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# Schema-congruency supports the formation of unitized representations: Evidence from event-related potentials☆

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A R T I C L E   I N F O

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A B S T R A C T

The main goal of the present study was to investigate whether schema-based encoding of novel word pairs (i.e., novel compound words) supports the formation of unitized representations and thus, associative familiarity-based recognition. We report two experiments that both comprise an incidental learning task, in which novel noun-noun compound words were presented in semantically congruent contexts, enabling schema-supported processing of both constituents, contrasted with a schema-neutral condition. In Experiment 1, the effects of schema congruency on memory performance were larger for associative memory performance than for item memory performance in a memory test in which intact, recombined, and new compound words had to be discriminated. This supports the view that schema congruency boosts associative memory by promoting unitization. When contrasting event-related potentials (ERPs) for hits with correct rejections or associative misses, an N400 attenuation effect (520–676 ms) indicating absolute familiarity was present in the congruent condition, but not in the neutral condition. In line with this, a direct comparison of ERPs on hits across conditions revealed more positive waveforms in the congruent than in the neutral condition. This suggests that absolute familiarity contributes to associative recognition memory when schema-supported processing is established. In Experiment 2, we tested whether schema congruency enables the formation of semantically overlapping representations. Therefore, we included semantically similar lure compound words in the test phase and compared false alarm rates to these lures across conditions. In line with our hypothesis, we found higher false alarm rates in the congruent as compared to the neutral condition. In conclusion, we provide converging evidence for the view that schema congruency enables the formation of unitized representations and supports familiarity-based memory retrieval.

Do you know the compound word *vegetable bible*? And if yes, does the word only feel familiar and you maybe know its meaning, or do you remember the specific episode when you first heard of it? The quality of your memory probably depends on several factors, for example how special the situation of the word's first occurrence was (did you have a heated discussion with your colleague, or did you just superficially read it in the media) and how often you already heard and used the word. Another important factor influencing if and how you remember the word might be how well you can make use of your prior world knowledge of the underlying concepts. If you know what both *vegetable* and *bible* mean, you can integrate both constituents into the novel whole word meaning, in this case *a dictionary used by gardeners*. This might be different when being told a vegetable bible was a dictionary used by teachers. In this case, you may not be able to embed both constituents into the novel whole word representation. An interesting and not yet explored question is how a congruent definition that is provided for a new compound word (e.g., *a dictionary used by gardeners*), enabling its prior knowledge-based processing, affects the way in which such novel compound words are remembered.

Traditionally, memory research converged on the idea that learning of novel associations relies on the hippocampus (e.g., Davachi, 2006), in which respective memory representations are initially stored. Only after time, storage is thought to be independent from the hippocampus, relying more on neocortical areas (i.e., systems consolidation, Dudai, 2012; Squire and Alvarez, 1995; see Gilboa and Moscovitch, 2021, for a recent review). However, in reviewing recent research, Hebscher et al. (2019) put forward the idea that new cortical engrams may be rapidly stored in neocortical areas if they can be associated with active,

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well-established cortical engrams. One factor promoting this relationship is relatedness to prior knowledge (Tse et al., 2007; 2011) and the idea of a prior-knowledge-driven, distinct learning mechanism dovetails with recent neuroscientific theories on schema-based learning (e.g., van Kesteren et al., 2012; Gilboa and Marlatte, 2017).

Memory schemas, originally introduced to memory research by Bartlett (1932), denote “higher-level knowledge structures that organize lower-level representations from long-term memory” (Gilboa and Marlatte, 2017, p.618). A schema is assumed to act as a template for online information processing by enabling the use of already existing (semantic) knowledge (Gilboa and Marlatte, 2017). More importantly, it also affects which aspects of events are encoded and retained in memory or are later forgotten (i.e., Pichert and Anderson, 1977; see Bartlett, 1932; Gilboa and Marlatte, 2017). Hereby, memory for to-be-learned schema-congruent information is better than memory for neutral or incongruent information (e.g., Höltje et al., 2019; Meßmer et al., 2021; Pichert and Anderson, 1977; Schulman, 1974). However, memory for schema-incongruent information can also be better than memory for neutral information), with this effect of schema-incongruency probably depending on different neurocognitive processes (e.g., Greve et al., 2019). Furthermore, prior knowledge has not only been found to influence episodic encoding of single items (e.g., Höltje et al., 2019), but also the encoding of associations between pre-experimentally unrelated items (e.g., Meßmer et al., 2021; Staresina et al., 2009). An interesting question is what kind of memory representations are formed by schema-based encoding of novel associations and how these novel associations are subsequently retrieved from memory.

Interestingly, it has been proposed that rapid non-hippocampal learning of associations is possible when associations are unitized (Hebscher et al., 2019; Henke, 2010). Unitized representations of associations are the result of a unitization process, by which to-be-associated items are integrated and then represented as a single entity (Graf and Schacter, 1989; Haskins et al., 2008; Quamme et al., 2007). Combining both approaches leads to the question whether prior knowledge-based learning supports associative memory through the formation of unitized representations. Here, schema congruency entails the necessary structure to provide an “object-creating framework” (Mayes et al., 2007, p. 126) which is required to form new units. With the current study, we aim to address this question by providing insights into the neurocognitive mechanisms underlying associative recognition of novel compound words, depending on whether or not its learning was supported by a preceding congruent definition.

The neurocognitive mechanisms underlying memory retrieval depend upon the type of memory, which is probed. One such type is recognition memory, i.e., memory for the previous occurrence of an event (e.g., *vegetable bible*; Mandler, 1980). In dual-process models of recognition memory (Yonelinas, 2002; Yonelinas et al., 2010), familiarity is defined as a fast-acting strength process, subjectively perceived as a feeling of knowing (e.g., “I know the word *vegetable bible*”; Mandler, 1980; Yonelinas, 2002), whereby recollection denotes the retrieval of specific details of a study event (e.g., “My colleague showed me this interesting article about *vegetable bibles*”; Yonelinas, 2002). Importantly, familiarity is not only relevant for item recognition (Mandler, 1980), but it can also contribute to associative recognition judgements when unitized representations have been formed (e.g., Ahmad and Hockley, 2014; 2017; Bader et al., 2010; Diana et al., 2011; Henke, 2010; Jäger et al., 2006; Parks and Yonelinas, 2015; Rhodes and Donaldson, 2007; 2008). In addition, whilst recollection is usually mediated by the hippocampus, familiarity is believed to rely on the integrity of a neocortical structure, the perirhinal cortex (Montaldi et al., 2006).

One way to estimate the contribution of familiarity and recollection to recognition judgements is the use of event-related potentials (ERPs). ERPs allow to monitor memory processes online and to dissociate neurocognitive processes with high temporal resolution. In recognition memory tasks, ERPs are typically contrasted between stimuli correctly identified as “old”, and correctly rejected as “new”. The old/new effect serves as an index of general memory success (Friedman and Johnson, 2000), and allows to compare memory-related ERP components across different recognition memory studies. Hereby, two such old/new effects are of special interest. A late, left-parietal old/new effect between 400 and 800ms after stimulus onset has been interpreted as reflecting recollection (Rugg and Curran, 2007). The putative correlate of familiarity, the FN400, onsets earlier (300–500ms after word onset) and has a frontally focused distribution (Woodruff et al., 2006; Rugg and Curran, 2007; see Paller et al., 2007, for a different view).

In an illustrative study on the role of familiarity for associative memory, Bader et al. (2010) presented participants with pre-experimentally unrelated word pairs, either together with a definition enabling their processing as a new compound word (unitization condition) or with a sentence in which the two words had to be filled in and were thus processed as separate items (control condition). In a subsequent (surprising) associative recognition memory test, participants had to indicate whether a word pair was intact, recombined, or new. Consistent with the view that unitized representations show less dependence on recollection but rather support familiarity-based recognition, they found ERP evidence for a higher contribution of familiarity-based recognition after unitization encoding, indicated by an early old/new effect, whereas the late parietal old/new effect, the putative correlate of recollection, was dominant in the control condition. Notably, in contrast to the typical mid-frontal distribution of the FN400, the early old/new effect in this study showed a posterior distribution, which was interpreted as an N400 (attenuation) effect, reflecting the larger conceptual fluency for unitized compound words than for unstudied word pairs.

In line with the idea that familiarity is not a single construct (e.g., Bridger et al., 2014), this N400 (attenuation) effect has been interpreted as reflecting absolute (baseline) familiarity (e.g., how familiar you would have rated vegetable bible before reading this paper; Mecklinger and Bader, 2020). In contrast, in a typical recognition memory experiment with pre-experimentally known items, relative familiarity contributes to recognition judgements (If you already knew vegetable bible before reading this paper, its additional occurrence makes this word relatively more familiar than what you would expect for this word based on its absolute familiarity; Mandler, 1980). In a recent neurocognitive model of recognition memory, Mecklinger and Bader (2020) propose that relative and absolute familiarity are two independent but interwoven mechanisms. While relative familiarity tracks the increment of a recent to a present exposure of an event, absolute familiarity can be diagnostic for recognition memory judgements for novel stimuli whenever those novel words are assigned a meaning in a learning situation. This is because in a memory test in which all stimuli are novel, the presence of an absolute familiarity signal can be attributed to prior occurrence of a stimulus (Mecklinger and Bader, 2020).

Thus, in the current study we combined the idea that new cortical engrams may be rapidly stored if the respective information relates to prior knowledge (Hebscher et al., 2019) with the approach of fast non-hippocampal associative learning for unitized associations (Henke, 2010). Hereby, our goal was to investigate whether newly learnt compound words can be unitized when the words constituting the to-be-learned compound are congruent with the definition given for this compound. This should then result in a larger contribution of absolute familiarity to recognition decisions. This question was addressed in Experiment 1.

## 1. Experiment 1

In this study, we manipulated schema congruency between a fictional definition and a novel compound word. During an incidental learning phase, participants rated the fit of novel German compound words, e.g., *Kasinohirte* (casinoshepherd), with either a semantically congruent fictional definition, *“Ein Angestellter, der eine Spielbank bewacht, heißt …”* (An employee who guards a gambling house is called

…) or a neutral definition, *"Ein Angestellter, der eine Markise bewacht, heißt …"* (An employee who guards an awning is called …). Whereby the second constituent of the compound word (shepherd) relates to a noun in the definition in both conditions (employee), the first constituent of the novel compound (casino), i.e., the modifier constituent, is only semantically related to a noun in the congruent condition (gambling house). This should facilitate integrating the compound word into the schema knowledge structure and thus enable schema-supported processing of the compound word as a whole in the congruent condition. In contrast, we assume that in the neutral condition, the compound words are processed as irrelevant with respect to the activated schema in the neutral condition (rather than schema-incongruent).

While a majority of studies exploring the circumstances under which unitized representations can be formed manipulate the congruency between two items (e.g., Ahmad and Hockley, 2014; Diana et al., 2011; Kriukova et al., 2013; Rhodes and Donaldson, 2007; Tibon et al., 2014), our approach was to manipulate the congruency between the to-be-associated words and a preceding fictional definition. Each participant was presented with each compound word with either its congruent or its neutral definition, with both, the neutral and a congruent context being presented across participants. In a subsequent associative memory test, participants were presented with intact compound words from the prior learning phase, recombined compound words, for which both constituents had been presented in the learning phase but within different compound words and completely new, i.e., yet unpresented, compound words. Their task was to classify each compound word as being intact, recombined, or new.

