and multimodal semantic memory network (Kutas & Federmeier, 2011). This view is supported by previous

work showing that the N400 effect is observed with a wide range of stimulus types like pictures (e.g., Nigam et al., 1992), familiar faces (e.g., Olivares et al., 1999), and environmental sounds (e.g., Van Petten & Rieffers, 1995).

Following the multimodal view of the N400 (Nigam et al., 1992), the age-related attenuation of online semantic processing for verbal materials (Payne & Federmeier, 2018; Wlotko et al., 2012) should be present also for other modalities, as for example pictures. Surprisingly, the empirical evidence for age-related differences in picture semantics is sparse.

In one of the few studies investigating the N400 with pictorial material in older adults, Chaby et al. (2001) used famous faces in a priming task, in which the prime consisted of a famous face with covered eyes followed by the target representing the same famous face either with the correct eyes (i.e., congruent) or with eyes of another famous person (i.e., incongruent). There were no age-related differences for the N400 effect (congruent vs. incongruent faces). Instead of using famous faces, Ostrosky-Solís et al. (1998) used more common pictorial items by conducting a picture-semantic matching task with categorically related (e.g., piano–violin) and unrelated (e.g., glasses–pan) line drawings in younger and healthy older adults. Participants saw two objects presented sequentially and had to judge whether the second picture is related to the first one. Both age groups, younger and older adults, showed an N400 effect, suggesting that semantic processing in older adults seems to be as sensitive to category congruency of picture pairs as in younger adults.

Cheimariou et al. (2019) implemented a similar task, in which participants had to judge the match between a picture and a following word: The first item was a picture, which either enabled a strong prediction for the upcoming word or not (i.e., predictive vs. nonpredictive condition). The following word could either match the image (e.g., “apple” following the picture of an apple) or not (e.g., “banana” following the picture of an apple). Younger adults showed an N400 effect for the predictive condition only, whereas for older adults, an N400 effect was observed for both the predictive and the nonpredictive conditions. Thus, older adults seem to rely less on predictive processing but more on integration mechanisms initiated by bottom-up information provided by the target word.

To sum up, these few studies (Chaby et al., 2001; Cheimariou et al., 2019; Ostrosky-Solís et al., 1998) represent the only studies investigating age effects in semantic processing indicated by the N400 for pictures instead of sentences, and none of these studies found an interaction between age and semantic relationship for the N400 amplitude (for a review, see Joyal et al., 2020).

### Semantic Relationships Based on Thematic Relations

Interestingly, both studies using pictorial materials (Cheimariou et al., 2019; Ostrosky-Solís et al., 1998) created semantic relationships based on categorical relations. Categorical relations are characterized by membership in a common category based on shared features (e.g., lion and tiger as members of the category “predator”). However, semantic relationships can also be based on thematic relations (Estes et al., 2011), which arise when two objects fulfill complementary roles in the same event as they either co-occur frequently together (e.g., wine glass and dinner plate) or are included in a certain action (e.g., hammer and nail).

Given that previous research about online semantic processing of pictorial materials only used categorical relations, there are three

main reasons why investigating thematic relations within object pairs is valuable. First, previous work suggests that the N400 is more sensitive to thematic than categorical relationships (Ortu et al., 2013; Rhodes & Donaldson, 2008). Second, from the perspective of the multimodal view of the N400 (Nigam et al., 1992), the study of the N400 should be extended to thematically related pictorial materials, rather than being limited to categorically related ones (Cheimariou et al., 2019; Ostrosky-Solís et al., 1998). Finally, thematically related object pairs represent a more ecologically valid type of semantic relationship compared to taxonomic relations because certain everyday objects (e.g., a knife and a cucumber)—despite belonging to different categories—frequently co-occur in daily life.

### Relationship Between N400 Effect and Behavioral Memory Performance

Considering the differential impact of healthy aging on semantic and episodic memory (Horn & Cattell, 1967; Naveh-Benjamin, 2000), as outlined above, an interesting and related aspect when investigating age-related differences in semantic processing is to look at long-term consequences of differential semantic processing for episodic memory formation. A few previous studies examined whether and how online semantic processing of sentences affects memory formation in younger and older adults (Payne & Federmeier, 2018; Wlotko et al., 2012). Surprisingly, while older adults as compared to younger adults showed attenuated N400 effects during encoding, there were no age-related differences in memory performance when memory for the sentence endings (Wlotko et al., 2012) or for the sentences (Payne & Federmeier, 2018) was tested in an ensuing recognition test. This suggests that, even though there is clear evidence that older adults' online semantic processing is attenuated, this attenuation does not affect their episodic memory for the semantic information. One possible reason for this dissociation might be the fact that memory performance in previous studies was tested using relatively easy item memory tasks, in which older adults perform highly similar to younger adults, whereas for associative memory, older adults typically perform worse than younger adults (Naveh-Benjamin, 2000). Thus, it is not known how age-related attenuation of online semantic processing might be associated with the age-related associative memory deficit.

### The Present Study

In the present study, we used sequentially presented object pairs because this allows investigating the N400 effect for the second object in isolation (Cheimariou et al., 2019; Ostrosky-Solís et al., 1998). As thematic relations are highly ecologically valid and reliably induce N400 effects (Ortu et al., 2013; Rhodes & Donaldson, 2008), we used thematically related object pairs. Thus, our study aims at investigating the following three research questions: First, are there age-related differences in online semantic processing of pictorial materials when the object pairs are thematically related instead of taxonomically related as it was examined before (Cheimariou et al., 2019; Ostrosky-Solís et al., 1998)? If so, then the N400 effect should be smaller in older adults as compared to younger adults.

Second, are age-related differences in online semantic processing also reflected in age-related differences in a behavioral measurement, that is, semantic congruency rating? Previous work shows that for both online semantic processing reflected by the N400 effect and

behavioral measurements of semantic processing, results regarding age-related differences are mixed (Chaby et al., 2001; Cheimariou et al., 2019; Ostrosky-Solís et al., 1998). On the one side, Cheimariou et al. (2019) and Ostrosky-Solís et al. (1998) found no age-related differences in accuracy for the picture-semantic matching tasks despite neural age-related changes. On the other side, Chaby et al. (2001) found that older adults performed worse in a semantic congruency task, while there were no differences in the N400 effect.

Finally, do such age-related differences in semantic processing transfer to episodic memory (i.e., associative memory)? The first two research questions were investigated using a semantic priming task. For the third research question, an ensuing associative recognition memory test for semantically related and unrelated picture pairs was applied.

## Method

### Transparency and Openness

We report how we determined our sample size, and describe all data exclusions, manipulations, and all measures in the study. All data and analysis code are available. Stimulus materials are copyright protected and cannot be provided. This study's design, its hypotheses, and its analyses were not preregistered.

