Biological Psychology 182 (2023) 108644

Contents lists available at ScienceDirect

Biological Psychology

journal homepage: www.elsevier.com/locate/biopsycho

# Chinese character unitization enhances item memory in addition to associative memory: Evidence from ERP and TFR

Chunyu Zhao [a], Yun Chen [b], Zaizhu Han [c], Chunyan Guo [a,*]

[a] Beijing Key Laboratory of Learning and Cognition, School of Psychology, Capital Normal University, Beijing, China
[b] College of Elementary Education, Capital Normal University, Beijing, China
[c] State Key Laboratory of Cognitive Neuroscience and Learning and IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, China

ARTICLE INFO

*Keywords:*
Unitization
Chinese characters
Item memory
Associative memory
Neural oscillation

ABSTRACT

While the effect of unitization on associative memory has been established, its effect on item memory remains debated. This study aimed to investigate the influence of unitization on item memory using Chinese characters to manipulate unitization and recording scalp EEG to elucidate the underlying neural mechanisms. In the learning phase, participants were asked to determine whether the character pairs presented could form a Chinese compound character. In the subsequent testing phase, participants performed item recognition and associative recognition tasks. Behavioral results revealed that unitization not only improved associative memory but also facilitated item memory. Event-related potential analysis indicated there were FN400 effect (related to familiarity) and LPC effect (related to recollection) during associative recognition after unitization, however, only the LPC effect was observed for the item recognition. More importantly, time-frequency analysis demonstrated stronger θ oscillations (associated with recollection) in the unitized condition compared to the non-unitized condition, which further partially mediated the reduction in RT during the item recognition. These results suggest that unitization enhances item memory through recollection, thereby leading to more confident recognition judgments, and that unitization does not impair item processing within an association but rather enables more precise and accurate processing.

## 1. Introduction

Episodic memory, which is a type of human long-term memory (Tulving, 1972), can be divided into item memory and associative memory. Item memory refers to the ability to learn and remember items, whereas associative memory refers to learning and remembering the relationship between the items. Unitization is a process that combines different items into a new unit (Graf & Schacter, 1989). For example, the two words "traffic" and "jam" can be united into a compound word "traffic jam". Numerous studies have shown that unitization can improve the performance of associative memory in healthy adults (Haskins et al., 2008; Rhodes & Donaldson, 2008; Lu et al., 2020), children (Robey & Riggins, 2017), elderly individuals (Zheng et al., 2015; Zheng et al., 2016; Memel & Ryan, 2017), and amnesic or brain-damaged patients (Giovanello et al., 2006; Quamme et al., 2007; Diana et al., 2010).

What is the cognitive mechanism by which unitization promotes associative memory? Existing literature suggests that unitization functions by binding disparate items into a whole, as indicated by its operational definition. Empirical support for this view is provided by studies demonstrating the presence of familiarity-based associative recognition after unitization. The dual-process model proposes that recognition of episodic memory is supported by either familiarity or recollection (Yonelinas, 2002). Familiarity is a fast and automatic process that provides a sense of prior exposure to an event but lacks specific details. Recollection, on the other hand, is slower and accompanied by more details, such as when and where an event occurred. As associative memory involves memories of both individual items and their associations, recognition of an association can usually only be supported by recollection. However, unitization permits familiarity-based associative recognition, which implies that the process of unitization has already integrated the original two items into a single unit for encoding (Jäger et al., 2006; Rhodes & Donaldson, 2007; Bader et al., 2010; Tibon & Levy, 2014; Tibon et al., 2014; Guillaume & Etienne, 2015; Li et al., 2019; Lu et al., 2020; Zhao et al., 2020).

For the neural indicators of familiarity and recollection, ERP (event-

* Correspondence to: NO. 23, Baiduizijia, Haidian District, Beijing 100048, China.
*E-mail address:* guocy@cnu.edu.cn (C. Guo).

https://doi.org/10.1016/j.biopsycho.2023.108644
Received 7 January 2023; Received in revised form 24 June 2023; Accepted 15 July 2023
Available online 17 July 2023

related potential) studies measure it based on the old/new effect. The FN400 component is prominent over mid-frontal electrodes and emerges 200 ~ 500 ms following the stimulus. The FN400 effect is characterized by a greater negative deflection for "new" stimuli relative to "old" stimuli, reflecting familiarity (Curran & Hancock, 2007). Conversely, the LPC component is typically observed over left parietal electrodes between 500 ~ 800 ms after stimulus onset. The LPC effect is characterized by a greater positive deflection for "old" stimuli than "new" stimuli, reflecting recollection (Rugg & Curran, 2007). Besides ERP investigations, non-time-locked frequency representations have been shown to be relevant to episodic memory (Nyhus & Curran, 2010; Hanslmayr et al., 2016; Herweg et al., 2019). Gruber et al. (2008) found that γ oscillation was higher for correctly identified "old" relative to "new" items, whereas θ oscillation was sensitive to source discrimination (usually supported by recollection). In addition, Herweg et al. (2016), utilizing simultaneous EEG–fMRI technology, identified that low-frequency oscillations in the θ and α band provide a mechanism to functionally bind the hippocampus and frontal cortex during successful recollection. These findings provide further insight into the neural basis of familiarity and recollection processes in episodic memory retrieval.