If schema-based encoding contributes to associative learning in this way, we expected a congruency effect to occur (Bein et al., 2014; 2015), i.e., better associative memory performance in the congruent as compared to the neutral condition. If novel compound words are learnt in this way, this should enhance their absolute familiarity and ensuing recognition memory decisions should be given on the basis of absolute familiarity. In line with this, we expect an N400 attenuation effect (the ERP correlate of absolute familiarity) for words learned in a congruent but not in a neutral context.

Additionally, following Parks and Yonelinas (2015), we assume that evidence for unitization can also be derived from a comparison of item and associative memory. If unitization enhances familiarity specifically for associations (and not for single items), there should be larger benefits for associative memory than for item memory in the (unitization supporting) congruent condition. Conversely, if congruency leads to similar benefits for item and associative memory this would imply that a common mechanism such as deep encoding or semantic elaboration may have boosted memory performance in both tests comparably.

## 1.1. Methods

### 1.1.1. Participants

$N = 43$ young adults volunteered for this study, having been recruited via flyers and local databases.

For the current analyses, data from $n = 10$ participants had to be excluded due to failures during recording ($n = 2$), because the stimulus materials were known from another study ($n = 1$), because they reported that they intentionally studied the stimuli or did not give an indication ($n = 5$) or did not provide more than or equal to 10 artifact-free trials ($n = 2$). Thus, the final sample consisted of $N = 33$ participants (22 females, 11 males, with an age range from 18 to 31, $Mdn = 23$ years, $SD = 3.72$).

The sample size estimation was originally conducted based on expected ERP effects in the learning phase which was the main effect of interest for this experiment (see Meβmer et al., 2021). However, to evaluate whether our sample size was adequate to detect effect sizes likely to occur, we conducted a sensitivity power analysis with G*Power (version 3.1.9.7; Faul et al., 2009; see Lakens, 2022) for a repeated measures MANOVA, within factors, with the parameters $\alpha = 0.05$, $1\text{-}\beta = 0.80$, $N = 33$, number of groups = 1, number of measurements = 2, correlation among repeated measurements = 0.5. This analysis revealed that effects larger than $Pillai = .20$ could theoretically be detected with a power of $1\text{-}\beta = 0.80$. The best effect size estimation for our effect of interest, i.e., whether the N400 attenuation effect (intact hits versus correct rejections) is larger in the congruent as compared to the neutral condition, can be obtained from Wiegand et al. (2010). In this study from our lab, the N400 attenuation effect has been found to be larger for trials for which the compound word has been rated as plausible given the definition as compared to trials rated as implausible. To obtain the effect size Pillai for this plausibility effect, we calculated a Plausibility (plausible, implausible) x Anteriority (frontal, parietal) x Laterality (left, middle, right) – MANOVA on mean amplitudes from the Wiegand et al. (2010) study. The respective Pillai was .28, the detection of which should be covered by our sample size. In addition, most of our experimental effects reported in the results section have effect sizes larger than $Pillai = 0.20$.

All participants performed significantly above chance level, which was verified with a binomial test ($p < .05$). All participants were students of Saarland University or volunteers from the community and reported being in good health, not suffering from any neurological or psychiatric conditions and having normal or corrected-to-normal vision. Further, all participants were right-handed, as assessed with the Oldfield Handedness Inventory (Oldfield, 1971), and reported being native speakers of German. Participants gave their informed consent and were reimbursed with 10E/h. Participants were debriefed after the experiment. The experiment was approved by the ethics committee of the Deutsche Gesellschaft für Sprachwissenschaft (#2017-07-180423).

### 1.1.2. Stimulus materials

For this study, stimulus materials comprised 240 novel compound words, each consisting of two unrelated nouns (e.g., casinoshepherd), together with a congruent and a neutral definition.

Example:

> *"Ein Angestellter, der eine Spielbank bewacht, heißt … Kasinohirte" (congruent)*
>
> (An employee who guards a gambling house is called … Casinoshepherd)
>
> *"Ein Angestellter, der eine Markise bewacht, heißt … Kasinohirte" (neutral)*
>
> (An employee who guards an awning is called … Casinoshepherd)

A definition was stated congruent when it reasonably explained how the two nouns could be combined to a new concept. In a rating study with an independent sample of participants, the congruent definition was rated as significantly better explaining how both constituents form the novel concept than the neutral definition (see Meβmer et al., 2021). This was achieved by establishing a systematic pattern of relationships between compound head, compound modifier and particular words of the definition sentence. As outlined before, the second constituent of the compound word (shepherd) is related to a definition noun in both conditions (employee), whereby the first constituent of the novel compound (casino), i.e., the modifier constituent, is only semantically related to a noun in the congruent condition (gambling house). The three dots following the definition in the example are for illustrative purposes, only, and were not shown in the experiment.

For the memory test, we additionally selected 120 recombined compound words, as well as 80 new compound words (see Meβmer et al., 2021). New compound words consisted of two unrelated nouns, which were not used elsewhere in the material. Recombined compound words were included to ensure that participants would not be able to solve the task by using item recognition alone and constructed by newly combining the modifier and the head of two different compound words. Hereby, only one out of two possible combinations were used. It was assured that the nouns still were semantically unrelated. The two compounds used for recombination were always of the same grammatical gender and contained the same type of interfix, if any. For instance, “*Sternensessel”* and “*Magnetenozean”*, both containing the interfix *–en* were recombined to “*Magnetensessel”,* containing the same interfix.

Compound words had a length ranging from 7 to 18 letters ($M = 11.98$, $SD = 2.09$), for to-be-learned compound words, ranging from 7 to 16 letters ($M = 11.93$, $SD = 2.03$) for recombined compound words, and ranging from 7 to 18 letters for new compound words ($M = 12.37$, $SD = 2.58$). The normalized lemma frequency (derived from dlexDB; Heister et al., 2011) for the constituents ranged from 0.02 to 264.38 occurrences per million for compound words and recombined compound words and from 0.11 to 394.69 for new compound words. For one noun, there was no respective entry. Compound constituents were rated as being semantically unrelated ($M = 1.30$, $SD = 0.23$, for compound words, $M = 1.28$, $SD = 0.22$, for recombined compound words and $M = 1.30$, $SD = 0.14$, for new compound words).

The selected stimuli were divided into two sets (Set 1 and Set 2), consisting of 120 compound words each. Two encoding lists were created, whereby for the first list, compound words of Set 1 were presented with a congruent context and compound words of Set 2 were presented with a neutral context. This assignment was reversed for the second list. Which encoding list was used varied across participants, whereby both lists were presented approximately equally often. For the test phase, stimuli were further divided into four subsets of 60 compound words, each, by halving Set 1 and Set 2, respectively. Compounds of each subset were presented as intact for one part of the participants and as recombined for the other part of the participants, so that when compound words of Set 1a and Set 2a were presented as intact compound words, the other half (Set 1b and Set 2b) was presented as recombined compound words, and vice versa. Each test list consisted of 120 intact compound words, 60 recombined compound words, and 80 new (yet unpresented) compound words. The new compound words were identical for each participant. Due to the exclusion of datasets mentioned above, the lists are not fully counterbalanced. However, each of the four combinations of encoding lists and test lists occurred approximately equally often.

### 1.1.3. *Procedure*

After having given their written–informed consent, participants completed several questionnaires, one about their general health, one about demographic aspects and the Oldfield Handedness Inventory (Oldfield, 1971). Next, electroencephalography (EEG) was applied, and participants were sat in a dimly lit, sound-absorbing chamber.

The experiment was created using E Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). The experiment proper consisted of an incidental encoding phase, a retention interval with a duration of approximately 10 min and a test phase. During the encoding phase, participants were presented with 240 definitions, half of them congruent and half of them neutral, followed by the respective novel compound word. Participants were instructed to rate on a scale from 1 (*not at all*) to 4 (*absolutely*) how well the novel compound word denotes the concept given by the definition. Participants responded on a keyboard by using the keys x, c, n, and m with their index and middle fingers of each hand. The trial procedure can be seen from Fig. 1. A trial started with a fixation cross, with a duration of 500 ms. Then, the definition was presented stepwise. The noun phrase was presented for 1000 ms, followed by the presentation of the relative clause and the words “is called” for additional 3500 ms. After another fixation cross with a continuously jittered duration from 950 to 1050 ms, the compound word was presented in the center of the screen for 2000 ms. A 500 ms blank screen followed the compound word. Then the answer screen appeared for up to 3 s but was terminated as soon as the participants gave their response. The answer screen contained the question of how well the compound word is described, as well as the labels for the response scale. The scale was ascending for a part of the participants and descending for the other part of participants. A 500 ms blank followed until the next trial started. Before the learning phase, participants completed eight practice trials to familiarize with the task. Data from the learning phase are reported in Meβmer et al. (2021).

The learning phase was followed by a 10-min retention interval. During this interval, participants performed two distractor tasks. At first,

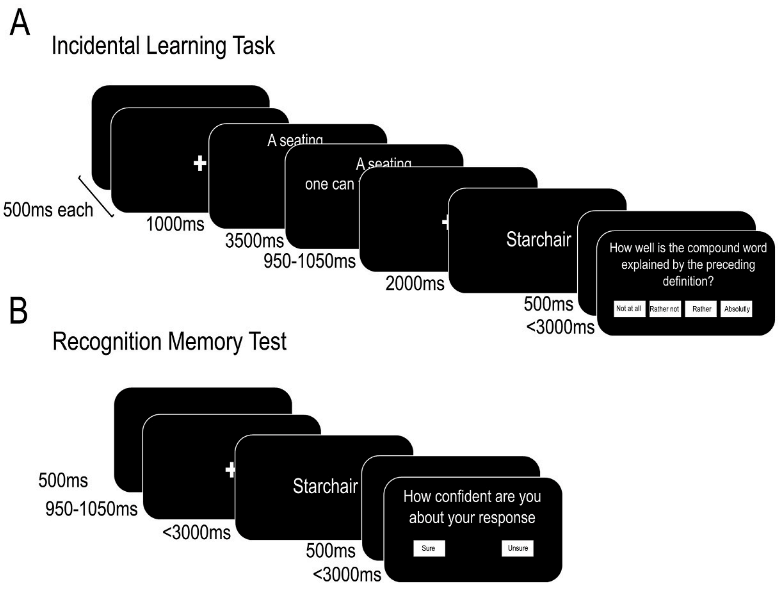

**Fig. 1.** Trial Procedures of Encoding and Test Phase.
Note. Panel A depicts the trial procedures of the incidental learning task. Panel B shows the trial procedures of the recognition memory test. The English translations of the stimulus materials are for illustrative purposes, only, as all stimuli were presented in German.

an adapted computerized version of the Digit Symbol Task (Wechsler, 1955) from Häuser et al. (2019) was performed for approximately 5 min, followed by 2.5 min of backwards counting in steps of 3. Only then, participants were told about the upcoming test phase. During the test phase, participants were presented with one of the two test list versions, consisting of 120 intact compound words, 60 recombined compound words and 80 new, i.e., yet unpresented compound words. A trial started with a continuously jittered fixation cross (950–1050 ms). Then, the compound word was presented (for up to 3000 ms), until participants gave their response. Participants gave their answer on a keyboard by using the keys f, j, and k to indicate if the compound word was intact, recombined or new. Key assignment was varied by using a latin-square design, ensuring that across participants, each response option was used with similar frequency. After a 500 ms blank screen, participants were asked to indicate their confidence on the previous response (sure or unsure) using their index fingers, whereby key assignment was ascending for a part of the participants and descending for the other part of participants. The confidence ratings were collected for an exploratory analysis of the subsequent memory effects in the learning phase (Meßmer et al., 2021). However, inspection of the data revealed that there is not enough variability for such an analysis. We therefore did not include confidence ratings in this report. The confidence scale remained on the screen for up to 3000 ms or until participants gave their response and was only presented if a response had been logged on the compound word. A trial ended with a blank screen, which was presented for 500 ms.