### Sample

The sample consisted of 32 younger adults ( $M = 23.1$ ,  $SD = 2.6$ , range = 20–33) and 31 older adults ( $M = 71.6$ ,  $SD = 4.6$ , range = 66–81). Table 1 includes all demographic data for both age groups. For the older adults, 52 participants were invited for a neuropsychological prescreening session. After excluding older adults who did not fulfill the inclusion criteria (see the Neuropsychological Screening section), a total of 32 older adults were invited to the second session (i.e., electroencephalogram [EEG] session). Sample size was determined by an a priori power analysis for ERP effects in the test phase that will be reported in another publication. For this purpose, a power analysis based on the effect of interest, that is, the interaction between condition and response found for older adults in a previous study investigating the influence of unitization on associative memory (Zheng et al., 2015),  $f = 0.53$ ,  $\alpha = .05$ , power = .80, resulted in a required sample size of  $n = 7$ . However, there was no previous study based on which an effect size for the age effect on this interaction could be estimated. Thus, a total of 32 participants in each

**Table 1**  
*Demographic Information and Neuropsychological Data of the Sample*

| Demographic and neuropsychological variable | Younger adult | Older adult  |
|---|---------------|--------------|
| <i>N</i>                                    | 32            | 31           |
| Gender distribution (female/male)           | 22/10         | 19/12        |
| $M_{\text{age}}$ (years)                    | 23.1 (2.57)   | 75.58 (4.60) |
| Age range (years)                           | 20–30         | 66–81        |
| Education (years)                           | 14.67 (1.60)  | 14.41 (2.69) |
| Neuropsychological data                     |               |              |
| Mini-Mental State Examination               |               | 29.22 (0.88) |
| Digit-Symbol Test                           |               | 48.83 (7.57) |

*Note.* Standard deviations are given in parentheses.

age group were tested to detect potential age-related differences while ensuring a counterbalancing of the design and achieving a substantial sample for inferential statistical analyses. Data of one older adult had to be excluded due to too small number of trials (i.e., less than eight) in one of the conditions for ERP averaging. Thus, the final sample for behavioral and ERP analyses consisted of 32 younger and 31 older adults. All participants were German native speakers, were 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. We did not collect data about the ethnic breakdown of our samples. Informed consent was required, and the younger adults received course credits or a payment of 10€/hr for their participation. The older adults received a payment of 10€/hr plus parking fees (3€). All data were collected between Summer 2021 and Spring 2022 at Saarland University in Germany. The experiment was approved by the ethics committee of the Faculty for Human and Business Sciences, Saarland University.

## Neuropsychological Screening

Before arriving at the first session, a screening on the telephone was completed with the older adults, in which general criteria such as age, native language, neurological and psychological diseases, and visual problems were assessed. The session with the neuropsychological screening lasted about 45 min and started with the neuropsychological test battery Consortium to Establish a Registry for Alzheimer's Disease-Plus (Monsch et al., 1997) that includes the following seven subtests: (a) verbal fluency, (b) Boston Naming Test, (c) Mini-Mental Status, (d) word-list memory (recall and recognition), (e) figural memory (copy and recall), (f) Trail Making Test A and B, and (g) phonemic fluency. Next, 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 conducted. The session concluded with the Edinburgh Handedness Inventory (Oldfield, 1971). Fifty-two older adults were tested, and only those participants who showed no severe deficits in all subtests of the Consortium to Establish a Registry for Alzheimer's Disease (i.e., min.  $-1.5 SD$ ; see Huffer et al., 2022, for a similar procedure<sup>1</sup>) were invited to the second session including the EEG experiment ( $n = 32$ ). Table 1 shows the demographic information as well as some neuropsychological data for the final sample included in all analyses. The two groups did not differ significantly in terms of years of education,  $t(61) = -0.45$ ,  $p = .65$ , or gender distribution,  $\chi^2(1) = 0.38$ ,  $p = .53$ . The older adults' performance in the Wechsler Digit-Symbol Substitution Test ( $M = 48.83$ ,  $SD = 7.57$ ), representing their perceptual speed of processing, corresponds to the normal range for this age group as indicated by results of previous studies (Ferdinand & Kray, 2013; Kray et al., 2008). The Mini-Mental State Examination (Folstein et al., 1975) serves as a short standardized test indicating severe cognitive impairments. All older adults had a normal Mini-Mental State Examination score ( $M = 29.22$ ,  $SD = 0.88$ , range = 27–30).

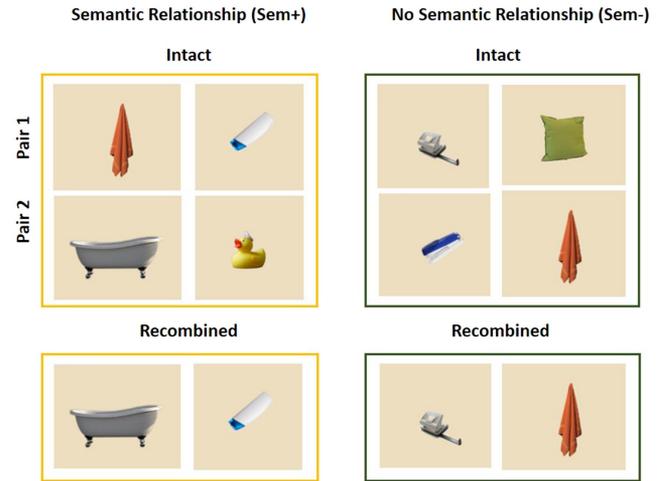
## EEG Session

### Stimulus Materials

The stimulus materials consisted of 640 single objects that were collected from various picture databases and internet sources and then edited with Photoshop CS6. These single objects were used in

**Figure 1**

*Examples for Intact and Recombined Object Pairs With and Without Semantic Relationships*



*Note.* One recombined object pair was always built on the basis of two intact object pairs. Sem+ intact: towel (upper left side) and body lotion (upper right), bathtub (lower left side) and rubber duck (lower right side); Sem+ recombined: bathtub (left side) and body lotion (right side); Sem- intact: punch (upper left side) and seat cushion (upper right side), stapler (lower left side) and towel (lower right side); Sem- recombined: punch (left side) and towel (right side). Pictures used in this figure are taken from the image database Pixabay (<https://pixabay.com/de/>) and show the same objects as used in the experiment. See the online article for the color version of this figure.

order to create 320 semantically related and 320 semantically unrelated object pairs as well as 160 corresponding recombined object pairs in each semantic relationship condition (see Figure 1 for stimulus examples). In a first step, 824 single objects were used to build 412 semantically related object pairs. For the purpose of counterbalancing the assignment of single objects to conditions, the same objects were used to build 412 semantically unrelated pairs. In both conditions, we built recombined pairs on the basis of two intact pairs each while maintaining their semantic (un-)relatedness (i.e., 206 recombined object pairs in each condition). The single objects had a height of 2–5 cm and a width of 2–4 cm. In a second step, the material was validated in two separate rating studies with younger and older adults. First, the semantically related object pairs were rated. This rating study was part of a larger rating study (see Huffer et al., 2022), in which the recognizability of the objects was evaluated by 36 younger ( $M = 23.22$  years, range = 19–30) and 36 older ( $M = 69.36$ , range = 65–80) adults, who did not participate in the EEG experiment. Recognizability of the objects was assessed by presenting the objects in a booklet in the same size as they would later be presented on the computer screen. While going through the booklet, participants were instructed to indicate those objects they could not recognize. Afterward, the actual object pairs were rated in

<sup>1</sup> The increased exclusion rate in the present study as compared to our previous study could be related to the fact that the screening and testing were conducted during the ongoing pandemic period of 2021, which might have affected the cognitive status, especially in older adults (Meyer & Zaiser, 2025).

a computer experiment by 12 younger ( $M = 23.75$  years, range = 21–26) and 12 older ( $M = 69.33$  years, range = 65–80) adults with regard to their semantic relationship. The participants had to judge the likelihood of the two objects to appear together in real life as currently presented (0 = *very unlikely* to 5 = *very likely*). Each participant saw all object pairs (412 intact and 206 recombined pairs in each condition) presented side by side.