While the effect of unitization on associative memory tends to be consistent, there remains a debate about its influence on item memory. The "benefits-costs" view argues that unitization could improve associative memory but at the cost of item memory because unitization will consume cognitive resources, which reduces the processing of items during the encoding phase (Ahmad & Hockley, 2014; Murray & Kensinger, 2012; Pilgrim et al., 2012; Shao & Weng, 2011). On the contrary, other researchers hold the view of "benefits-only". Unitizations could improve associative memory but not impede (even promote) item memory because unitization is accomplished on the basis of full processing of the items (Hockley & Cristi, 1996; Liu et al., 2020; Liu & Guo, 2019; Parks & Yonelinas, 2015; Zhao & Guo, 2023). Clarifying this controversy would help us understand whether and how unitization affects the encoding of items when they are integrated into a whole.

These seemingly contradictory viewpoints can be reconciled. On the one hand, we propose that unitization impairs familiarity during item recognition, consistent with the notion of "benefits-costs" as suggested by previous research (Pilgrim et al., 2012). The lack of consensus in previous studies regarding this point may be attributed to the confounding effects of item-specific encoding rather than pure associative encoding during unitization. On the other hand, unitization does not impair, and may even enhance, behavioral performance during item recognition, as revealed by the majority of previous studies (Hockley & Cristi, 1996; Liu et al., 2020; Liu & Guo, 2019; Parks & Yonelinas, 2015; Pilgrim et al., 2012; Zhao & Guo, 2023). This perspective is also consistent with the hypothesis of encoding variability (Martin, 1968) and recent findings in the field of working memory (Allen et al., 2021; Chung et al., 2022). Finally, the observed enhancement in behavioral performance coupled with a decrease in familiarity will lead to the inference of an increased recollection during item recognition.

The current study combines the paradigms of item recognition and associative recognition to explore the effects of unitization on item memory in addition to associative memory (Liu et al., 2020). Chinese compound characters were used to manipulate unitization and to minimize item-specific encoding during unitization, as the characters comprising the compound character have no direct associated meanings to the compound character. For example, the meaning of the compound character "叶" (*/ye4/*, leaf) is different from the constituent "口" (*/kou3/*, mouth) or "十" (*/shi2/*, ten). By adopting this approach, participants are encouraged to minimize their engagement with the item-specific encoding and instead focus on the encoding of the association during unitization. The scalp electroencephalogram (EEG) was recorded during the experiment to explore the underlying neural mechanism associated with recognition. We hypothesize that item memory will not be impaired and may even be enhanced in our study. While the "benefits-costs" view recognizes the potential negative effects of unitization on item recognition, we contend that such harm is limited to familiarity. To maintain the performance of item recognition, we further postulate that recollection may be enhanced.

## 2. Methods

### *2.1. Participants*

Based on our previous research (Zhao & Guo, 2023), the effect size (Cohen's *d*) of unitization on item memory was 1.01. A sample size of 13 is required to examine this effect (calculated by G*power 3.1 with a confidence level of 0.05, power of 0.9, and a paired-sample *t*-test). In the current study, 31 right-handed undergraduate or graduate students were recruited. Six participants did not complete the experiment due to personal reasons. The remaining 25 participants included 11 males and 14 females (19–28 years old). All of the students were native Chinese speakers with normal or corrected-to-normal vision. We obtained informed consent from each participant before the experiment. This study was approved by the Ethics Committee of the School of Psychology of Capital Normal University, Beijing, China.

### *2.2. Materials*

The formal experiment consisted of 8 blocks, each comprising 120 Chinese characters. Each block involved learning and testing phase (see Fig. 1). In the learning phase, 100 characters were paired to form 25 unitized pairs [UP; the two characters can form a compound character; e.g., "山" (*/shan1/*, mountain) and "夹" (*/jia2/*, clip) could be formed into "峡" (*/xia2/*, gorge), the information within parentheses denotes the pronunciation and meaning of the character] and 25 non-unitized pairs [NP; the two characters cannot form a compound character; e.g., "本" (*/ben3/*, foundation) and "大" (*/da4/*, big)]. The associative testing phase included 4 types of character pairs: associative unitized same pairs (AU-same) were the same as the UP, associative unitized rearranged pairs (AU-rearranged) were rearranged from the UP, associative non-unitized same pairs (AN-same) were same as the NP, and associative non-unitized rearranged pairs (AU-rearranged) were rearranged from the NP. Each of the types included 10 characters pairs. In the item testing phase, there were 3 types of character pairs: (1) 5 pairs out of the 25 UP pairs could form 10 single characters (item unitized same characters, IU-same); (2) 5 pairs out of the 25 NP could form 10 single characters (item non-unitized same characters, IN-same); and 20 new characters (item new characters, I-new) which never appeared in the learning phase. A total of 548 Chinese characters were used in the 8 blocks, in which 136 characters only appeared in one block and the remaining 412 characters appeared repeatedly in the first 4 blocks and the last 4 blocks. Familiarity with these characters was matched between conditions. The characters were presented with a horizontal and vertical visual angle of 1.43° in white on a black background.