Stimulus presentation was pseudo-randomized for the encoding and test phase, with the limitation of not more than 3 consecutive trials in the same context condition (encoding phase) or not more than 3 consecutive trials requiring the same response (test phase). In both phases, there were self-paced breaks after 60 trials (encoding phase) or 65 trials (test phase), respectively.

### *1.1.4. Data acquisition and pre-processing*

The EEG was continuously recorded from 28 Ag/AgCl scalp electrodes (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), using BrainVision Recorder 1.0 (Brain Products, Gilching, Germany), whereby all electrodes except from A2 were embedded in an elastic cap (Easycap, Hersching, Germany). Electrode positions followed the extended international 10–20 system (Jasper, 1958). AFz was chosen as ground electrode and two additional electrodes were applied on the left (A1) and right (A2) mastoid, respectively. The signal was online referenced to the left mastoid electrode (A1) with the exception of one participant for whom some eye and mastoid electrode channels had been interchanged by mistake. For this dataset, data were online referenced to the left canthus electrode. Channel assignment was corrected offline and in an additional step, data were re-referenced to left mastoid so that before the actual pre-processing, all datasets had the same reference. Electroocular activity was assessed via four additional electrodes, which were placed above and below the right eye and outside the outer canthi of both eyes. All electrode impedances were kept below 5 kOhm with the exception of the electroocular electrodes' impedances. Data were sampled at 500 Hz. An online filter from 0.016 Hz (time constant 10 s) to 250 Hz was applied.

Offline, the data were pre-processed using the EEGLAB (version 2019.1; Delorme and Makeig, 2004) and ERPLAB (version 7.0; Lopez-Calderon and Luck, 2014) toolboxes for MATLAB (MathWorks, Inc.). First, the data were down sampled to 250 Hz and re-referenced to the average of the left and right mastoid. Thereafter, data were filtered with a second-order Butterworth bandpass-filter from 0.05 Hz to 30 Hz (-6 dB half-amplitude cutoff, with DC removal) and 50 Hz powerline fluctuations were removed with a Parks- McClellan notch filter (default setting order 180; with DC removal; see Parks and McClellan, 1972 for the original algorithm). Data were pre-segmented by discarding all data points exceeding a time period from 1000 ms before a stimulus onset marker to 2500 ms after a stimulus onset marker. Then, bad segments and experimental breaks, as well as practice trials, were manually discarded. Thereafter, the weights and sphere matrix of an independent component analysis (ICA)[1] run with the infomax algorithm *runica* ICA were applied, and components associated with eye movements and muscular artifacts were identified and removed (up to 5 components per participant). Data were then segmented into epochs of 1696 ms around compound word onset, including a 200 ms baseline. Following baseline correction, a semi-automatic artifact rejection was applied, using the following criteria: a maximally allowed amplitude of −75 up to 75 μV, a maximal difference of values of 100 μV during intervals of 200 ms (window steps of 100 ms), a maximally allowed voltage step of 50 μV/s and a maximum of 200 ms of sample points with a deviation from −0.5 to 0.5 μV from the maximum voltage in this epoch.

### *1.1.5. Data analysis*

Similar to Kamp et al. (2016), we included the definition fit rating of the learning phase as an additional constraint to both, behavioral data analysis and ERPs of the test phase, as although definitions were created (and rated) to map on the congruent vs. neutral definition distinction, there might be participant-specific variations of definition goodness within conditions (Wiegand et al., 2010). Therefore, hits to intact compound words in the congruent condition were only included if they were rated with a 3 *(rather)* or 4 *(absolutely)* on the 4-point scale in the initial learning phase, whereby inclusion of hits for intact compound words in the neutral condition required a rating of 1 *(not at all)* or 2 *(rather not)*. To calculate average hits, $M = 32.06$ trials (*SD* 9.36, *range* 11–49) were used in the congruent condition and $M = 23.46$ trials (*SD* 7.53, *range* 11–41) were used in the neutral condition. Correct rejections were based on $M = 49.12$ trials (*SD* 13.01, *range* 15–71).

For all analyses, the significance criterion of $p < .05$ was applied. Data were analyzed using R (version 3.6.1; R Core Team, 2019) and RStudio (Version February 1, 5001; RStudio Team, 2019) and IBM SPSS statistics (version 26). Whenever non-hypothesis-driven multiple testing was required, the Bonferroni-Holm correction (Holm, 1979) was applied. The reported corrected *p*-values were calculated with the function *p.adjust* of the R package *stats* (R Core Team, 2019).

Associative memory performance was estimated by the measure $Pr_{As}$ (hits-false alarms), the difference between the probability of an intact response to an intact compound word (hits) and the probability of an intact response to a recombined item (false alarms; see de Chastelaine et al., 2016; Huffer et al., 2022, for similar procedures). In this metric, the false alarm rate includes recombined pairs mistakenly recognized as intact relative to all recombined pairs with at least correct item memory (recombined pairs as recombined and recombined pairs as intact). This false alarm rate was subtracted from the hit rate, which was calculated as the proportion of intact pairs correctly recognized as intact relative to all intact pairs with at least correct item memory (intact pairs as intact and intact pairs as recombined). To examine whether the congruency manipulation affects associative and item memory performance in the same way, an additional metric for item memory ($Pr_{It}$) was calculated. Item memory refers to the ability to generally discriminate pairs containing old constituents (items) (i.e., intact and recombined pairs) from pairs containing new items, i.e., new pairs. Accordingly, the item hit rate was calculated as the sum of all intact or recombined items classified as either intact or recombined, divided by the sum of all intact and recombined trials. The item false alarm rate was calculated as the sum of all new compound words classified as intact or recombined, divided by the number of new items, i.e., 80. Behavioral outliers were defined as extreme values, i.e., with a standardized *z*-value greater than 3.29 above or smaller than −3.29 below the mean (Field, 2009, p. 179). One dataset

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[1] The ICA was run with a more conservative second-order Butterworth bandpass-filter from 0.5 Hz to 30 Hz (-6 dB half-amplitude cutoff, with DC removal) to optimize performance.

was detected as a behavioral outlier. We calculated all behavioral analyses once with and once without this dataset, with no qualitative differences between the respective results. Therefore, we report the results with this dataset included.

As sphericity is usually violated in EEG data, we used the multivariate approach of repeated measure analysis of variance (MANOVA) for ERP analyses, which is more robust against such violations of sphericity (Dien and Santuzzi, 2005; Picton et al., 2000). Significant effects are further explored in follow-up MANOVAs and paired-samples *t* tests. As measures of effect size, we report Hedges's $g_{av}$ for effects from paired-samples *t* tests with the formula provided in the spreadsheet (Version 5) from Lakens (2013) and Pillai's trace, which is identical to partial eta-squared ($\eta_p^2$), for multivariate analyses of variance (MANOVAs), respectively.

Following a recommendation of Luck and Gaspelin (2017), to avoid unnecessary accumulation of type I errors, we eliminated all factors that were not relevant for our hypotheses from our MANOVA designs. Hence, all analyses were restricted to a subset of electrodes relevant for the respective analyses. As we expected the N400 attenuation effect as a measure of absolute familiarity to be broadly distributed across the scalp (Bader et al., 2010; Wiegand et al., 2010; see Mecklinger and Bader, 2020 for a review), we chose a broad array of electrodes (i.e., F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) for the analyses of this effect. To quantify the late parietal old/new effect, typically showing a left lateralization for language materials (Rugg and Curran, 2007), we chose the electrodes P3, Pz, P4 to statistically confirm the left lateralization. In addition, all topographical analyses were conducted with the electrodes F3, Fz, F4, C3, Cz, C4, P3, Pz, P4.

As can be seen from Fig. 3, the N400 component appears to be prolonged in the current study. Due to this temporal extension, we aimed to define two N400 (absolute familiarity) time windows of 200ms duration, each, post hoc. Those should be centered around the two N400 peaks for correct rejections at electrodes Cz, in the two time windows from 300 to 500 ms and 500 to 700 ms. Those are at 464 ms and 576 ms, respectively. However, this approach would have resulted in two overlapping N400 time windows. Thus, to cover the whole variance in the vicinity of the two N400 peaks in two non-overlapping time windows, we took the arithmetic mean between both peaks (i.e., 520 ms) and defined the first time window from 364 to 520 ms and the second time window from 520 to 676ms. To obtain an independent and non-overlapping time window for the late parietal old/new effect, indicative of recollection (e.g., Rugg and Curran, 2007), a third adjacent time window from 676 to 876 ms was chosen.

A two-step procedure was used for the analysis of the ERP effects. First, we tested whether there are statistically significant old/new effects in both conditions. For this purpose, we ran a MANOVA with the factors type (intact hit, correct rejection), anteriority (frontal, central, parietal) and laterality (left, middle, right) for each condition in both N400 (absolute familiarity) time windows. For the late parietal old/new effect, the correlate of recollection, a MANOVA with the factors type (intact hit, correct rejection) and laterality (left, middle, right) was calculated for parietal electrodes for each condition. In a next step, we were interested in whether old/new effects differ across congruency conditions. As the ERPs to correct rejections are condition-unspecific, the critical comparison to test whether old/new effects differ across congruency conditions is to contrast the ERPs to congruent and neutral hits. Thus, we tested whether there are condition-specific differences between intact hit ERPs using a MANOVA with the factors congruency (congruent, neutral), anteriority (frontal, central, parietal) and laterality (left, middle, right) for the first and the second N400 (absolute familiarity) time window. For the third time window, we conducted a MANOVA with the factors congruency (congruent, neutral) and laterality (left, middle, right) at parietal electrodes at which the late parietal component (LPC) is largest. For the sake of readability, we only report significant effects including the factors congruency or type.

## 1.2. Results

### 1.2.1. Behavioral results

The behavioral data for both, item and associative memory performance are illustrated in Table 1.

In line with our hypothesis, associative memory performance, indicated by $Pr_{As}$, was higher in the congruent than in the neutral condition, $t(32) = 4.88$, $p < .001$, $g_{av} = 1.00$ (one-sided; $M_{congruent} = 0.50$, $SD = 0.24$, $M_{neutral} = 0.27$, $SD = 0.21$; see Fig. 2). To explore the contribution of hits and false alarms to this condition difference, we calculated a Congruency (congruent, neutral) x Type (hit, false alarm) – MANOVA. This analysis revealed a main effect of congruency, $Pillai = .31$, $F(1, 32) = 14.05$, $p = .001$, a main effect of type, $Pillai = .83$, $F(1, 32) = 151.22$, $p < .001$, and a significant interaction, $Pillai = .43$, $F(1, 32) = 23.81$, $p < .001$. Further examination revealed that only hit rates differed significantly across conditions, $t(32) = 10.64$ $p < .001$, $g_{av} = 1.51$ (one-sided; $M_{congruent} = 0.81$, $SD = 0.12$, $M_{neutral} = 0.61$, $SD = 0.14$), whereas no such difference was found for false alarm rates, $t(32) = -0.63$, $p = .534$, $g_{av} = 0.13$ ($M_{congruent} = 0.32$, $SD = 0.21$, $M_{neutral} = 0.34$, $SD = 0.21$).