Only single objects that were recognized by at least 80% of the participants of both age groups were included into the material set. Then, based on younger adults' ratings, the 320 object pairs with the highest semantic relatedness rating were selected. After selecting these semantically related object pairs, some of the semantically unrelated object pairs had to be changed in order to be able to fully counterbalance the assignment of the single objects to both semantic relation conditions across participants (i.e., one participant learned one single object in either a semantically related or unrelated object pair). Thus, a second rating study with 16 younger ( $M = 24.62$  years, range = 18–30) and 16 older ( $M = 73.62$  years, range = 67–85) adults was conducted in order to validate the 320 semantically unrelated object pairs (and their 160 corresponding recombined pairs) corresponding to the selected 320 object pairs with semantic relationships. The procedure for the rating was the same as in the first rating study, except for the fact that the second rating study was conducted as an online study due to the COVID-19 pandemic.

Table 2 shows the total means regarding semantic relationship for the intact and recombined pairs in both age groups. For both age groups, as expected, the semantically related object pairs achieved significantly higher ratings as compared to the semantically unrelated object pairs—younger adults: intact,  $t(638) = 52.99$ ,  $p < .001$ ,  $g_s = 4.17$ , and recombined,  $t(318) = 28.32$ ,  $p < .001$ ,  $g_s = 3.18$ ; older adults: intact,  $t(638) = 49.51$ ,  $p < .001$ ,  $g_s = 3.92$ , and recombined,  $t(318) = 27.58$ ,  $p < .001$ ,  $g_s = 3.08$ . For the semantically related object pairs, there was a difference between the rating for the intact and recombined object pairs in both age groups—younger adults: Sem+,  $t(478) = 5.35$ ,  $p < .001$ ,  $g_s = 0.51$ ; older adults: Sem+,  $t(478) = 4.39$ ,  $p < .001$ ,  $g_s = 0.43$ . For the semantically unrelated object pairs, there were no differences between intact and recombined object pairs in both age groups—younger adults: Sem–,  $t(478) = 1.71$ ,  $p = .09$ ,  $g_s = 0.17$ ; older adults: Sem–,  $t(478) = 0.85$ ,  $p = .39$ ,  $g_s = 0.07$ . Furthermore, there were no age-related differences for the rating of the object pairs except for a marginally significant difference between younger and older adults for the semantically related intact object pairs—Sem+ intact,  $t(638) = 1.92$ ,  $p = .05$ ,  $g_s = 0.15$ ; Sem+ recombined,  $t(318) = 0.49$ ,  $p = .62$ ,  $g_s = 0.35$ ; Sem– intact,  $t(638) =$

1.31,  $p = .19$ ,  $g_s = 0.11$ ; Sem– recombined,  $t(318) = 0.31$ ,  $p = .75$ ,  $g_s = 0.02$ . However, when looking at the effect sizes regarding the age-related difference ( $g_s = 0.15$ ) and the difference between semantically related intact and recombined object pairs (younger adults:  $g_s = 0.51$ ; older adults:  $g_s = 0.43$ ), it is clear that the differences are rather small and negligible given that the manipulation of the semantic relationship was effective in both age groups.

Study lists consisted of 120 semantically related and 120 semantically unrelated object pairs. Test lists consisted of 40 intact pairs, 40 recombined pairs, and 40 new pairs in each condition. Across the test lists, each object pair appeared once as a new and intact pair and twice as a recombined pair in each semantic relation condition. The assignment of object pairs to conditions was counterbalanced across subjects.

### Procedure

The EEG session lasted about 3 hr. 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 preparation of the EEG, the participants were familiarized with all single objects used later in the experiment by looking through a booklet containing the single objects. Afterward, the participants 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 1,920 × 1,080 pixels. The experiment was programmed and presented with E-Prime 2 software (Psychology Software Tools, Inc., Pittsburg, Pennsylvania). All objects were presented against a beige background with a size of 500 × 500 pixels.

Before the actual experiment, a practice block including one study and one test phase was conducted. Twenty-four additional object pairs were used that were not selected for the actual experiment. The practice study phase consisted of a semantic priming task including 18 object pairs (nine pairs with semantic relationship, nine pairs without semantic relationship). For the practice test phase, 18 object pairs were used, half of them including a semantic relationship (three pairs per condition intact/recombined/new) and the other half of them including no semantic relationship (again, three pairs per condition intact/recombined/new). The practice block followed the procedure from the actual experiment. The only exception was that participants received feedback after each trial during the test phase, 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 resulting in 60 trials (30 per condition) per study and test block. 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 semantic relationship were presented in a row and, in the test phase, each combination of semantic relationship (Sem+ or Sem–) and status condition (intact, recombined, or new) appeared not more than three times in a row. Each study block started with four additional, and each test block started with three additional example trials. Figure 2 shows the trial procedure for the study and test phases, respectively. During the study phase, a semantic priming task was implemented by presenting the object pairs sequentially. The participants had to judge the semantic relationships between the object pairs after the second object by rating how likely it is that both presented objects co-occur

**Table 2**

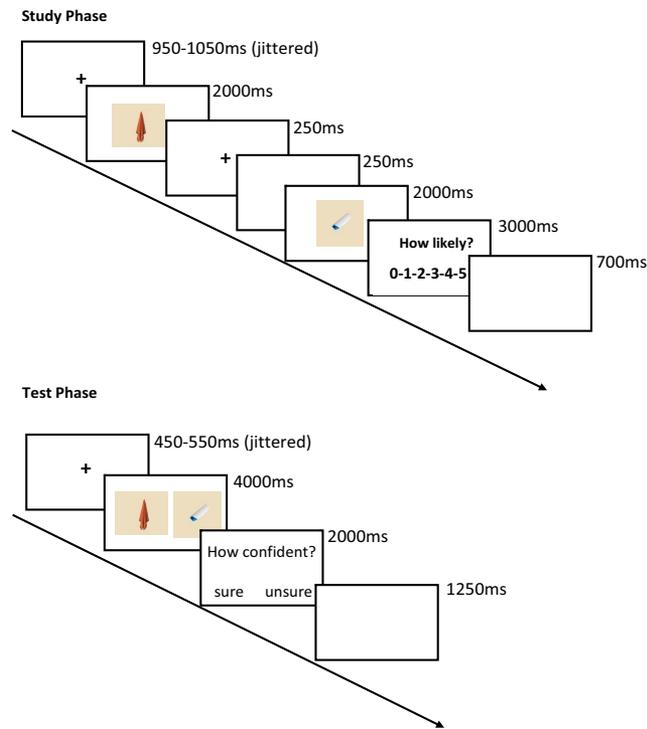
*Means for Semantic Relationship of the Final Set of Intact and Recombined Pairs for Both Age Groups*

| Age group and object pair condition | Semantic relationship |             |
|-------------------------------------|-----------------------|-------------|
|                                     | Sem+                  | Sem–        |
| Younger adults                      |                       |             |
| Intact                              | 4.02 (0.98)           | 0.64 (0.59) |
| Recombined                          | 3.47 (1.24)           | 0.55 (0.38) |
| Older adults                        |                       |             |
| Intact                              | 3.87 (1.05)           | 0.58 (0.55) |
| Recombined                          | 3.40 (1.20)           | 0.54 (0.53) |

*Note.* Standard deviations are given in parentheses.