### *2.3. Procedure*

Each participant first performed the practice trials. There was a one-minute break between two consecutive blocks within the first four blocks and the second four blocks. Meanwhile, there was a one-month interval between the first four blocks and the last four blocks to avoid interference caused by the characters from the first 4 blocks appearing in the latter 4 blocks. The order of these blocks was counterbalanced across the participants. Each block contained a learning, a distraction, and two testing phases.

In the learning phase, each trial began with a cross presented for 900 ~ 1100 ms, followed by a character pair presented for 3000 ms. Participants were asked to distinguish whether the character pair could or not form a compound character and were instructed to remember the two characters and their relationship. Their responses were made by their left and right index fingers. The response buttons for the conditions

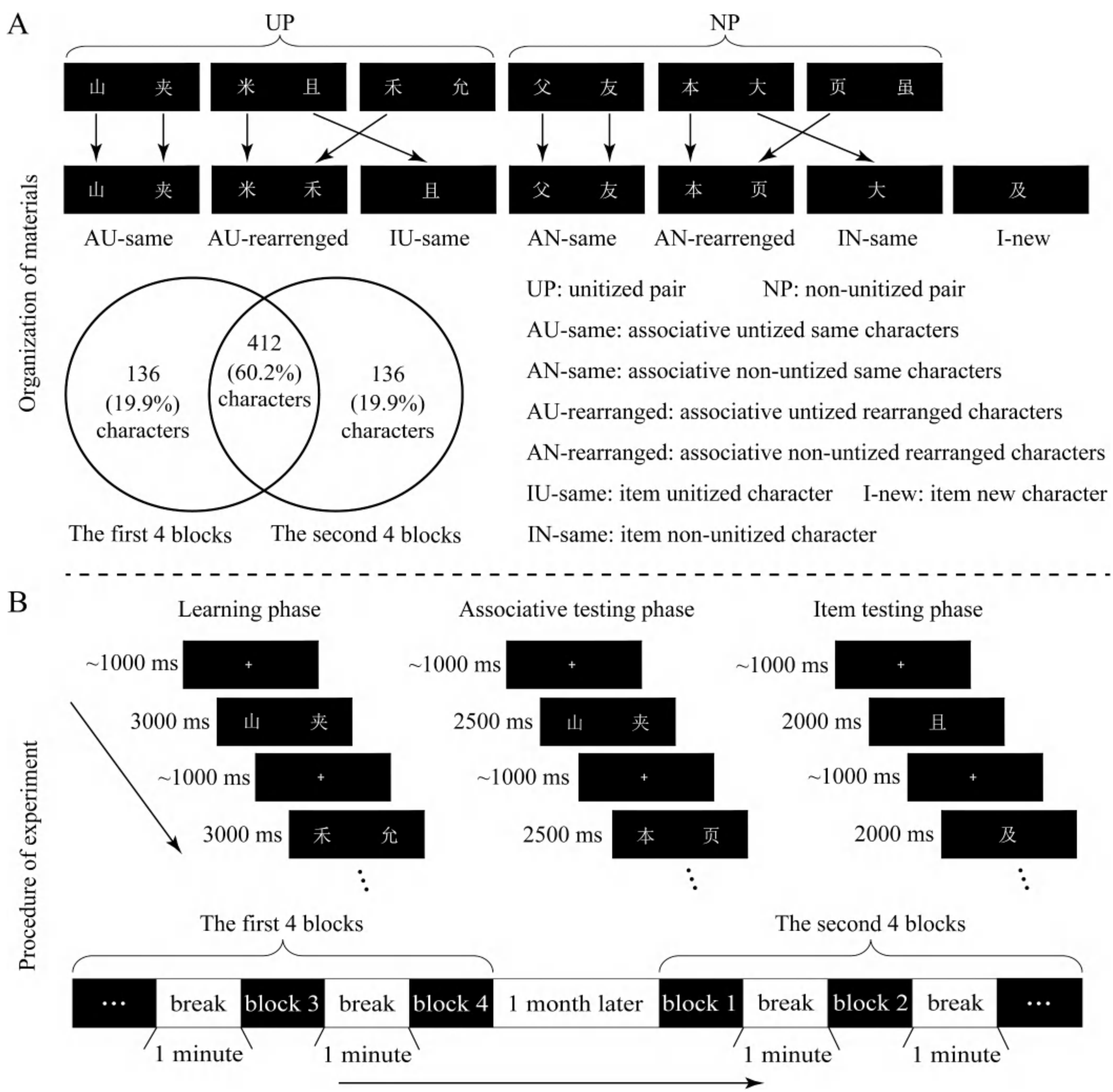


**Fig. 1.** The organization of the experimental materials and procedure. A: the stimulus combinations between the learning and testing phases (top), as well as the number of characters across the eight experimental blocks (bottom). B: the experimental procedures within (top) and between (bottom) blocks.

were counterbalanced across the participants. After the learning phase, a distraction task was performed. Participants were required to count backward from a three-digit number by three for 1 min and to report the results in a loud manner.