To address the idea that associative memory benefits more than item memory from the schema congruency-driven formation of unitized representations, we calculated a Congruency (congruent, neutral) x Memory Type (Item, Association) – MANOVA on *Pr* Scores. This analysis revealed a main effect of congruency, $Pillai = .57$, $F(1, 32) = 42.39$, $p < .001$, a main effect of memory type, $Pillai = .29$, $F(1, 32) = 12.80$, $p = .001$, and a significant interaction, $Pillai = .19$, $F(1, 32) = 7.50$, $p = .010$, whereby the congruency effect was larger for $Pr_{As}$ scores (see above) than for $Pr_{It}$ scores, albeit there was also a congruency effect on $Pr_{It}$ scores, $t(32) = 6.09$, $p < .001$, $g_{av} = 0.58$ ($M_{congruent} = 0.54$, $SD = 0.16$, $M_{neutral} = 0.45$, $SD = 0.15$; see Fig. 2).

### 1.2.2. ERP results

Fig. 3 depicts the grand average ERP waveforms elicited by the compound words in the test phase. In order to test whether there are differences in absolute familiarity between conditions, we had planned to analyze variations in the N400 within a time window from 300 to 500 ms (Mecklinger and Bader, 2020). However, as especially evident in the ERPs to correctly rejected new compound words, the N400 appears to comprise the already mentioned two consecutive peaks and extends approximately 200ms beyond the 300–500 ms time window. Whilst waveforms for correctly rejected new compounds and hits in the neutral condition are highly similar between 350 and 700 ms, the N400 for congruent hits is attenuated in the second half of this prolonged N400 time window. This effect is broadly distributed across the scalp and present at all electrodes. This N400 attenuation effect is followed by a later old/new effect with a more left-lateralized scalp topography in both conditions, which is present between 700 and 900 ms. The late old/new effect takes the form of more positive ERPs for hits than correct rejections. These observations were examined in a series of statistical analyses.

**Old/new effects in the congruent condition.** A Type x Anteriority x Laterality-MANOVA revealed no significant effects including the type factor in the first time window (all $Pillai < .14$, $p_s > .247$). The Type x Anteriority x Laterality-MANOVA in the second time window revealed a significant main effect of type, $Pillai = .26$, $F(1, 32) = 11.45$, $p = .002$ and a significant Type x Laterality-Interaction, $Pillai = .25$, $F(2, 31) =$

**Table 1**
Behavioral data.

| | Associative memory | | Item memory | |
|---|---|---|---|---|
| | congruent | neutral | congruent | neutral |
| Pr *score* | .50 (.24) | .27 (.21) | .54 (.16) | .45 (.15) |
| *Hit rate* | .81 (.12) | .61 (.14) | .86 (.08) | .76 (.11) |
| *FA rate* | .32 (.21) | .34 (.21) | .32 (.15) | |

Note. Standard deviations are given in parentheses.

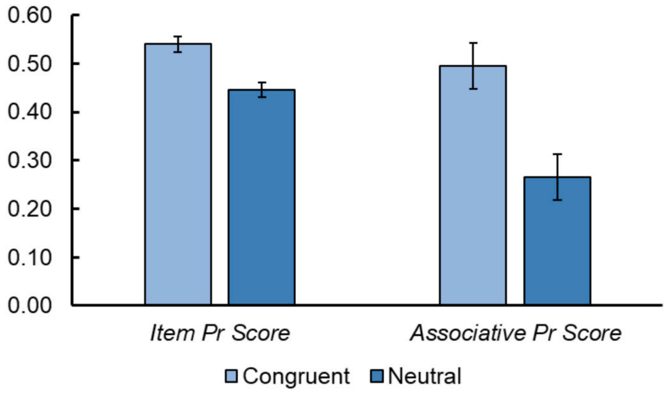

**Fig. 2.** Mean Item and Associative Pr Scores.
Note. The error bar depicts the standard error of the mean difference, obtained for the congruent versus neutral-comparison for the item and the associative Pr score, respectively.

5.07, $p = .012$. To resolve the Type x Laterality-Interaction, we averaged mean amplitudes across the anteriority factor and calculated Bonferroni-Holm-corrected paired-samples *t* tests, comparing hits and correct rejections for left, middle and right electrode sites, separately. These revealed significant differences with more positive waveforms for hits versus correct rejections at left, middle and right clusters, whereby effect sizes are larger at left and middle sites than at right sites (left: $t(32) = 3.66$, $p = .003$, $g_{av} = 0.26$; middle: $t(32) = 3.58$, $p = .003$, $g_{av} = 0.27$; right: $t(32) = 2.48$, $p = .019$, $g_{av} = 0.19$).

The Type x Laterality-MANOVA in the third time window from 676 to 876 ms revealed a significant main effect of type, *Pillai* = .24, $F(1, 32) = 10.29$, $p = .003$, and a significant interaction between type and laterality, *Pillai* = .46, $F(2, 31) = 13.36$, $p < .001$. Follow-up paired-samples *t* tests for each electrode, separately, revealed a significant old/new-difference at electrode P3, $t(32) = 5.29$, $p < .001$, one-sided, $g_{av} = 0.54$, and Pz, $t(32) = 2.94$, $p = .003$, one-sided, $g_{av} = 0.31$. To sum up, for the congruent condition, we found an earlier N400 attenuation effect present at all analyzed electrodes in the second time window (520–676 ms) and a later old/new effect which we analyzed at parietal recording sites in the third time window (676–876 ms).

**Old/new effects in the neutral condition**. A Type x Anteriority x Laterality-MANOVA in the first time window revealed no significant effects (all *Pillai* <.23, $p_s > .093$). The Type x Anteriority x Laterality-MANOVA in the second time window revealed a significant Type x Anteriority-Interaction, *Pillai* = .24, $F(2, 31) = 4.85$, $p = .015$ and a significant Type x Laterality-Interaction, *Pillai* = .29, $F(2, 31) = 6.30$, $p = .005$. To resolve the significant interaction of laterality and type, mean amplitudes were averaged across the anteriority factor and Bonferroni-Holm-corrected paired-samples *t* tests were calculated for left, middle and right electrode clusters, separately, comparing hits in the neutral condition and correct rejections. These revealed no significant differences (all $p_s > .978$, $g_{av} < 0.08$). To resolve the significant interaction of anteriority and type, mean amplitudes were averaged across laterality and Bonferroni-Holm-corrected paired-samples *t* tests were calculated for frontal, central and parietal electrode clusters, separately, comparing hits in the neutral condition and correct rejections. Again, no significant differences were found (all $p_s > .618$, $g_{av} < 0.12$).

The Type x Laterality-MANOVA in the late time window from 676 to 876 ms revealed a significant interaction of type and laterality, *Pillai* = .32, $F(2, 31) = 7.26$, $p = .003$. Follow-up paired-samples *t* tests comparing ERPs to hits and correct rejections at each electrode, separately, revealed a significant effect at electrode P3, $t(32) = 2.26$, $p = .016$, one-sided, $g_{av} = 0.26$. In conclusion, we only found a significant left-parietal old/new effect in the third time window.

**Congruency effects on ERPs to hits.** In a next step, we were interested in whether old/new effects differ across congruency conditions. As the intact and recombined word pairs of both conditions were presented together with the same new word pairs, the ERPs to correct rejections were the same in the aforementioned analyses of old/new effects. For this reason, we contrasted the ERPs for hits in both conditions using a MANOVA with the factors congruency, anteriority and laterality. In the first time window, this MANOVA did not reveal any significant effects (all *Pillai* <.09, $p_s > .437$). For the second time window, the Congruency x Anteriority x Laterality - MANOVA yielded a significant main effect of condition, *Pillai* = .14, $F(1, 32) = 5.02$, $p = .032$, reflecting more positive ERPs for hits in the congruent than in the neutral condition, across all electrode sites (see Fig. 4A). No other effect including the condition factor was significant.

The Congruency x Laterality - MANOVA on parietal electrodes in the third time window from 676 to 876 ms revealed a significant interaction of congruency and laterality, *Pillai* = .20, $F(2, 31) = 3.95$, $p = .030$. Follow-up, Bonferroni-Holm corrected paired-samples *t* tests calculated at each electrode, separately, revealed a marginally significant effect of congruency at electrode P3, $t(32) = 2.49$, $p = .054$, $g_{av} = 0.25$. Thus, statistically reliable differences between hits in the congruent and the neutral condition were found in the second, absolute familiarity time window, indicating that absolute familiarity differs across congruency conditions. There was no significant effect of congruency in the third (recollection) time window.

**Exploratory analysis of ERPs on associative misses.** Contrasting ERPs for intact and new word pairs is a frequently used procedure in the ERP literature on associative recognition memory (e.g., Bader et al., 2010; Greve et al., 2007; Kriukova et al., 2013; Rhodes and Donaldson, 2007; Wiegand et al., 2010; but see Kamp et al., 2016; Huffer et al., 2022). However, intact and new word pairs differ in both, item and associative information. Therefore, the N400 attenuation effect does not necessarily reflect solely associative familiarity but could rather mirror neural activity related to successful item memory.

To dispel doubts about the associative nature of the N400 attenuation effect observed in the ERP contrast between intact hits and correct rejections, we followed the suggestion of an anonymous reviewer and considered another ERP contrast, i.e., intact hits versus associative misses (intact compound words erroneously classified as recombined; see also Kwon et al., 2023). This is because the wrong classification as 'recombined' requires correct item memory of the underlying constituents but implicates a lack of associative memory. Consequently, intact hits and associative misses are equated in item memory and differ only in associative memory. If the N400 attenuation effect for intact hits compared to correct rejections reflects absolute (associative) familiarity, a topographically similar ERP effect should be present in the intact hit/associative miss-contrast in the 520–676 ms time window. Thus, if absolute familiarity contributes more to associative recognition memory in the congruent than in the neutral condition, we expect the putative ERP correlate of absolute familiarity (intact hit/associative miss contrast) to be larger for correctly classified intact pairs relative to associative misses in the congruent but not in the neutral condition. This is exactly what we found.

A subset of $n = 19$ participants provided at least six artifact-free trials for the ERPs on associative misses and were included in this analysis (see Fig. 5). The analysis focused on mean amplitudes at electrode Pz, as this is where both the N400 attenuation effect in the intact hit/correct rejection contrast in our study and in the design- and stimulus-wise similar study by Bader et al. (2010) were maximal. We calculated a Congruency x Type (hit, miss)- MANOVA on mean amplitudes at electrode Pz in the time window from 520 to 676 ms. This analysis revealed a significant interaction, *Pillai* = .29, $F(1, 18) = 7.24$, $p = .015$. Follow-up paired-samples *t* tests revealed more positive waveforms for hits than misses in the congruent condition, $t(18) = 2.22$, $p = .039$, $g_{av} = 0.31$ and more negative waveforms for hits than misses in the neutral condition, $t(18) = -2.15$, $p = .046$, $g_{av} = 0.36$.