**Figure 2**

*Trial Procedure for the Study (Sequential Presentation of the Object Pairs) and Test Phase (Simultaneous Presentation of the Object Pairs)*



*Note.* See the online article for the color version of this figure.

in the real world (0 = *very unlikely*, 5 = *very likely*) using a response box with six buttons. The assignment of the buttons to the response options was counterbalanced across subjects. In addition, they were instructed to memorize the object pairs for the next part of the experiment. A study trial started with a fixation cross for 1,000 ms (randomly jittered between 950 and 1,050 ms), and then, the first object of the object pair was presented for 2,000 ms. Afterward, a short fixation cross appeared for 250 ms and was followed by a short blank screen for 250 ms. Then, the second object of the object pair was presented for 2,000 ms. Thereafter, the rating question with the corresponding scale (i.e., from 0 to 5) appeared on the screen for 3,000 ms. As soon as a response was given, the trial concluded with a 700-ms blank screen (see Figure 2). The order in which the object pairs were presented was counterbalanced across participants. 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 that lasted approximately 3 min. Here, the participants had to indicate whether the given arithmetic equations were correct or incorrect. In the test phase, object pairs were presented simultaneously side by side. Participants had to judge if the presented object pair was old, recombined, or new by pressing one of three buttons on the response box. The assignment of the three buttons to the response options was counterbalanced across subjects. Each test trial started with a fixation cross for 500 ms (randomly jittered between 450 and 550 ms). Afterward, the object pair was presented

side by side for 4,000 ms. The presentation side of the objects was counterbalanced across subjects and maintained from the study to the test phase. 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 screen with a binary confidence rating appeared for 2,000 ms. Here, the subjects had to judge how confident they were with their response (sure–unsure) by pressing one of two buttons on the response box. Response assignments were counterbalanced across subjects. After rating their confidence, a blank screen for 1,250 ms finished the trial (see Figure 2). After completing all four study–test blocks, the participants concluded the session with an unrelated active oddball task. At the end of the session, subjects completed a follow-up survey, were debriefed, and were paid for their participation.

### EEG Recording and Analyses

The EEG was recorded using BrainVision Recorder V1.02 (Brain Products GmbH) 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 phases. Four additional electrodes were placed around the eyes (two electrodes above and below the right eye and two electrodes at the outer canthi of both eyes) to measure the vertical and horizontal electrooculogram. An electrode placed on the left mastoid (A1) serves as an online reference, and AFz was used as a ground electrode. Electrode impedances were kept below 5 k $\Omega$ . The EEG was amplified with a BrainAmp DC amplifier (Brain Products GmbH) from 0.016 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 semiautomatic algorithm implemented in BrainVision Analyzer 2.1 was applied to the continuous EEG data (Ocular Correction independent component analysis). After re-referencing the left and right mastoid electrodes, the continuous EEG was divided into segments that started 200 ms before stimulus presentation and ended 2,000 ms after stimulus onset. Baseline correction was applied relative to the 200-ms time interval prestimulus onset. Thereafter, segments containing amplitudes greater or smaller than  $\pm 70$   $\mu$ V were excluded. Afterward, averaging was conducted for each condition with a minimum of eight trials per condition. The mean trial numbers and ranges were as follows: object pairs with semantic relationship (younger adults: 105.9 [13–120]; older adults: 95.9 [29–119]) and object pairs without semantic relationship (younger adults: 107.7 [26–120]; older adults: 96.0 [40–120]). Grand averages were calculated for each condition.

### Analyses

All statistical analyses were conducted with R Version 3.6.1 and RStudio (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” (RStudio

Team, 2019) was used for computing  $t$  tests for independent and dependent samples in order to disentangle significant interactions. In addition to standard hypothesis testing, Bayesian statistics were implemented in order to quantify evidence supporting the null hypothesis when results of  $t$  tests suggested no significant differences. Therefore, the package “BayesFactor” (Morey & Rouder, 2023) was used to analyze the Bayes factor testing the null hypothesis against the alternative hypothesis (i.e.,  $BF_{01}$ ). When the Bayes factor is greater than 3, “moderate evidence” for the null model, and thus, the absence of significant differences, is favored (Rouder et al., 2009; Schönbrodt & Wagenmakers, 2018). The package “DescTools” (Signorell, 2020) was used to compute the effect size generalized eta squared ( $\eta^2_G$ ). The effect size Hedges’s  $g$  for the between-subjects and within-subjects comparisons was conducted based on the formula by Lakens (2013). The  $\alpha$  level was set to .05.

### Behavioral Analyses

**Study Phase.** For the analysis of the judgment task during the study phase, the mean rating of the semantic relations based on the given ratings during encoding was calculated for semantically related and semantically unrelated object pairs. In the following, the term “behavioral congruency effect” refers to the behavioral effect of semantic relationships, that is, a significantly higher congruency rating for semantically related object pairs as compared to semantically unrelated object pairs.

These ratings were included in a mixed-model ANOVA with age group (younger/older) as the between-subjects factor and semantic relationship (Sem+/Sem–) as the within-subjects factor.

**Test Phase.** To quantify the associative and item memory performance during the test phase, two different indices were computed (see Huffer et al., 2022). First, for the associative memory index, the associative false alarm rate was subtracted from the associative hit rate. The associative false alarm rate includes recombined object pairs mistakenly recognized as old relative to all recombined pairs with at least correct item memory (recombined pairs judged as recombined and recombined pairs judged as old). The associative hit rate is 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 judged as old and old object pairs judged as recombined).

We also computed an item memory index in order to establish a correspondence with other aging studies on memory- and age-related changes of the N400 without age-related differences in memory performance (i.e., item memory) at the same time. 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) can be observed in our sample (Old & Naveh-Benjamin, 2008). For the item memory index, the item false alarm rate was subtracted from the item hit rate. The item hit rate is the proportion of object pairs with correct item memory (old object pairs judged as old, old object pairs judged as recombined, recombined object pairs judged as recombined, recombined object pairs judged as old) relative to all object pairs that could be known from the study phase (old and recombined object pairs). The item false alarm rate is the proportion of new object pairs that are mistakenly recognized as known on an item basis (new object pairs judged as old and new object pairs judged as recombined) relative to all new object pairs.

The indices were included in a three-factorial mixed-model ANOVA with the between-subjects factor age group (younger/older) and the two within-subjects factors semantic relationship (Sem+/Sem–) and memory type (item/associative).

### Electrophysiological Analyses

In the current article, we only report EEG data from the study phase. Nine representative electrodes were selected: F3, Fz, and F4 for frontal; C3, Cz, and C4 for central; and P3, Pz, and P4 for parietal scalp distribution of the ERP effects (Bridger et al., 2017; Huffer et al., 2022). For both age groups, the time window 300–500 ms poststimulus onset of the second object within one object pair was analyzed.

First, a global ANOVA was conducted including the between-subjects factor age group (younger/older) and the within-subjects factors semantic relationship (Sem+/Sem–), laterality (left/middle/right), and location (frontal/central/parietal). In case of significant interactions, these were further unraveled by ANOVAs and pairwise  $t$  tests.