For the associative testing phase, the same and rearranged pairs were presented in a pseudo-randomized order to ensure that the number of consecutive repetitions of the same response did not exceed three times. Each trial began with a cross presented for 900 ~ 1100 ms followed by a character pair for 2500 ms. In the item testing phase, the same and new characters were presented. Each trial began with a cross presented for 900 ~ 1100 ms, followed by a character for 2000 ms. Participants were instructed to distinguish whether the character pairs or characters were the same as in the learning phase or not with their left and right index fingers. The response buttons to the conditions and the order of the associative test and item test were counterbalanced across the participants.

### *2.4. Data acquisition and preprocessing*

Presentation and recording of these stimuli and responses were controlled by Presentation software. The EEG data were recorded from 62 Ag/AgCl electrodes using the NeuroScan SynAmps system and the impedance was maintained below 7 kΩ. Signals were amplified with a bandpass filter of 0.05 ~ 100 Hz and sampled at a rate of 500 Hz. All channels were referenced to the left mastoid during the recording.

EEG signals were preprocessed using the EEGLAB toolbox (Delorme & Makeig, 2004) and in-house scripts in MATLAB 2020b (MathWorks). For associative recognition, the EEG data were re-referenced to the averaged mastoids and filtered with a bandpass filter of 0.1 ~ 40 Hz. Eye movements and/or blink noises were identified and corrected using the independent component analysis (ICA) algorithm. The continuous EEG data were then segmented into 1.2-second epochs (−200 ~ 1000 ms relative to the stimulus onset), and the data before the stimulus (−200 ~ 0 ms) is used for baseline correction. Afterward, epochs were rejected if they had a drift exceeding ± 75μV. For item recognition, the EEG data were filtered with a bandpass filter of 0.1 ~ 100 Hz and segmented into 1.9-second epochs (−700 ~ 1200 ms). Other preprocessing operations were the same as for associative recognition. The number of accepted trials for each condition exceeded the minimum trials required in previous literature (≥16) for all participants. Results were as follows: AU-same (mean = 67, range = 49 ~ 78), AU-rearranged (mean = 62, range = 46 ~ 78), AN-same (mean = 49, range = 28 ~ 72), AN-rearranged (mean = 50, range = 34 ~ 69), IU-same (mean = 56, range = 39 ~ 73), IN-same (mean = 45, range = 25 ~ 69), and I-new (mean = 103, range = 58 ~ 142).

### 2.5. Data analysis

#### 2.5.1. Behavioral data analysis

In the learning phase, the averaged accuracy and reaction time (RT) for the UP and NP were reported. In the testing phase, the hit rate (Hit) for the same pairs, correct rejection (CR) for the rearranged pairs or new characters, and the performance of recognition (Pr,Pr = Hit – false alarms) were calculated. Paired-sample *t*-test and repeated-measures ANOVA were conducted in SPSS 25 (International Business Machines Corporation, Armonk, New York, USA). The *Greenhouse-Geisser* correction was applied when the data conflicted with the sphericity hypothesis. The *LSD* correction was used for the post hoc comparisons. Due to the limitations of null hypothesis significance tests (NHST) in assessing the null hypothesis (Wagenmakers, 2007), Bayesian factor analysis was performed on the non-significant results to effectively address the research questions raised in this paper. When the Bayes factor (BF) is between 1 and 3, there is weak evidence supporting $H_1$; for BF values between 1/3 and 1, weakly supporting $H_0$; and in the range of 1/10–1/3, moderately supporting $H_0$ (Wagenmakers et al., 2018).

#### 2.5.2. ERP analysis

The remaining trials after preprocessing were averaged within each condition using the EEGLAB toolbox and in-house scripts in MATLAB 2020b (MathWorks). According to previous studies (Curran & Hancock, 2007; Rugg & Curran, 2007), we mainly focused on the ERP components relative to familiarity (FN400) and recollection (LPC). The scalp location and time window were determined according to the classic FN400 and LPC in addition to the waveform in our study. Specifically, for associative recognition, the FN400 was specified by averaging the amplitudes over the middle frontal channels (F3, Fz, F4, FC3, FCz, and FC4) within the time window of 200 ~ 400 ms after stimuli. The LPC was specified by averaging the amplitudes over the left parietal channels (CP1, CP3, CP5, P1, P3, and P5) within 500 ~ 800 ms. For the item recognition, the LPC was specified by averaging the amplitudes over the left parietal channels (CP1, CP3, CP5, P1, P3, and P5) and time window of 400 ~ 700 ms (the LPC was earlier than associative recognition after checking the waveform of item recognition). The definition of FN400 in item recognition was the same as that of associative recognition. If the rearranged or new characters showed significantly greater negative deflection than the same pairs or characters in FN400, there was a significant FN400 old/new effect. If the same characters showed significantly greater positive deflections than the rearranged or new ones in LPC, there was a significant LPC old/new effect.