As apparent from Fig. 5, the topography of the congruent intact hit/associative miss (520–676ms; Fig. 5B) is similar to the topography of the

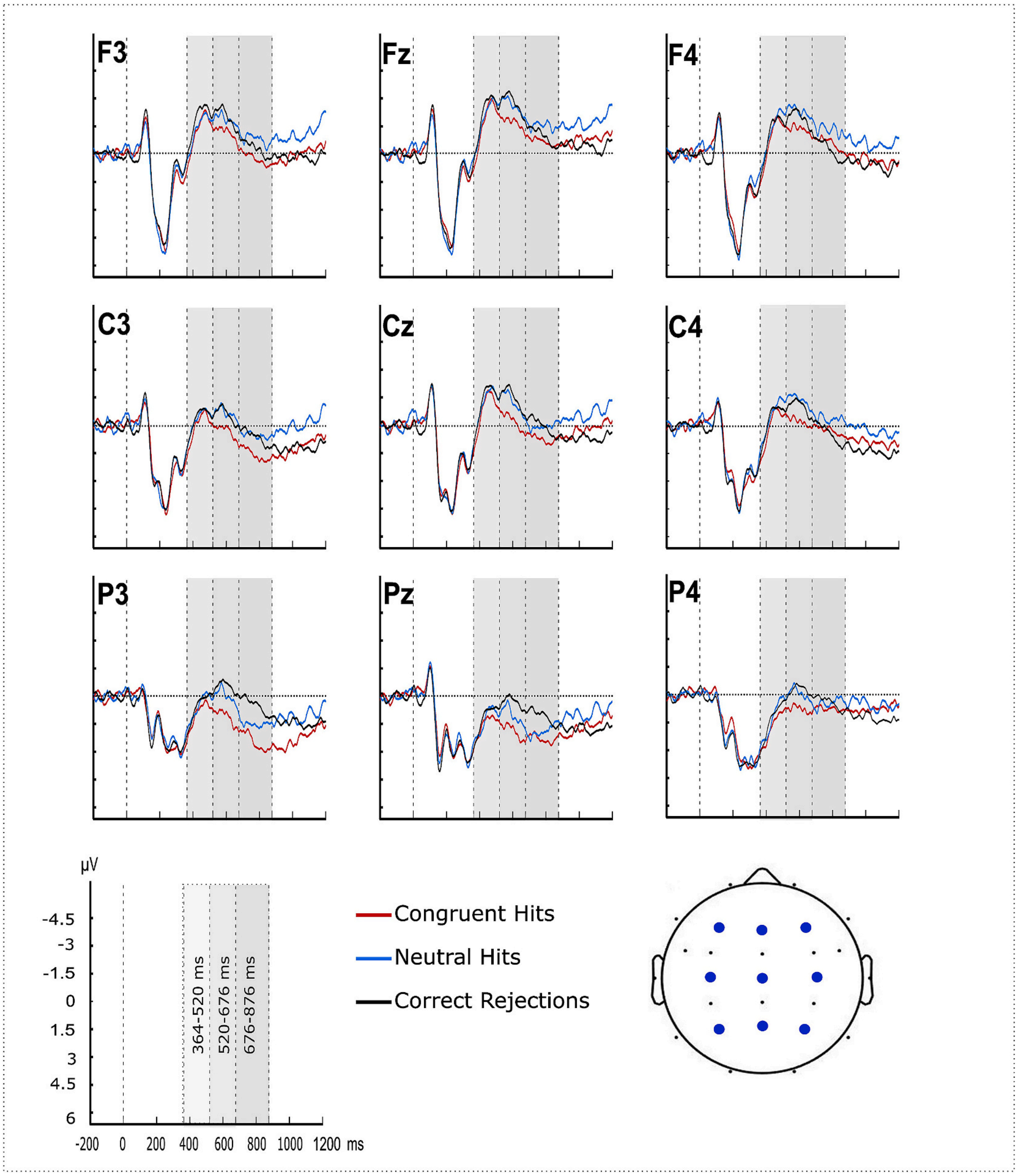

**Fig. 3.** ERP waveforms of hits and correct rejections for the nine analyzed electrodes.

intact hit/correct rejection-N400 attenuation effect in the same time window (Fig. 4A) and strikingly resembles the topography of the early old/new effect (350–500ms) in Bader et al. (2010). In addition, both contrasts reveal the same variation with experimental condition: Effects are larger in the congruent as compared to the neutral condition with more positive waveforms to intact hits as compared to the control condition, i.e., correct rejections or associative misses. Thus, we feel safe to interpret them as both reflecting the same experimental (N400 attenuation) ERP effect.

In a next step, we tested whether waveforms on intact hits and associative misses differ in the late (recollection) time window from 676 to 876 ms. For this analysis, we used the same posterior electrodes as in the analysis of the late parietal old/new effect, i.e., P3/4, Pz. Hence, we calculated a Congruency x Type (hit, miss) x Laterality (left, middle, right) - MANOVA on mean amplitudes at posterior electrodes in the late (recollection) time window from 676 to 876 ms. This analysis did not reveal any significant effects including congruency or type ($p_s > .114$).

To conclude, even though this result is only based on a subset of participants, it nevertheless supports the view that there is a larger contribution of absolute familiarity to recognition memory decisions in the congruent, as compared to the neutral condition. Besides, we did not find ERP differences between intact hits and associative misses in the late, recollection time window. As from statistical null results it is not possible to make inferences about the absence of an experimental effect, we refrain from further discussing this pattern of results.

### 1.3. Discussion

With Experiment 1, we sought to investigate whether schema congruency promotes the formation of unitized representations of pre-experimentally unrelated associations and boosts ensuing familiarity-based recognition.

We presumed that if unitization enhances familiarity specifically for associations (rather than for single items), there should be larger benefits for associative memory than for item memory in the (unitization supporting) schema-congruent condition (see Parks and Yonelinas, 2015). This is what we found: the behavioral congruency effect was larger for associative than for item memory. Of note, we also found that

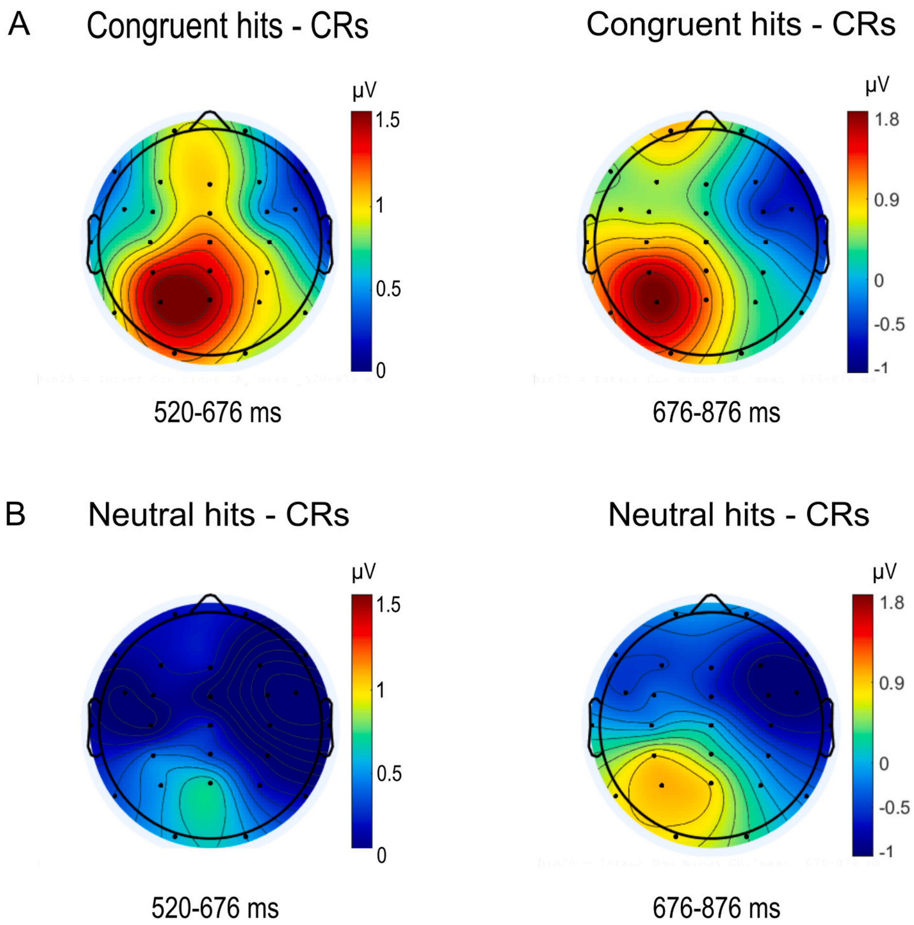

**Fig. 4.** Topographic maps.
Note. Printed are topographic maps (Hits minus Correct Rejections, CRs) in the congruent condition (Panel A) and in the neutral condition (Panel B) for the two later time windows (520–676ms and 676–876 ms).

item memory benefitted from schema congruency. As unitization is no binary state, but rather considered as a continuum (Parks and Yonelinas, 2015; Yonelinas et al., 2010), it is plausible that item information of both constituents of the novel unit is still available to some extent and can be boosted by the schema congruency manipulation. However, as associative memory nevertheless benefitted more from schema congruency than item memory, our results support the view that congruency exerts its influence mainly by promoting unitization and not by generally boosting semantic elaboration or deeper encoding (Craik and Tulving, 1975). In the latter case, we would have expected similar benefits from the congruency manipulation for item and associative memory.

We also predicted that if schema congruency enables the formation of unitized representations, absolute familiarity should contribute to recognition memory judgements. To test this hypothesis, we analyzed ERP differences between intact (old) and new word pairs. This ERP contrast shows an N400 attenuation effect (520–676 ms) with a broad, posterior topographical distribution, which is larger for the congruent than the neutral condition.

Although the old/new effect is a standard measure for retrieval success for both item, and associative memory, an objection could be that ERP differences between old (intact) and new items cannot unequivocally be attributed to the retrieval of associative information because intact and new word pairs differ in both, item and associative information. To cope with this issue, we considered another ERP contrast in which item memory is controlled for, i.e., hits on intact compound words versus associative misses. If the N400 attenuation effect in the intact-new contrast reflects absolute familiarity for the compound word, we expect a similar N400 effect to occur in the intact hit/associative miss contrast. Consistent with this view, in an exploratory analysis with 19 participants we found an ERP effect with more positive waveforms for hits than associative misses in the congruent condition in the same time window (520–676ms) at a mid-parietal site. As the topographies of the effects in the intact-new and in the intact hit/associative miss contrast (cf. Figs. 3 and 5) are highly similar to each other and show the same covariation with experimental conditions, we feel safe to interpret them as both reflecting the same experimental (N400 attenuation) ERP effect.

Compared to other studies, the N400 attenuation effect as a correlate of absolute familiarity onsetted about 200 ms later in our study and had a slightly longer temporal extension (Bader et al., 2010; Kamp et al., 2016; see Diana et al., 2011 for another study in which familiarity ERPs were delayed). However, for the following two reasons we think that the interpretation of this effect as a correlate of absolute familiarity is nonetheless plausible. First, the alternative explanation, namely that the N400 attenuation effect reflects early onsetting recollection is highly unlikely, given that the LPC is described as a “phasic, positive-going, parietally maximal ERP modulation” (Rugg and Curran, 2007, p. 252), which is not in line with the presence of a negativity with a central maximum between 500 and 700 ms (cf. Fig. 3).