## Results

### Behavioral Results

#### Study Phase

Table 3 shows the mean ratings for semantically related and semantically unrelated object pairs within each age group. The mixed-model ANOVA of the mean ratings revealed a significant main effect of semantic relationship,  $F(1, 61) = 3089.81, p < .001, \eta^2_G = 0.95$ , indicating the expected behavioral congruency effect—that is, semantically related object pairs were rated as significantly more congruent than semantically unrelated object pairs. Neither the main effect of age group nor the Age Group  $\times$  Semantic Relationship interaction reached significance. Thus, there were no age differences either in the ratings of semantically related object pairs,  $t(61) = 0.32, p = .74, g_s = 0.08, BF_{01} = 3.71$ , or for the ratings of the semantically unrelated object pairs,  $t(61) = -0.37, p = .70, g_s = 0.09, BF_{01} = 3.66$ . As both Bayes factors are greater than 3, the null model is favored (Rouder et al., 2009).

#### Test Phase

Table 4 shows the means for the performance indices of item and associative memory as well as accuracy for intact, recombined, and new object pairs. There were main effects of age group,  $F(1, 61) = 44.20, p < .001, \eta^2_G = 0.32$ ; semantic relationship,  $F(1, 61) = 98.83, p < .001, \eta^2_G = 0.10$ ; and memory type,  $F(1, 61) = 170.13, p < .001, \eta^2_G = 0.37$ . Furthermore, there was a significant interaction between

**Table 3**  
*Mean Semantic Congruency Ratings During the Study Phase*

| Age group      | Semantic relationship |             |
|----------------|-----------------------|-------------|
|                | Sem+                  | Sem–        |
| Younger adults | 4.08 (0.36)           | 0.68 (0.38) |
| Older adults   | 4.11 (0.37)           | 0.64 (0.42) |

*Note.* Standard deviations are given in parentheses.

**Table 4**  
*Behavioral Performance of the Test Phase*

| Memory variable | Younger adult |             | Older adult |             |
|-----------------|---------------|-------------|-------------|-------------|
|                 | Sem+          | Sem−        | Sem+        | Sem−        |
| PR score        |               |             |             |             |
| Item            | 0.86 (0.08)   | 0.80 (0.10) | 0.74 (0.19) | 0.66 (0.23) |
| Association     | 0.74 (0.13)   | 0.61 (0.16) | 0.46 (0.15) | 0.31 (0.14) |
| Accuracy        |               |             |             |             |
| Old             | 0.88 (0.09)   | 0.71 (0.14) | 0.80 (0.15) | 0.57 (0.20) |
| Recombined      | 0.79 (0.11)   | 0.77 (0.13) | 0.51 (0.18) | 0.53 (0.23) |
| New             | 0.90 (0.07)   | 0.87 (0.08) | 0.77 (0.21) | 0.74 (0.23) |

Note. Standard deviations are given in parentheses. PR = percentile rank.

age group and memory type,  $F(1, 61) = 18.80, p < .001, \eta^2_G = 0.06$ . Memory type-specific analyses revealed better item,  $t(61) = -3.34, p = .001, g_s = 0.81$ , and associative memory,  $t(61) = -8.69, p < .001, g_s = 2.20$ , for younger than older adults with larger effect sizes for associative memory. This pattern of results corresponds to the frequently reported age-related associative memory deficit (e.g., Naveh-Benjamin, 2000). In addition, there was a significant interaction between semantic relationship and memory,  $F(1, 61) = 12.01, p < .001, \eta^2_G = 0.01$ . Memory type-specific analyses revealed significant differences between related and unrelated object pairs for item memory,  $t(62) = 5.45, p < .001, g_{av} = 0.39$ , and associative memory,  $t(62) = 8.56, p < .001, g_{av} = 0.67$ , with larger effect sizes for associative memory than for item memory. This suggests that in both age groups, the memory benefit from semantic relationships was larger for associative than for item memory. None of the other interactions reached significance ( $ps > .53$ ).

To sum up, both age groups judged the semantic relationships in a similar manner, reflected in the similar congruency ratings of the object pairs during the study phase. Furthermore, the expected age-related associative memory deficit was observed, with larger age-related differences for associative than for item memory. Interestingly, however, younger and older adults' memory performance benefitted in a similar way from the presence of semantic relationships, with the largest effects for associative memory for both groups.

## ERP Results

Figure 3 shows the averaged ERP waveforms for the second objects of semantically related and semantically unrelated object pairs for younger and older adults, respectively. As apparent from both figures, there are noticeable between-group differences in the ERP waveforms, in that the older adults' ERPs in the N400 interval are more positive-going than the younger adults' ERPs. Furthermore, there is a pronounced N400 effect for younger adults (i.e., more positive-going waveforms in the Sem+ vs. Sem− condition), while this effect was clearly attenuated or absent for older adults (see Figure 4 for the topographical maps for the N400 effect in both age groups).

### N400 Effect on the Second Object of the Object Pairs (300–500 ms)

As a first step, we run a global four-factorial ANOVA with the between-subjects factor age group (younger/older) and the within-

subjects factors semantic relationship (Sem+/Sem−), laterality (left/middle/right), and location (frontal/central/parietal). Table 5 gives an overview of the results of this ANOVA, depicting only the significant effects and interactions including semantic relationship. As the four-way interaction Age Group  $\times$  Semantic Relationship  $\times$  Laterality  $\times$  Location was significant,  $F(4, 244) = 2.97, p = .02, \eta^2_G < 0.01$ , follow-up three-factorial ANOVAs were conducted separately for each age group.

**Younger Adults.** The three-way ANOVA revealed main effects of semantic relationship,  $F(1, 31) = 78.86, p < .001, \eta^2_G = 0.07$ ; laterality,  $F(2, 62) = 7.64, p = .001, \eta^2_G = 0.01$ ; and location,  $F(2, 62) = 126.47, p < .001, \eta^2_G = 0.33$ . In addition, there were significant interactions between laterality and location,  $F(4, 124) = 6.31, p < .001, \eta^2_G < 0.01$ ; semantic relationship and laterality,  $F(2, 62) = 6.76, p = .002, \eta^2_G < 0.01$ ; and semantic relationship and location,  $F(2, 62) = 7.25, p = .001, \eta^2_G < 0.01$ . Dissolving these latter two interactions, pairwise comparisons for each location pooled across laterality as well as for each laterality pooled across location were conducted. There were significant N400 effects for all three location levels (all  $ps < .001$ ), with the largest effects for central electrodes,  $t(31) = 9.20, p < .001, g_{av} = 0.59$ , and the smallest effects for parietal electrodes,  $t(31) = 7.82, p < .001, g_{av} = 0.44$ . Furthermore, the analyses showed significant N400 effects at all three laterality levels (all  $ps < .001$ ), with the largest effects for right electrodes,  $t(31) = 8.76, p < .001, g_{av} = 0.61$ , and the smallest effects for middle electrodes,  $t(31) = 8.69, p < .001, g_{av} = 0.55$ .