#### 2.5.3. Time-frequency analysis

The time-frequency representation (TFR) was calculated via wavelet analysis in a range of 0.1 ~ 100 Hz using the Letswave7 toolbox (https://github.com/NOCIONS/letswave7) and in-house scripts in MATLAB 2020b (MathWorks). Single-trial EEG data were convolved with complex Morlet wavelets. The magnitudes of the complex wavelet transforms were squared to obtain the spectral power. The spectral power was averaged across trials and then normalized to percentages relative to the baseline (−500 ~ −100 ms) power to obtain the event-related spectral perturbation (ERSP). Finally, to eliminate edge artifacts, only data within the time window of interest (−500 ~ 1000 ms) were kept.

To determine the significant time window and scalp area, the power was first averaged within 4 ~ 8 Hz (θ band), 40 ~ 60 Hz (low γ band), and 60 ~ 100 Hz (high γ band) at each time point and channel. Second, a cluster-based permutation *t*-test was conducted on each channel to identify the significant time window (two-tailed, 10,000 times, threshold = 0.05). This approach avoided the multiple comparisons problems and allowed us to incorporate biophysically motivated constraints into the test statistic, which could increase the sensitivity of the statistical test (Maris & Oostenveld, 2007). Finally, significant channels adjacent to the scalp were clustered, and the clusters containing more than 4 electrodes were considered to be a significant area.

#### 2.5.4. Mediation analysis

Previous studies have demonstrated that a fast RT reflected a high-confidence response, whereas a slower RT reflected a low-confidence response (Rotello & Zeng, 2008; Gimbel & Brewer, 2011). To further investigate what kind of metacognition was associated with item recognition through θ oscillation after unitization, we conducted a mediation analysis. If the θ or γ oscillation mediates or partially mediates the RT reduction, it would suggest that this oscillation was related to high confidence response, otherwise, it was related to low confidence response.

A two-condition within-participant statistical mediation analysis (Montoya & Hayes, 2017) was performed between the oscillations and RT using Mplus7 (https://www.statmodel.com/). First, the ERSP of the θ band over the significant 8 channels (Pz, P1, P3, P5, P7, PO3, PO5, and PO7) in the time-frequency analysis, and the RT for the correct responses were averaged as mediator and dependent variables. Second, two regression models of the mediator (*M*) and the dependent variable (*Y*) were formalized in unitized and non-unitized conditions:

$$Y_1 = g_{10} + g_{11}M_1 + \varepsilon_{1Y} \tag{1}$$

$$Y_2 = g_{20} + g_{21}M_2 + \varepsilon_{2Y} \tag{2}$$

In Eq. (1), the $Y_1$, $M_1$, $g_{10}$, $g_{11}$, and $\varepsilon_{1Y}$, represent respectively the RT, θ oscillation, intercept, regression coefficient, and errors under the unitized condition. In Eq. (2), the meanings of these parameters are the same as in Eq. (1), except that under the non-unitized condition. After subtracting Eq. 2 from Eq. 1, we obtained Eq. 3:

$$Y_2 - Y_1 = h + b(M_2 - M_1) + d(M_1 + M_2) + \varepsilon_3 \tag{3}$$

where $h = g_{20} - g_{10}$, $b = (g_{21} + g_{11})/2$, $d = (g_{21} - g_{11})/2$, and $\varepsilon_3 = \varepsilon_{2Y} - \varepsilon_{1Y}$. To ensure that $c'$ can be interpreted as the average difference of *Y* between the conditions that remained after accounting for the difference of *M* between the conditions, the $(M_1 + M_2)$ should be centralized. After that, we obtained Eq. 4:

$$Y_2 - Y_1 = c' + b(M_2 - M_1) + d(M_1 + M_2) + \varepsilon_3 \tag{4}$$

In Eq. (4), the $c'$, $b$, $d$, and $\varepsilon_3$ represent respectively the direct effect of unitization on RT, the contribution of θ oscillation differences to the RT differences between conditions, the interaction of unitization and θ oscillation on the RT, and errors. Third, the effects of *X* on *Y* and *X* on *M* were formalized:

$$Y_2 - Y_1 = c + \varepsilon_1 \tag{5}$$

$$M_2 - M_1 = a + \varepsilon_2 \tag{6}$$

Finally, the total effect of unitization on RT is $c$ from Eq. 5 (Fig. 2 upper). The direct effect $c'$ is from Eq. 4, and the indirect effect through