Second, the N400 attenuation effect we are interested in is temporally bound to the occurrence of the underlying N400 component. In our experiment, the N400 component to new compound words, is extended. This is of relevance, as the N400 to new compound words can serve as a proxy for the processing of two words as a compound word. Because the N400 component is prolonged by approximately 180 ms for these new

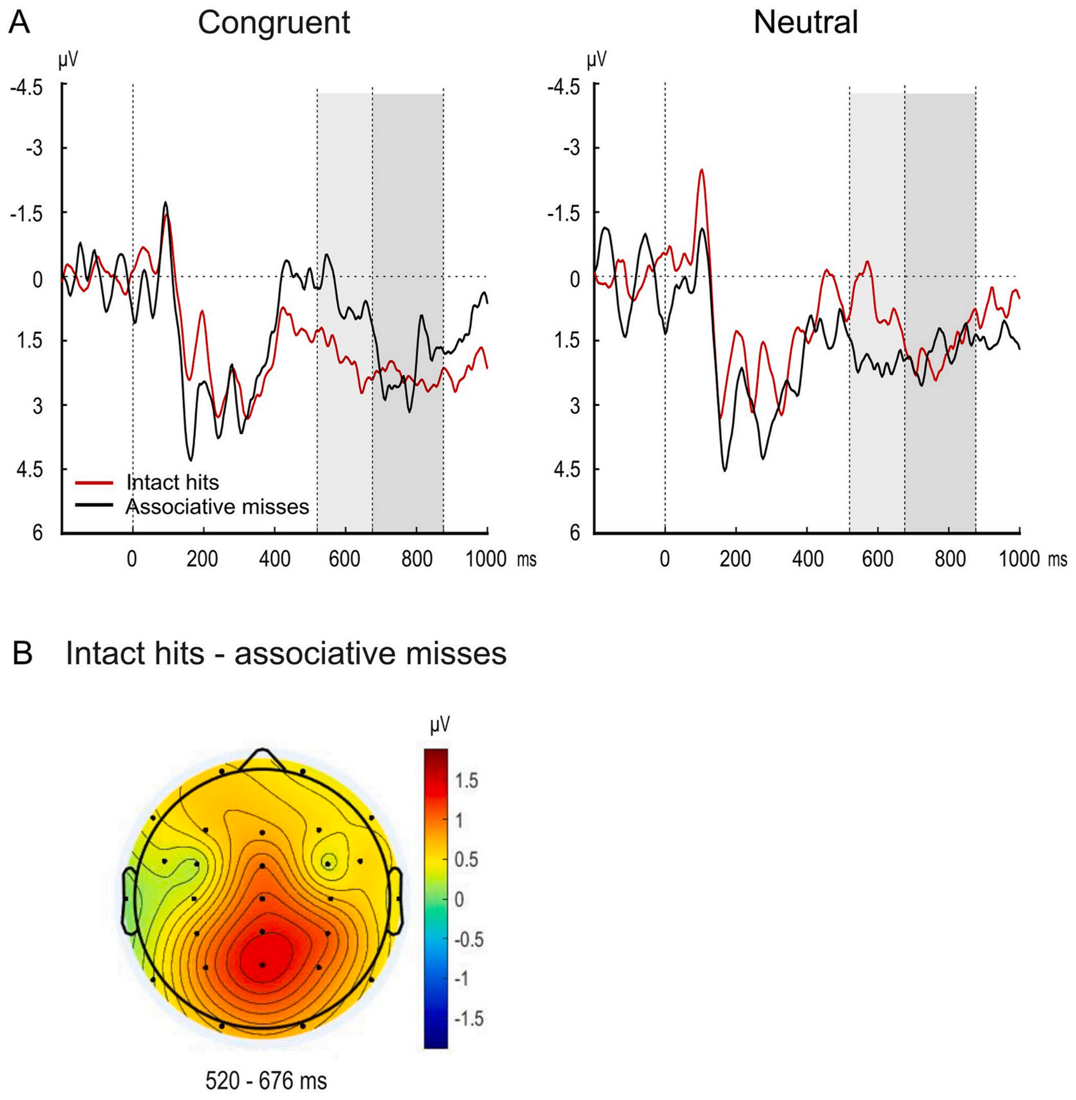

**Fig. 5.** ERPs of intact hits and associative misses.
Note. Panel A depicts ERPs on intact compound words correctly classified (intact hits) and erroneously classified as recombined (associative misses) at electrode Pz in the congruent and in the neutral condition. The early time window from 520 to 676 ms is highlighted in light grey, the later time window from 676 to 876 ms in dark grey. Panel B depicts a topographic map (intact hit minus associative miss) in the congruent condition in the time window from 520 to 676 ms.

compound words, and a similar temporal extension has been observed for the initial presentation of the novel compound words during learning (Meβmer et al., 2021), we are confident that it was the processing of the compound words per se which was prolonged and that this also holds for learned compound words.

The prolonged N400 to compound words might be a consequence of the simultaneous presentation of both compound word constituents, provoking processing of the underlying concepts of both. This is different to most N400 studies, in which the N400 is measured stimulus-locked to a single word (see Kutas and Federmeier, 2011, for a review). Thus, the cumbersome semantic processing of two nouns and their semantic integration might have delayed the processes reflected by the N400.

A question that follows from what we elaborated on before is why the N400 component on compound words is not only prolonged relative to N400 elicited by monomorphic words, but also relative to other ERP studies with novel compound words (e.g., Bader et al., 2010; Wiegand et al., 2010). Critically, in contrast to these studies, compound words in the present study were presented without a space between both constituent words and sometimes contained interfixes and it is possible that the space-free presentation delayed compound processing. Support for this view comes from a study by Inhoff et al. (2000), investigating the effect of spaces versus presentation without spaces between compound constituents. The concatenative presentation of a compound word without a space in between constituents (as in the preset study) hampered reading, resulting in increased naming latencies and gaze durations during reading. Therefore, we feel safe to conclude that it was the specific way of compound presentation which temporally extended the N400 component und thereby delayed the N400 attenuation effect in the current study.

In Experiment 2, we tested whether schema congruency enables the formation of semantically overlapping representations. By this we aimed at providing further and converging evidence for the view that schema congruency enables the formation of unitized representations and their familiarity-based recognition.

## 2. Experiment 2

In contrast to detailed hippocampal associations, unitized representations are assumed to be formed and stored in neocortical brain regions (e.g., Ford et al., 2010; Haskins et al., 2008; Henke, 2010). This assumption is based on different types of empirical evidence: First, amnestic patients can still recognize associations that are unitized (Quamme et al., 2007). Second, the perirhinal cortex (PRC) but not the hippocampus contributes to encoding of unitized representations (Ford et al., 2010; Haskins et al., 2008). The memory representations stored in the neocortical system are assumed to be overlapping, thereby holding shared features with related memories (Mayes et al., 2007; McClelland et al., 1995). From those representations, familiarity signals can be computed (Norman and O'Reilly, 2003; see O'Reilly and Norman, 2002), the strength of which depends on the overlap of the test item and the study item representation (Mayes et al., 2007; Norman and O'Reilly, 2003; see also Sadeh et al., 2014). In contrast, hippocampal representations are orthogonal also for similar items.

As non-hippocampal representations are overlapping when they share features, highly similar stimuli will erroneously activate representations of originally learned information and by this elicit a familiarity signal, driving false recognition (Norman and O'Reilly, 2003). Empirical evidence for this view comes from research showing that familiarity contributes to false recognition of similar lure items (Curran, 2000; Nessler et al., 2001; Nessler and Mecklinger, 2003; but see Tibon et al., 2018, who did not find evidence for a generalization of unitized representations).

From this it follows that in a recognition memory test, false alarms to (semantically) similar lure items can be used to infer the presence of overlapping representations: In an experimental condition in which neocortical representations and therefore familiarity-based processing dominate task performance, highly similar lures should be harder to reject as new. Consequently, if schema-congruency supports the formation of such overlapping representations and their familiarity-based recognition, we would expect higher false alarm rates on semantically related lure items in the schema-congruent as compared to a schema-neutral condition and this effect should be present solely for semantically related lures but not for unrelated (recombined) words.

## 2.1. Methods

### 2.1.1. Pre-registration

The current experiment has been pre-registered with AsPredicted (https://aspredicted.org/). The pre-registration can be accessed from https://aspredicted.org/qj27u.pdf.

### 2.1.2. Estimation of required sample size

To determine the required sample size to detect our effect of interest, $d_z = 0.50$ was obtained from the $F$ value of the Congruency (congruent, incongruent) x Item type (old item, lure) interaction on the proportion of old responses from Packard et al. (2017, Exp. 2). Based on this effect, a power analysis was calculated for a paired samples $t$-test with the parameters $\alpha = .05$, $1\text{-}\beta = 0.80$, two-sided, using the R package *pwr*. The required sample size, based on this analysis is $N = 34$. Thus, the analyzed sample size of $N = 35$ would theoretically result in a sufficiently powered study.[2]

### 2.1.3. Participants

A sample of $N = 48$ young adults[3] volunteered for this study, having been recruited via flyers and local databases. Participants were asked to take part in the study if they are not suffering from any neurological or psychiatric conditions. We pre-experimentally determined that datasets would be excluded if the same response were made in more than 90% of the trials, if less than 90% of the trials were responded to or if more than 20% of trials are responded to within less than 200 ms. Three datasets were excluded as they did not respond to at least 90% of experimental trials (learning phase or test phase were considered separately). Data from $n = 2$ participants had to be excluded because they reported that they intentionally studied the stimuli or took part in an experiment using the same stimuli ($n = 8$). The final sample consisted of $N = 35$ participants (24 females, age *range*: 18 to 30, $Mdn = 22$ years, $SD = 2.90$). Further, all participants were right-handed, as assessed with the Oldfield Handedness Inventory (Oldfield, 1971), and reported being native speakers of German. Participants gave their informed consent and were reimbursed with 10E/h or course credit. Participants were debriefed after the experiment. The study was approved by the ethics committee of the Faculty of Human and Business Sciences at Saarland University.

### 2.1.4. Stimulus materials

The 240 stimuli from experiment 1 were used in the current experiment within identical encoding lists. Which encoding list was used was fully counterbalanced across participants. For the test phase, we additionally used semantic lure compound words. Therefore, the original compound word was modified by exchanging the second constituent with a semantically related word, e.g., Hutpflanze (Hatplant) was modified to Hutpalme (Hatpalmtree). The normalized lemma frequency of the second constituent ranged from 0.01 to 233.63 occurrences per million (dlexDB; Heister et al., 2011). Lure compound words had a length of 8–20 letters ($M = 12.35$, $SD = 2.29$).

For the test lists, the two encoding lists were further divided into five subsets of 24 compound words, which were used to create 48 intact compound words, 24 lure compound words and 24 recombined compound words (using two subsets[4]) for each condition. We presented twice as many intact compound words as lure and recombined compound words because this requires an equal amount of old and new responses. Across subjects, each compound word was equally often presented in its lure form and twice as many times in its intact and recombined form. Each test list consisted of 96 intact compound words, 48 recombined compound words, and 48 lure compound words. Stimulus presentation in the experiment was pseudo-randomized for the encoding and test phase, with the limitation of not more than 3 consecutive trials in the same context condition (encoding phase) or not more than 3 consecutive trials requiring the same response (test phase). Due to our exclusion criteria, we did not achieve a fully counterbalanced design. However, all stimulus lists were shown approximately equally often.