**Older Adults.** The three-way ANOVA revealed main effects of semantic relationship,  $F(1, 30) = 4.28, p = .047, \eta^2_G < 0.01$ ; laterality,  $F(2, 60) = 10.61, p < .001, \eta^2_G < 0.01$ ; and location,  $F(2, 60) = 26.69, p < .001, \eta^2_G = 0.08$ . In addition, there were significant interactions between semantic relationship and laterality,  $F(2, 60) = 15.98, p < .001, \eta^2_G < 0.01$ , as well as between laterality and location,  $F(4, 120) = 5.38, p = .002, \eta^2_G < 0.01$ . Furthermore, the three-way interaction was significant,  $F(4, 120) = 5.84, p < .001, \eta^2_G < 0.01$ . This interaction was followed by two-way ANOVAs for each location level and revealed significant interactions between semantic relationship and laterality for each location—frontal:  $F(2, 60) = 17.01, p < .001, \eta^2_G < 0.01$ ; central:  $F(2, 60) = 12.91, p < .001, \eta^2_G < 0.01$ ; parietal:  $F(2, 60) = 8.60, p < .001, \eta^2_G < 0.01$ . Dissolving these two-way interactions by pairwise comparisons showed significant N400 effects, representing more positive-going waveforms for object pairs with semantic relationship, for the following electrodes: right frontal,  $t(30) = 2.19, p = .036, g_{av} = 0.13$ ; middle central,  $t(30) = 2.07, p = .047, g_{av} = 0.12$ ; right central,  $t(30) = 3.39, p = .001, g_{av} = 0.22$ ; and right parietal,  $t(30) = 3.06, p = .004, g_{av} = 0.26$ . For the remaining electrodes, there were no significant differences between semantically related and unrelated object pairs (all  $ps > .06$ ).

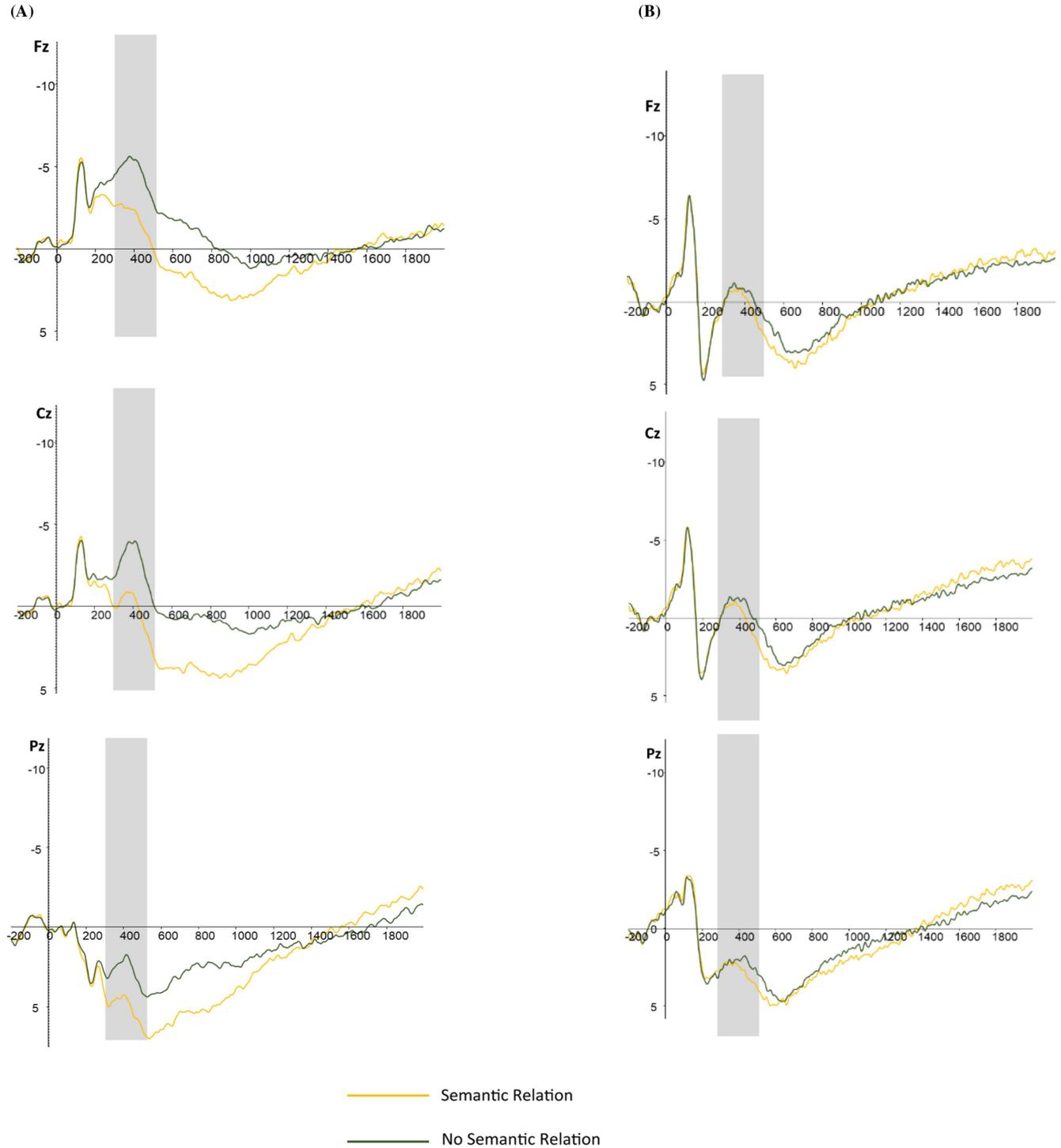
To sum up the ERP results, younger adults show a clear semantic N400 effect with a broad topographic distribution, whereas for older adults, this N400 effect is either smaller (i.e., at frontal [F4], central [Cz, C4], and parietal [P4] electrodes) or absent (i.e., at frontal [Fz, F3], central [C3], and parietal [P3, Pz] electrodes).

### Exploratory Analysis of Correlation Between Semantic Processing and Memory Benefit

As the behavioral and ERP results suggest that semantic processing during encoding is orthogonal to associative memory

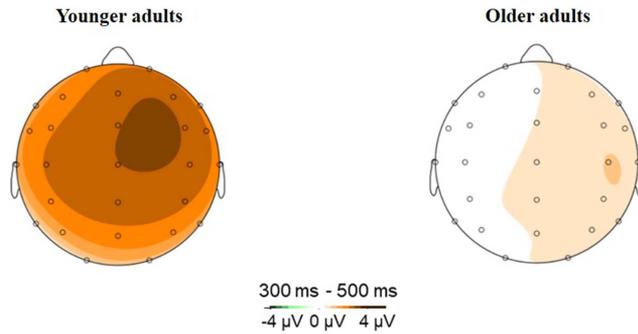
**Figure 3**

*Event-Related Potential Waveforms for the Second Object of Semantically Related and Semantically Unrelated Object Pairs for Younger and Older Adults*



*Note.* Panel A shows the data for younger adults, and Panel B shows the data for older adults. Data are depicted at the Fz, Cz, and Pz electrodes. See the online article for the color version of this figure.