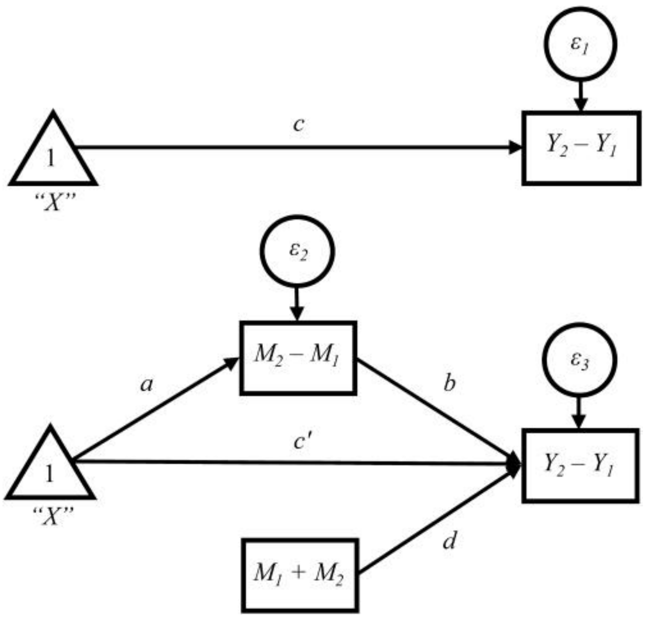


**Fig. 2.** A within-participant mediation model in path diagram form. $X$ represents the independent variable (a binary variable), which is unitization in this study; $Y_1$ and $Y_2$ represent dependent variables, which are the RTs under unitized and non-unitized conditions; $M_1$ and $M_2$ represent the mediators, which are the θ oscillations under unitized and non-unitized conditions; $e_1$, $e_2$, and $e_3$ are random errors. $a$ represents the effect of unitization on the θ oscillation; $b$ represents the contribution of θ oscillation differences to the RT differences; $c$ represents the total effect of unitization on RT; $c'$ represents the direct effect of unitization on RT; $d$ represents the interaction of unitization and θ oscillation on RT.

the mediator $a$ is from Eq. 6 and b is from Eq. 4 (Fig. 2 lower). The paths required to build the within-participant design mediation model were all obtained. The indirect effect was estimated as $a \times b$ using the bootstrap confidence interval (CI; the indirect effect was considered significant if 0 was not within the 95 % CI).

## 3. Results

### 3.1. Behavioral performance

#### 3.1.1. Learning phase

The average accuracy of the participants for all stimuli (all condition: $M = 0.89$, $SD = 0.03$; unitized condition: $M = 0.83$, $SD = 0.06$; non-unitized condition: $M = 0.94$, $SD = 0.05$) was significantly higher than the chance level [$t_{(1,\ 24)} = 59.23$, $p < 0.001$, Cohen'$d = 11.85$, chance level $= 0.5$]. Moreover, their average RT to all stimuli ($M = 1.42$ s, $SD = 0.26$ s; unitized condition: $M = 1.32$, $SD = 0.28$; non-unitized condition: $M = 1.51$, $SD = 0.29$) was significantly faster than the deadline required by the experiment [$t_{(1,\ 24)} = 29.57$, $p < 0.001$, Cohen'$d = 5.91$, deadline $= 3$ s]. These findings suggest that participants were able to make accurate judgments within the specified time frame based on the instructions.

#### 3.1.2. Associative recognition

The behavioral results on the Hit/CR, Pr values for the associative recognition task are shown in Table 1 and Fig. 3. For the Hit and CR, a two-way ANOVA (unitization × pair type) revealed a significant main effect of unitization [$F_{(1,\ 24)} = 268.76$, $p < 0.001$, $partial\text{-}\eta^2 = 0.92$] and a significant interaction [$F_{(1,\ 24)} = 4.71$, $p < 0.05$, $partial\text{-}\eta^2 = 0.16$]. However, the main effect of pair type was not significant [$F_{(1,\ 24)} = 0.38$, $p = 0.55$, $BF_{(pair\ type)} = 0.29$]. Decomposition of the interaction revealed that Hit was significantly higher than CR under the unitized condition [$t_{(1,\ 24)} = 3.19$, $p < 0.01$, Cohen'$d = 0.70$], but Hit and CR were comparable under the non-unitized condition [$t_{(1,\ 24)} = 0.59$, $p = 0.56$, $BF_{10} = 0.24$]. Pr was significantly higher under the unitized condition than under the non-unitized condition [$t_{(1,\ 24)} = 16.39$, $p < 0.001$, Cohen'$d = 0.78$].

#### 3.1.3. Item recognition

The behavioral results on the Hit/CR and Pr for item recognition are shown in Table 1 and Fig. 4. For the Hit and CR of item recognition, one-way ANOVA revealed a significant main effect [$F_{(1.23,\ 29.51)} = 8.89$, $p < 0.01$, $partial\text{-}\eta^2 = 0.27$]. The post hoc comparisons revealed that the difference was not significant between the Hit for the IU-same characters and CR for the I-new characters [$t_{(1,\ 24)} = 1.52$, $p = 0.14$, $BF_{10} = 0.58$] and between the Hit for the IN-same characters and CR for the I-new characters [$t_{(1,\ 24)} = 2.02$, $p = 0.06$, $BF_{10} = 1.19$]. For the Pr, paired-sample $t$-test revealed that Pr in the unitized condition was significantly higher than that in the non-unitized condition [$t_{(1,\ 24)} = 8.86$, $p < 0.001$, Cohen'$d = 1.23$].