### 2.1.5. Procedure

After having given their written–informed consent, participants completed a language questionnaire and the Oldfield Handedness Inventory (Oldfield, 1971). The experiment was created using E Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). The experiment proper consisted of an incidental encoding phase, a retention interval with a duration of about 10 min and a test phase. All stimuli of encoding and test phase were presented in white font against a black background. The learning phase was identical to experiment 1 with one exception: The jittered fixation crosses before the compound word presentation (in learning and test phase) was set to a fixed time of 1000ms.

The encoding phase was followed by a retention interval. During this interval, participants performed two distractor tasks. At first, an adapted computerized version of the Digit Symbol Task (Wechsler, 1955) from

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[2] We noticed that the pre-registered power analysis was incorrect. Therefore, we report a corrected power analysis.

[3] Exclusion of datasets due to prior participation or intentional learning was monitored during data collection and were replaced as far as possible to achieve a counterbalanced design. By this, one additional dataset was collected too much by mistake and was discarded before the data were analyzed.

[4] As only a single recombined compound word was created out of two intact compound words, twice as many learnt compound words are required for later recombined compound words as for later intact compound words.

Häuser et al. (2019) was performed for approximately 5 min, followed by 3 min of solving mathematical equations. Only then, participants were told about the upcoming test phase. During the test phase, participants were presented with one of five test list versions, consisting of 96 intact compound words, 48 recombined compound words and 48 lure compound words. The test phase is identical to experiment 1 with the exception that the jittered fixation crosses before the compound word presentation (in learning and test phase) was set to a fixed time of 1000ms and that participants should perform an old/new judgement on each word by using the keys f and j. In both, learning and test phase, there were self-paced breaks after 60 trials (encoding phase) or 48 trials (test phase), respectively. Before the test phase, there were 3 practice trials during which participants could familiarize themselves with the task.

### 2.1.6. *Data analysis*

For all analyses, the significance criterion of $p < .05$ was applied. Data were analyzed using R (version 4.2.1; R Core Team, 2022) and RStudio (Version, 2022.7.2.576; RStudio Team, 2022). The packages *dplyr* (version 1.0.10; Wickham et al., 2022), *tidyverse* (Wickham et al., 2019), *naniar* (version 0.6.1; Tierney et al., 2021), *pwr* (version 1.3–0; Champely, 2020), *pastecs* (version 1.3.21; Grosjean and Ibanez, 2018) and *afex* (version 1.2–0; Singmann et al., 2022) were used. Whenever non-hypothesis-driven multiple testing was required, the Bonferroni-Holm correction (Holm, 1979) was applied. The reported corrected *p*-values were calculated with the function p.adjust of the R package *stats* (R Core Team, 2022). To capture associative memory performance, associative hit rates, associative false alarm rates and associative Pr scores[5] were calculated similar as in Experiment 1. Note that in those scores, missing responses are not considered. In addition, proportion false alarm rates on recombined and lure compound words were calculated as the proportion of lure or recombined compound words classified as old, thus considering missing responses.

Behavioral outliers were defined as extreme values, i.e., with a standardized z-value greater than 3.29 above the mean (Field, 2009, p. 179). Hypotheses are tested with ANOVAs and paired-samples *t* tests. As measures of effect size, we report Hedges' $g_{av}$ for effects from paired samples t tests with the formula provided in the spreadsheet (Version 5; Lakens, 2013) and partial eta squared ($\eta_p^2$) for results of the ANOVA.

## 2.2. *Results*

### 2.2.1. *Associative memory performance considering intact and recombined compound words*

In a first step, we were interested in replicating the pattern of results from Experiment 1 in that associative memory performance (indicated by an associative *Pr* score considering intact and recombined compound words) benefits from schema congruency. As predicted, a paired samples *t*-test on associative *Pr* scores revealed better associative memory performance in the congruent than in the neutral condition, $t(34) = 4.88$, $p < .001$, $g_{av} = 0.61$ ($M_{congruent} = 0.47$, $SD_{congruent} = 0.23$, $M_{neutral} = 0.33$, $SD_{neutral} = 0.23$). Moreover, a Congruency (congruent, neutral) x Type (Hit, False alarm) – ANOVA revealed a significant main effect of congruency, $F(1, 34) = 12.70$, $p = .001$, $\eta_p^2 = 0.27$, a significant main effect of type, $F(1, 34) = 124.81$, $p < .001$, $\eta_p^2 = 0.79$ and a significant two-way interaction, $F(1, 34) = 23.81$, $p < .001$, $\eta_p^2 = 0.41$. Follow-up paired samples *t* tests revealed that associative hit rates were higher in the congruent than in the neutral condition, $t(34) = 6.14$, $p < .001$, $g_{av} = 1.02$ (one-sided; $M_{congruent} = 0.76$, $SD_{congruent} = 0.11$, $M_{neutral} = 0.64$, $SD_{neutral} = 0.13$). Similar to Experiment 1, we did not find significant across-condition differences in associative false alarm rates considering recombined compound words, $t(34) = -0.76$, $p = .454$, $g_{av} = 0.09$ (two-sided; $M_{congruent} = 0.29$, $SD_{congruent} = 0.19$, $M_{neutral} = 0.31$, $SD_{neutral} = 0.17$).[6] Thus, as the pattern of results is highly similar to Experiment 1, we conclude that despite small changes in the experimental design, associative memory effects induced by schema congruency in the present series of experiments can be considered as robust. The complete descriptive statistics can be seen from Table 2.

**Table 2**

Descriptive statistics (mean and standard deviation) of Experiment 2.

| | Schema congruency during learning | |
|---|---|---|
| | Congruent | Neutral |
| *Associative Memory Performance* | | |
| Associative hit rate | .76 (.11) | .64 (.13) |
| Associative false alarm rate (rec) | .29 (.19) | .31 (.17) |
| Associative false alarm rate (lure) | .35 (.16) | .29 (.16) |
| Associative Pr score (rec) | .47 (.23) | .33 (.23) |
| Associative Pr score (lure) | .41 (.17) | .35 (.19) |
| *Proportion False alarm rates* | | |
| Recombined | .28 (.19) | .30 (.17) |
| Lure | .33 (.15) | .28 (.16) |

*Note.* Standard deviations are shown in parentheses. *Rec* stands for recombined compound words, *lure* for semantically related lure compound words.

### 2.2.2. *Proportion false alarm rates on recombined and lure compound words*

Proportion false alarm rates on recombined and lure compound words can be seen in Table 2. Testing our main hypothesis that false alarm rates for lure compound words are larger in the congruent than in the neutral condition, a paired-samples *t*-test on lure false alarms rates revealed the expected pattern of results with more false alarms in the congruent than in the neutral condition, $t(34) = 2.33$, $p = .013$, $g_{av} = 0.34$ (one-sided).

In a next step, we were interested in directly comparing false alarm rates to lures and recombined compound words to show that the increased false alarm rate in the congruent condition was specific to the related lures and cannot be explained by generally more old responses in the congruent condition .[7] Therefore, we first calculated comparable false alarm rates on recombined compound words as the percentage of recombined compound words erroneously classified as old. Then, we tested whether the congruency effect was larger for lures than for recombined compounds with a Congruency (congruent, neutral) x Type (lure, recombined) – ANOVA on false alarm percentage scores.

The Congruency x Type - ANOVA revealed no significant main effect of congruency, $F(1, 34) = 1.34$, $p = .255$, $\eta_p^2 = 0.04$, no significant main effect of Type, $F(1, 34) = 0.47$, $p = .496$, $\eta_p^2 = 0.01$, but a significant interaction, $F(1, 34) = 5.43$, $p = .026$, $\eta_p^2 = 0.14$. In contrast to the significant across-condition difference in false alarms on semantically

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[5] Item memory scores, which we erroneously pre-registered, were not analyzed as the experiment did not include new compound words.

[6] To test whether memory performance still differs across conditions when performance on lure compound words rather than recombined compound words is considered, we calculated an adjusted associative lure false alarm rate. Here, the number of erroneous old responses on lures is relativized by the number of lures either classified as *old* or *new*, not taking missing responses into account. A congruency (congruent, neutral) x Type (Hit, False alarm) – ANOVA revealed a significant main effect of congruency, $F(1, 34) = 30.23$, $p < .001$, $\eta_p^2 = 0.47$, a significant main effect of type, $F(1, 34) = 216.81$, $p < .001$, $\eta_p^2 = 0.86$ and a significant two-way interaction, $F(1, 34) = 4.65$, $p = .038$, $\eta_p^2 = 0.12$. The interaction reflects that the difference in associative hits across conditions is larger than the difference in adjusted false alarm rates on lures, $t(34) = 2.49$, $p = .009$, $g_{av} = 0.38$ (one-sided; $M_{congruent} = 0.35$, $SD_{congruent} = 0.16$, $M_{neutral} = 0.29$, $SD_{neutral} = 0.16$), suggesting that memory performance is still better in the congruent than in the neutral condition, even if performance on lures compound words is considered (a summary of descriptive statistics can be seen from Table 2). Those analyses were not preregistered.

[7] This exploratory analysis was not preregistered.

related lures (see above), we did not find statistically reliable differences in false alarms on recombined compound words, $t(34) = -0.73$, $p = .472$, $g_{av} = 0.08$.

### 2.3. Discussion

We hypothesized that if schema congruency enables the formation of unitized representations and their familiarity-based recognition, the overlapping nature of those representations would lead to higher false alarm rates on semantically related lure items in the schema-congruent as compared to a schema-neutral condition. To test this hypothesis, we repeated Experiment 1 with slight modifications of the recognition memory test: First, semantic lure compound words were presented instead of new, never seen compound words and second, participants performed old/new judgements instead of intact/recombined/new judgements on each word.

In line with the idea that representations formed under the influence of a schema are overlapping, we found higher false alarm rates for lure compound words in the congruent as compared to the neutral condition. Crucially, schema congruency did not boost the proportion of old responses in general, as false alarm rates on recombined compound words did not differ across conditions. Thus, this pattern of results indicates that in the congruent condition, overlapping representations have been formed which are sensitive to the semantic content of the new concept.

The result of more false alarms on semantically related lures in the congruent than in the neutral condition is well in line with the assumption that recognition of those associations formed under the influence of a congruent schema are recognized via familiarity. Thus, we provide converging evidence in that schema-based encoding of novel associations enables the formation of unitized representations which can be recognized by familiarity.

## 3. General discussion

In the present study, our goal was to investigate if schema congruency promotes the formation of unitized representations out of pre-experimentally unrelated associations, and whether these representations can be recognized based on changes in their absolute familiarity. This idea was motivated by new insights on neocortical learning (Hebscher et al., 2019). Here, we combined the idea that new cortical engrams may be rapidly encoded if the respective information relates to prior schema knowledge (Hebscher et al., 2019) with the approach of rapid non-hippocampal associative learning for unitized associations (Henke, 2010).

From a theoretical point of view, schema-based encoding of novel compound words by means of a congruent definition bears the potential to serve as a conceptual knowledge structure. This knowledge structure constitutes the whole word meaning, as well as information about the contribution of each constituent to the whole word meaning. In being processed against the backdrop of this conceptual knowledge structure, the word representations of the constituents can be linked on a conceptual level, and thereby, the newly learnt compound words can be unitized. Based on this reasoning, we sought to investigate whether schema congruency enables the formation of unitized representations and their familiarity-based recognition. This research question was addressed in two experiments.