**Figure 4**  
*Topographical Maps for the N400 Effect (Related Minus Unrelated Objects) for Younger and Older Adults (300–500 ms)*



Note. See the online article for the color version of this figure.

benefit induced by semantic relationships (i.e., there were clear age-related differences in the N400 effect, but no age-related differences in associative memory benefit), we further explored this pattern of results by conducting Pearson's product-moment correlations between measurements reflecting semantic processing (i.e., N400 effect and behavioral congruency rating) on the one hand and the associative memory benefit (the difference between the associative memory index for semantically related and unrelated pairs) on the other hand for younger and older adults, separately. In addition, the Bayes factor for each correlation index is reported in order to support nonsignificant correlations. We aimed at investigating how the following two aspects of semantic processing do relate to the benefit for associative memory: First, regarding the online semantic processing of the semantic relationships (i.e., N400 effect), a larger N400 effect might reflect more predictive processing initiated by the first object, leading to facilitated processing of the semantically related object pairs. This might lead to better elaboration of these object pairs and better associative memory for these associations. Second, regarding the behavioral measurement of the semantic processing (i.e., behavioral congruency effect), perceiving semantically related object pairs as more congruent than semantically unrelated object pairs might reflect the successful integration of the semantically related object pairs into the semantic network after seeing both objects. This might result in deeper

**Table 5**  
*Outcomes of Global Analysis of Variance for the Second Object of the Object Pairs*

| Effect   | 300–500 ms |
|--|------------|
| SemanticRel (1, 61)                                | 62.59***   |
| SemanticRel × Age (1, 61)                          | 24.68***   |
| SemanticRel × Laterality (2, 122)                  | 16.10***   |
| SemanticRel × Location (2, 122)                    | 6.45*      |
| SemanticRel × Age × Location (2, 122)              | 6.23*      |
| SemanticRel × Laterality × Location (4, 244)       | 4.61**     |
| Age × SemanticRel × Laterality × Location (4, 244) | 2.97*      |

Note. Shown are *F* values (in parentheses) only for significant effects and interactions including the factor semantic relationship in the global analysis of variance. SemanticRel = semantic relationship.  
 \*  $p < .05$ . \*\*  $p < .01$ . \*\*\*  $p < .001$ .

processing of these object pairs and, thus, benefit associative memory performance for these pairs.

**Younger Adults.** For younger adults, the correlation including the N400 effect was calculated for the pooled central electrodes, where the ERP effect was largest. There was no significant correlation between the N400 effect and the associative memory benefit induced by semantic relationships ( $r = 0.14$ ,  $p = .44$ ;  $BF_{01} = 2.00$ ). Furthermore, the behavioral congruency effect during encoding (i.e., behavioral measurement of semantic processing) did not correlate with the associative memory benefit ( $r = 0.15$ ,  $p = .40$ ;  $BF_{01} = 1.90$ ).

**Older Adults.** For older adults, the correlation including the N400 effect was calculated for electrode C4, as the ERP effect was largest at this site. The N400 effect during encoding did not correlate significantly with the associative memory benefit induced by semantic relationships ( $r = 0.18$ ,  $p = .33$ ;  $BF_{01} = 1.70$ ). Interestingly, however, there was a significant correlation between the behavioral congruency effect during encoding and associative memory benefit ( $r = .48$ ,  $p < .01$ ).

To sum up, younger adults' semantic processing during encoding seems to be unrelated to the associative memory benefit by semantic relationships. For older adults, the online semantic processing during encoding seems to be unrelated to benefiting from semantic relationships for their associative memory as well. However, their processing of the semantically related object pairs reflected in the behavioral measurement correlates with their associative memory benefit by semantic relationships.

## Discussion

The goal of the current experiment was to investigate whether there are age-related differences in the online semantic processing of thematically related pictorial materials, as reflected by the N400 effect. Furthermore, we aimed at investigating whether such age-related differences are paralleled by age-related differences in behavioral measures of semantic processing, that is, a semantic congruency rating. Finally, we wanted to assess whether such age-related differences in semantic processing transfer to associative memory for semantically related object pairs. We combined a semantic priming task during the study phase with semantically related and unrelated picture pairs with an ensuing associative memory task. Interestingly, the N400 attenuation for the semantically related object pairs was smaller for older adults than for younger adults, suggesting that the online semantic processing of pictorial materials is attenuated in older adults. However, these age-related differences in online semantic processing are not reflected in behavioral measurements of semantic processing, as younger and older adults made highly similar semantic congruency ratings in the priming task. Furthermore, the age-related differences in online semantic processing are not paralleled by differences in the semantic benefit for associative episodic memory. Both age groups, younger and older adults, showed a similar associative memory benefit from the semantic relationships between the objects.

## No Age-Related Differences in Behavioral Measurements of Semantic Processing and Episodic Memory

Behavioral results showed no age-related differences in the congruency ratings of the object pairs. This pattern of results fits to

previous evidence for the absence of age-related differences in semantic judgment tasks (Cheimariou et al., 2019; Ostrosky-Solís et al., 1998). Cheimariou et al. (2019) found no difference between younger adults' and older adults' accuracy in judging the categorical match between a picture and a subsequently presented word. Similar results were observed in the study by Ostrosky-Solís et al. (1998), where age groups did not differ in their congruency judgments for categorically related and unrelated picture pairs.

Consistent with the similar semantic congruency ratings in both age groups, we observed a similar memory benefit by the presence of semantic relationships for the associative memory for semantically related object pairs in younger and older adults, suggesting that our semantic relationships supported associative memory in older age as previous work has shown (Delhaye et al., 2019).

Thus, considering only our behavioral results, the impression might arise that younger and older adults do not differ in their semantic processing of the object pairs. This supports the view that semantic knowledge (i.e., part of crystallized intelligence and pragmatics) remains intact in older age (Baltes et al., 1998; Horn & Cattell, 1967). However, examining the results for the N400 effect as an indicator of the online semantic processing revealed clear age-related differences in the underlying neuronal mechanisms.

### Age-Related Differences in Neuronal Semantic Processing

We found a diminished N400 effect (i.e., larger negativity for semantically unrelated than related object pairs) in older adults as compared to younger adults. One general aspect worth mentioning is the morphological differences in the ERPs when comparing the N400 effects between both age groups. These differences are not atypical in ERP studies with different age groups and most likely reflect consequences of structural brain aging (Mark & Rugg, 1998). If we take the N400 effect as a proxy for predictive lexical processing, our results fit to previous work using verbal materials showing less predictive processing in older adults (Payne & Federmeier, 2018; Wlotko et al., 2012). As outlined in the introduction, Payne and Federmeier (2018) found no attenuation of the N400 word frequency effect with increasing word position within an unfolding sentence for older adults (in contrast to younger adults). The authors took this result pattern to reflect stronger reliance of older adults on bottom-up stimulus-driven integration processes by adapting a “wait and see” approach instead of using more cognitively demanding top-down context-driven mechanisms to extract the meaning of the sentence. However, as we found no age-related differences in the semantic congruency ratings, our data may suggest that older adults tend to wait for the second object instead of generating predictions for the second object immediately after having seen the first object. Nevertheless, after seeing the second object of the object pair, we assume that older adults are still able to semantically integrate the two objects similarly to younger adults.

One possible explanation for initiating less predictive processing in older age might be a decrease of executive resources (Ryskin & Nieuwland, 2023) and, thus, attenuated self-initiated processing ( Craik, 1983). This decrease of predictive processing (i.e., the “wait and see” approach) gets especially obvious when contexts are weakly constraining, and the buildup of expectancies is impeded. In the present study, after presentation of the first object, there is a broad range of possibilities for which object could occur second.

Thus, the thematically related picture pairs in the present study reflect a rather weakly constraining context similar to the condition in Wlotko et al. (2012), in which the N400 was similarly reduced for older adults. Furthermore, Cheimariou et al. (2019) considered their picture-word pairs as a weakly constraining context because the picture showing a semantic category (vs. a picture of a specific object) does not support predictive processing, as a number of semantically related category members can be activated. Thus, given that the present study used picture pairs in which the first object allowed activation of a number of thematically related objects, the observed diminished N400 effects in older adults might represent reduced predictive processes due to the weak environmental support, which especially promotes a “wait and see” approach in older age.