### 3.2. ERP results

#### 3.2.1. Old/new effect during associative recognition

The grand average ERP and topographical maps of associative recognition for both the unitized and the non-unitized conditions are shown in Fig. 5. For the FN400, two-way ANOVA (unitization × pair type) indicated a significant main effect of pair type [$F_{(1,\ 24)} = 14.04$, $p < 0.001$, $partial\text{-}\eta^2 = 0.37$]. The main effect of unitization [$F_{(1,\ 24)} = 1.10$, $p = 0.31$, $BF_{(unitization)} = 0.35$] and the interaction [$F_{(1,\ 24)} = 0.26$, $p = 0.61$, $BF_{(unitization\ \times\ pair\ type)} = 0.35$] were not significant. According to previous studies, the early old/new effect was significant under the unitized condition, but not under the non-unitized condition. Planned comparisons were conducted to examine the difference in early old/new effects between unitized and non-unitized conditions. The results showed that there was a significant effect of FN400 for the unitized condition [$t_{(1,\ 24)} = 2.84$, $p < 0.01$, Cohen'$d = 2.22$]. However, this effect was not significant for the non-unitized condition [$t_{(1,\ 24)} = 1.94$, $p = 0.06$, $BF_{10} = 1.06$].

For the LPC, two-way ANOVA (unitization × pair type) showed a significant main effect of the pair type [$F_{(1,\ 24)} = 74.11$, $p < 0.001$, $partial\text{-}\eta^2 = 0.76$]. The main effect of unitization [$F_{(1,\ 24)} = 3.96$, $p = 0.06$, $BF_{(unitization)} = 2.40$] and the interaction [$F_{(1,\ 24)} = 3.60$, $p = 0.07$, $BF_{(unitization\ \times\ pair\ type)} = 0.85$] were not significant.

#### 3.2.2. Old/new effect during item recognition

The grand average ERP and topographical maps of item recognition for unitized and non-unitized conditions are shown in Fig. 6. For the FN400, one-way ANOVA revealed that the main effect was not significant [$F_{(2,\ 23)} = 0.02$, $p = 0.98$, $BF_{(main\ effect)} = 0.12$]. Moreover, post hoc

**Table 1**
The Hit/CR and Pr for different conditions ($M \pm SE$).

| | Associative recognition | | | | Item recognition | | |
|---|---|---|---|---|---|---|---|
| | AU-same | AU-rearranged | AN-same | AN-rearranged | IU-same | IN-same | I-new |
| Hit/CR | 0.91 ± 0.06 | 0.86 ± 0.09 | 0.67 ± 0.16 | 0.69 ± 0.10 | 0.79 ± 0.11 | 0.64 ± 0.13 | 0.73 ± 0.12 |
| Pr | 0.77 ± 0.13 | | 0.36 ± 0.18 | | 0.51 ± 0.12 | 0.36 ± 0.13 | |

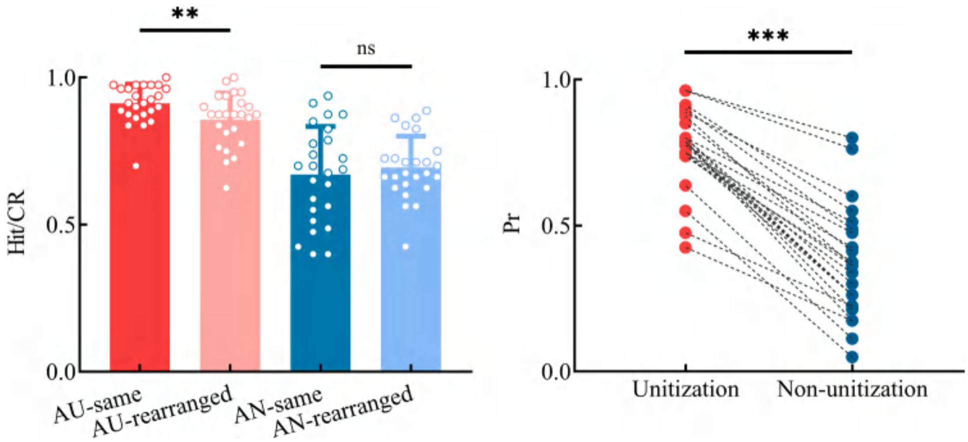


**Fig. 3.** Hit/CR and Pr under unitized and non-unitized conditions for associative recognition; the bar on the left represents the *SD*. Hit: hit rate, CR: correct rejection, Pr: performance of recognition = Hit – false alarms, *** represents $p < 0.001$.