In line with our hypothesis that schema-congruency enables the formation of unitized representations, the behavioral congruency effect in Experiment 1 was larger for associative than for item memory. Hence, our results support the view that congruency exerts its influence mainly by promoting unitization and not by generally boosting semantic elaboration or deeper encoding (Craik and Tulving, 1975). In the latter case, we would have expected similar benefits from the congruency manipulation for item and associative memory.

The ERP results of Experiment 1 show an N400 attenuation effect (520–676 ms) with a broad, posterior topographical distribution, which is larger for the congruent as compared to the neutral condition. This N400 effect is present in the initial intact hits/correct rejections as well as in an exploratory analysis of an intact hits/associative misses-contrast. Although the N400 attenuation effect in our study is unconventional in its temporal characteristics (520–676ms instead of 300–500ms), we consider it as a valid measure for absolute familiarity given its topography, the morphology of the underling N400 component and its similarity with an N400 component observed for the learning phase (Meßmer et al., 2021; see also discussion of Experiment 1).

Similar N400 attenuation effects have been taken as a measure of diagnostic fluency in situations in which fluency is salient, as e.g., for novel compound words having a meaning (Bader et al., 2010; Wiegand et al., 2010; see Mecklinger and Bader, 2020). This broadly distributed N400 attenuation effect differs topographically and functionally from the FN400 effect, which is usually found in recognition memory experiments (see Bader and Mecklinger, 2017, for a dissociation of both effects in a single experiment). Hereby, the absolute familiarity signal is evoked by the assignment of a meaning to the compound word representation, provided by the congruent definition (see Mecklinger and Bader, 2020). In our study, we assume that the congruent definition serves as a schema (cf. Gilboa and Marlatte, 2017) that enables the rapid acquisition and semantic integration of such a compound word meaning, probably resulting in the formation of a unitized representation. The presence of such a matching template has been argued to influence how fast novel units can be formed (Mayes et al., 2007). Semantic integration then results in an absolute familiarity signal that is diagnostic in a test setting in which the non-studied words are new and should not elicit absolute familiarity.

An objection against the view that the N400 attenuation effect in Experiment 1 reflects absolute familiarity could be that we infer on familiarity from ERP measures alone, as Experiment 1 did not include direct additional behavioral measures of familiarity, for example receiver operating characteristics (Yonelinas et al., 1994).

Nonetheless, ERP studies of recognition memory have provided ample evidence that ERP components with specific temporal and topographic characteristics are closely associated with memory processes (such as familiarity and recollection). Some of these studies have validated ERP measures of familiarity by showing similar effects of experimental manipulations on behavioral and corresponding ERP measures (Bruett and Leynes, 2015; Migo et al., 2009; Bader et al., 2020). Hereby, the FN400 is a reliable and objective measure of familiarity memory, as its amplitude has consistently been found to be sensitive to common operational definitions of relative familiarity (see Rugg and Curran, 2007, for a review). More importantly, N400 (attenuation) effects indicative for absolute familiarity or conceptual fluency have been reported in a remarkable number of ERP studies from different laboratories (Strózak et al., 2016; Woollams et al., 2008; Yang et al., 2019; Bruett and Leynes, 2015).

Importantly, with Experiment 2, we provide indirect behavioral evidence for our hypothesis that schema congruency enables familiarity-based recognition by enabling the formation of unitized representations. It has been argued previously that as non-hippocampal representations are overlapping when they share features, similar lures can elicit a false familiarity signal (Norman and O'Reilly, 2003). We found higher false alarm rates to semantically related lures in the congruent condition than in the neutral condition. This supports our hypothesis that schema-based learning leads to the creation of unitized representations which are recognized on the basis of familiarity. Additional empirical support for this interpretation comes from a study by Webb et al. (2016) investigated the contribution of familiarity and recollection to recognition of schema-related and unrelated target objects. Visual scenes served as schema and the contribution of familiarity and recollection was assessed with by collecting 'Remember/Know/New' judgements. The behavioral results show that for familiarity-based decisions ('know'), false alarm rates were equal to hit rates for schema-congruent objects, whilst hits were higher than false alarm rates for schema-incongruent objects. Thus, if there is a schematic relation between targets and semantically similar lures, discrimination based on familiarity more likely fails than for unrelated objects. In contrast, for recollection-based decisions hit rates were larger than false alarm rates in both conditions. Thus, also in this study, schema-based encoding resulted in overlapping representations. To conclude, with the larger N400 attenuation effect (experiment 1) and higher false alarm rates on semantically related lures (experiment 2) in the congruent as compared to the neutral condition, we provide evidence in favor of the idea that schema congruency during encoding supports the formation of unitized representations and their familiarity-based recognition.

Evidence in that schema-congruency promotes familiarity-based remembering of already known items was also obtained in a behavioral study by Souza et al. (2022). In their second experiment, participants were presented with images of common objects, belonging to one of eight categories. Objects were either shown within a perceptual encoding condition, in which participants had to decide how complex the object is, or in a conceptual schema encoding condition, in which they had to decide whether the object belongs to its respective category. Items were either typical or atypical for their category. In a later recognition test, a remember/know/guess procedure was applied (Gardiner, 1988), in which guess responses include low confidence inferential judgments and uncertain conscious states (Gardiner, 1988; see Souza et al., 2022). The authors found that guess responses were more pronounced for typical items, what the authors interpret in that more familiarity contributes to recognition of typical items. Whilst those data provide evidence for schema-based learning increasing the contribution of familiarity to recognition decisions for known single items, in the current study, we provide evidence in that novel associations learned under the influence of a schema can be recognized by means of absolute (associative) familiarity.

Neural evidence for schema-based learning supporting the formation and recognition of unitized representations of novel associations and familiarity-based remembering comes from a brain imaging study by Bader et al. (2014). In this study, unitization was established similar to the present study, by means of a congruent definition. Interestingly, the medial prefrontal cortex, a region known to be critical for schema-congruent encoding (e.g. van Kesteren et al., 2010; see van Kesteren et al., 2012), was found to be more active during recognition of unitized associations than during item recognition and activation in familiarity-related brain regions (in the inferior frontal gyrus and in the parahippocampal gyrus extending into the fusiform gyrus) were selectively found in the congruent definition group. A recent brain imaging study showed that new information (here noun-adjective word pairs) that is initially inconsistent with prior knowledge undergoes a shift from novelty to familiarity in the time course of repeated presentations. In fact, this shift is indicated by convergence, meaning that initially different neural representations of the newly learned word pairs in lateral temporal and frontal brain regions, the medial prefrontal cortex and the medial temporal lobe changed throughout a few repetitions and gradually became indistinguishable from those of familiar word pairs (Yacoby et al., 2021). The results of those studies (Bader et al., 2014; Yacoby et al., 2021) can be interpreted in that rapid neocortical learning, probably underlying both prior knowledge-based and repetition-based learning (see Hebscher et al., 2019), supports familiarity.

Interestingly, the ERP absolute familiarity effect in the congruent condition fits well with an idea we proposed earlier in that three interleaved processes[8] underlie the schema-congruency based learning of novel compounds (Meßmer et al., 2021). First, semantic priming of the modifier component by the congruent context results from the additional semantic relationship between the modifier and the context and enables schema-supported processing of the compound word as a whole. Second, context-independent semantic integration of both constituents occurs that depends on lexical characteristics of the constituents. Hereby, a context-independent compound representation can be formed which could then – in a third process - be reconciled with the context meaning. Hereby, a conceptually integrated compound representation is formed, linking the new whole-word meaning with prior knowledge as provided by the congruent definition. This integration into prior knowledge structures in turn enables the formation of a unitized, conceptual representation and familiarity-based remembering in an ensuing memory test (Mecklinger and Bader, 2020)

In applying a broader scope, the formation of unitized representations has been considered to be part of the processing of a larger anterior temporal memory system including – amongst others – the PRC and anterior HC (Ranganath and Ritchey, 2012). This system is assumed to support familiarity-based remembering. The role of this system in language-related tasks might be creating and modifying concepts following novel experiences. Hereby, it is plausible that unitization might be one operation performed by this system if novel associations forming novel concepts are acquired. Inherent to the assumption of the anterior temporal system operating on concepts is a low resolution on episodic details. This resonates with the assumption that the anterior HC as part of the anterior temporal system forms semantic gist representations (Gilboa and Moscovitch, 2021; Sekeres et al., 2018). Crucially, it has been proposed that schema congruency drives gist extraction and that representations formed under the influence of a schema are less detailed (Gilboa and Marlatte, 2017; Spalding et al., 2015; Sweegers et al., 2015). The results of Experiment 2 are in line with the idea that schema congruency drives associative learning by enabling the formation of overlapping, unitized representations. However, those representations seem to be less detailed, resulting in worse discrimination of semantically similar lure compound words for schema-congruent information.

Albeit the current study provides evidence in that schema congruency during encoding enables the formation of unitized representations and their later familiarity-based recognition, there are some limitations. First, as already discussed in more detail in the report of Experiment 1, the N400 attenuation effect is temporally delayed in the current study, which weakens the interpretation that schema congruency supports recognition via absolute familiarity. Second, although the N400 attenuation effect in the intact hits/associative misses-contrast highly resembles the initial N400 attenuation effect, it is exploratory and only based on data for a subset of participants. This concern could be addressed in a follow-up study with modified trial numbers to improve the signal-to-noise ratio.

Third, with the observation of higher false alarm rates on semantically related lure compound words, we provide additional indirect evidence for absolute familiarity contributing to recognition of compound words encoded under the influence of a congruent schema. Nevertheless, as this additional evidence remains indirect, more research is needed to first, clarify the reasons for the temporal extension of the N400 attenuation effect and second, to confirm that it reflects absolute familiarity contributing to recognition of novel associations learned under the influence of a congruent schema.

## 4. Conclusion

In the present study, we investigated the influence of schema-based learning on conceptual unitization of novel compound word associations by using a manipulation of schema congruency.

In Experiment 1, similar to previous studies (Bader et al., 2010; Kamp et al., 2016; Wiegand et al., 2010), we found a larger N400 attenuation effect, the ERP correlate of absolute familiarity (Bridger et al., 2014), in the schema-congruent condition, suggesting that newly learned compounds can be unitized when the words constituting the

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[8] Please note that presentation order in the text does not correspond to a sequential model. Rather, our data indicate at least partly parallel processing (see Meßmer et al., 2021).

compound are congruent with a prior schema context. In line with a recent neurocognitive model (Mecklinger and Bader, 2020), we interpret this N400 attenuation effect to reflect the contribution of absolute familiarity to recognition judgements. In Experiment 2, we found higher false alarm rates on semantically similar compound words in the congruent as compared to the neutral condition, indicating that schema congruency enables the formation of unitized representations and supports familiarity-based memory retrieval. Thus, we provide converging evidence for the view that schema congruency enables the formation of unitized representations and supports familiarity-based associative memory retrieval. Thereby, our results add to brain imaging studies on schema-congruency based learning and remembering (Bein et al., 2014; van Kesteren et al., 2012; Sommer et al., 2022) and shed light on the temporal characteristics underlying the recognition of information which was encoded under the influence of a schema.

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## CRediT authorship contribution statement

**Julia A. Meßmer:** 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, Writing – original draft.

## Declaration of competing interest

None.

## Data availability

Stimulus materials are available from https://osf.io/d7w5a/and data files are available from https://osf.io/6h7db/

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