Interestingly, however, older adults' associative memory in the present study benefited from semantic relationships to a similar extent as younger adults' associative memory. Thus, older adults' online predictive semantic processing during encoding seems to be unrelated to the processes that contribute to associative memory benefit by semantic relations. This is supported by the additional correlation analyses that showed no significant correlations between the N400 effect during encoding with the associative memory benefit for neither younger nor older adults. This result pattern (i.e., attenuated predictive processing in older age but no age-related differences in associative memory benefit) might correspond to evidence about the impact of age on the structure and dynamics of semantic networks investigated by Jongman and Federmeier (2022). For both age groups, the authors found robust and comparable effects of neighborhood size on the N400 (i.e., larger N400 for words with larger neighborhood size), reflecting the structure of the lexico-semantic network. However, older adults showed smaller N400 repetition effects (i.e., larger negativity for initial presentation of a single word than for repeated presentation), representing processing dynamics of the semantic network. Assuming that our N400 effect indicates a dynamic aspect of the semantic networks as online predictive processing has to happen fast and concurrently with the comprehension process, our results suggest an age-related decline in the semantic network dynamics. However, given that the younger and older adults' associative memory benefitted similarly from semantic relations, the structure of the older adults' semantic network seems to be stable so that they could integrate the semantically related object pairs when they have sufficient time for semantic processing. This idea of older adults' successful semantic integration boosting their associative memory is further supported by the significant correlation between the behavioral congruency effect during encoding and the associative memory benefit. It is conceivable that older adults compensated their attenuated dynamics of the semantic network (i.e., reflected by their attenuated N400 effect) by relying more on integrating object pairs within their semantic network structure (i.e., a similar behavioral congruency effect during encoding for younger and older adults).

An additional aspect that might contribute to diminished N400 effects in older adults, and thus less predictive processing, could be low category fluency (Federmeier et al., 2010). Following this reasoning, we correlated older adults' verbal fluency (assessed in the Consortium to Establish a Registry for Alzheimer's Disease by naming as many animals as possible for 1 min) with the size of the N400 effect in older adults, but we found no significant correlation. However, the absence of a significant correlation could be explained by the fact that the picture pairs in the present study show less overlap with verbal fluency due to their different modalities, in

contrast to Federmeier et al. (2010), who used verbal materials in both fluency and experimental tasks.

Referring to previous studies investigating age-related differences in online semantic processing of pictorial materials (e.g., Ostrosky-Solís et al., 1998), the question arises why we found attenuated N400 effects in older adults as compared to younger adults, whereas Ostrosky-Solís et al. (1998) found similar N400 effects in both age groups. One critical difference between the picture pairs implemented in their study and the present study is the kind of semantic relationships. Ostrosky-Solís et al. used categorically related object pairs, whereas we employed thematic relations. One possibility might be that categorical relations facilitate predictive processing as compared to thematic relations, as related category members might come faster to one's mind when one member is presented as the first object at least as long as participants know that there will only be categorically related members as second objects. However, previous work has shown that associations and not categorical relations are essential for the N400 effect, supporting the idea that meaning is acquired via associations that are generated by frequent co-occurrence of distinct elements within one's own experience (Ortu et al., 2013; Rhodes & Donaldson, 2008). As outlined in the introduction, the thematic relationships within the object pairs in the present study bear similarity with the association word pairs used in previous work. Related to this, the attenuated N400 effects in older adults in the present study might not only arise from weak environmental support due to the picture pairs. Alternatively, older adults' accumulated experience during life could change their internal model of the world and lead to a denser semantic memory space, allowing broader predictions and activation of more exemplars, even less semantically related ones, as compared to younger adults (Cutler et al., 2025; Ryskin & Nieuwland, 2023). Thus, a cue might activate more potentially related information so that, in the following, even "unexpected" sensory input can be integrated similarly to expected input. This might apply especially for thematic relations in pictures and word pairs (Ortu et al., 2013), which are based on frequent co-occurrence of the elements in daily life, for which older adults might have collected more experiences during their past. Consequently, due to their increased experience with everyday objects and their broader semantic network, older adults might be less "surprised" by rather unusual co-occurrences of objects. This might lead to thematically unrelated object pairs being integrated in a similar way to thematically related object pairs, resulting in the observed attenuated N400 effects. Nevertheless, the discrepancy between our ERP results and the ERP results by Ostrosky-Solís et al. emphasizes the importance of expanding the research about online semantic processing of pictorial materials by using different kinds of semantic relationships.

## Caveats and Conclusion

Even though our study revealed important insights into age-related differences in online semantic processing of pictorial materials, some limitations should be mentioned. During the study phase, participants had to judge the semantic congruency of the object pairs. At the same time, they were instructed to encode the object pairs for an upcoming associative memory test. Thus, it might be possible that a dual-task situation was created, which might have been especially demanding for older adults, causing

their observed reduced predictive processing. However, the observation that the semantic congruency ratings were highly similar in both age groups argues against the view that it was the high processing demands that prevented older adults from engaging in predictive processing.

Second, the use of an intentional encoding task could have exacerbated age-related associative memory deficit given that older adults are less capable than younger adults in efficiently using strategies to encode associations (Naveh-Benjamin et al., 2009). However, we needed to implement separate study-test cycles with relatively small numbers of object pairings per cycle to ensure substantial memory performance in both age groups. Multiple study-test blocks rule out incidental encoding. Furthermore, even though we used an intentional encoding task, older adults were able to benefit from the presence of semantic relationships for their associative memory in a similar way to younger adults. This latter finding argues against an intensification of age-related memory deficits through the use of an intentional encoding task.

In addition, even if we assume that the sequential presentation of thematically related object pairs bears similarity with weakly constraining sentence contexts, measuring predictive processing with picture pairs is more difficult than with sentences, as within pairs only the first picture serves as context to support predictions regarding the second picture. Future studies could use picture stories, which can be paralleled more easily with sentences, in order to investigate age-related differences in online processing of picture semantics.

Last, our samples were relatively homogeneous in terms of level of education. Furthermore, the participants were drawn from Germany, representing a Westernized country. Thus, future studies should investigate the generalizability of our results with participants from more heterogeneous ethnic backgrounds as well as education levels.

In conclusion, to our knowledge, this is the first study revealing age-related differences in the online semantic processing of pictorial materials using thematically related object pairs. Our data show that neural correlates of semantic processing are dissociable from behavioral measurements of semantic processing. On the one side, the diminished N400 attenuation effect for older adults reflecting clear age differences in the online semantic processing might result either from less predictive processing due to weakly constraining contexts (i.e., thematically related picture pairs) or from broader predictions of older adults due to their increased experience with everyday life objects. On the other side, the highly similar semantic congruency rating indicates a similar perception of the semantic relations in both age groups. Our result pattern adds on to evidence from previous studies using verbal and sentential materials (Payne & Federmeier, 2018; Wlotko et al., 2012), showing that older adults use less top-down predictive processing and have more difficulties to build up a message-level representation. Instead, older adults seem to rely more on bottom-up integrative processes that are initiated not before the second object is presented. Interestingly, we found no age-related differences in the benefit from the presence of semantic relationships for the associative memory. Thus, even though the online semantic processing is attenuated in older adults, older adults seem not to be disadvantaged compared to younger adults in order to benefit from semantic relationships for their associative memory. One possibility might be that, when older adults have sufficient time, their

semantic processing is intact (i.e., congruency rating), enabling the integration of the semantically related object pairs within their stable semantic network after having seen both objects. Thus, they might compensate their decreased dynamics of the semantic network indexed by the attenuated N400 effects.

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