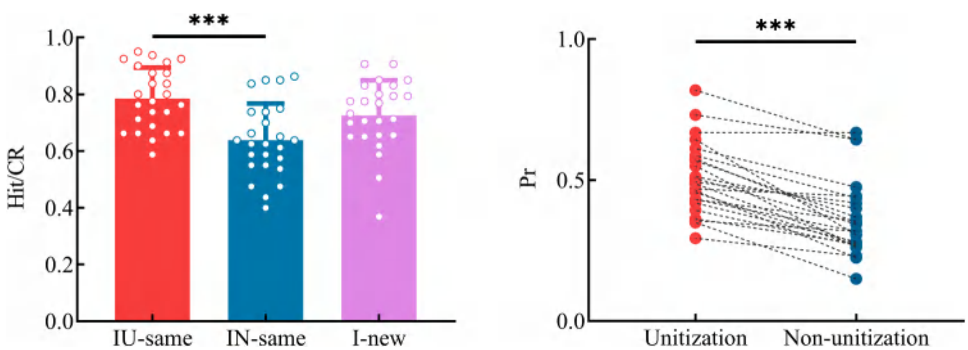


**Fig. 4.** Hit/CR and Pr under unitized and non-unitized conditions for item recognition, the bar on the left represents the *SD*. Hit: hit rate, CR: correct rejection, Pr: performance of recognition = Hit – false alarms, *** represents $p < 0.001$.

comparisons revealed that the FN400 effect was not significant for the unitized condition [$t_{(1, 24)} = 0.13$, $p = 0.90$, $BF_{10} = 0.21$] and the non-unitized condition [$t_{(1, 24)} = 0.12$, $p = 0.91$, $BF_{10} = 0.21$]. Furthermore, the FN400 components between the two conditions were not significant [$t_{(1, 24)} = 0.17$, $p = 0.86$, $BF_{10} = 0.22$].

For the LPC, one-way ANOVA revealed that the main effect was not significant [$F_{(2, 23)} = 8.82$, $p < 0.001$, $partial\text{-}\eta^2 = 0.43$]. Post hoc comparisons showed a significant LPC effect for both the unitized condition [$t_{(1, 24)} = 4.16$, $p < 0.001$, Cohen'$d = 0.55$] and the non-unitized condition [$t_{(1, 24)} = 2.20$, $p < 0.05$, Cohen'$d = 0.34$]. Furthermore, the LPC components between the two conditions were not significant [$t_{(1, 24)} = 1.89$, $p = 0.07$, $BF_{10} = 0.97$].

### 3.3. TFR results

The neural oscillation only in the θ band was significantly different between the conditions (Fig. 7). Specifically, there were larger ERSP for IU-same than IN-same at 8 electrodes approximately 400 ~ 1000 ms (Pz, 464 ~ 900 ms, $p < 0.05$; P1, 424 ~ 1000 ms, $p < 0.05$; P3, 570 ~ 1000 ms, $p < 0.05$; P5, 600 ~ 1000 ms, $p < 0.05$; P7, 600 ~ 994 ms, $p = 0.05$; PO3, 498 ~ 1000 ms, $p < 0.05$; PO5, 630 ~ 1000 ms, $p = 0.05$; and PO7, 614 ~ 1000 ms, $p < 0.05$). In addition, low γ and high γ bands were not different between the two conditions at any electrode ($ps > 0.05$). Due to the utilization of cluster-based permutation tests for the TFR, Bayesian analysis cannot be performed as NHST. Therefore, the results of Bayes factors were not reported here.

### 3.4. Mediation results

Given that the RT of item recognition was less than 1000 ms, we averaged the ERSP within 400 ~ 900 ms on the 8 electrodes (Pz, P1, P3, P5, P7, PO3, PO5, and PO7) as the mediator (the selection of electrodes came from TFR Results). Mediation results showed that the indirect effect ($a \times b = -0.009$, 95 % CI = $-0.019 \sim -0.001$) and the direct effect ($c' = -0.048$, 99.5 % CI = $-0.090 \sim -0.013$) were significant (Fig. 8). The effect size of the mediator was $P_M = (a \times b)/c = 0.16$. The results indicated that unitization reduced the RT of recognition, which was also partially mediated by θ oscillation.

## 4. Discussion

Previous studies have shown that unitization can combine two unrelated items into a unified representation, resulting in familiarity-based associative recognition. The present study aims to explore the effects of unitization on item memory and its underlying neural mechanism. The key findings are as follows: (1) associative memory was increased and there was familiarity-based associative recognition after Chinese character unitization; (2) Chinese character unitization improved item memory; (3) although the difference was not significant between ERP during item recognition, the synchronization of θ oscillations was stronger under unitized than non-unitized condition; and (4) this θ oscillation, which is related to recollection, partially mediated the contribution of the unitization to the decrease of RT.

### 4.1. The effect of unitization on associative memory

Before delving into the impact of unitization on item memory, we would like to provide a brief account of its influence on associative memory in our study to substantiate the effectiveness of manipulation. The Chinese character unitization adheres to the standard definition of

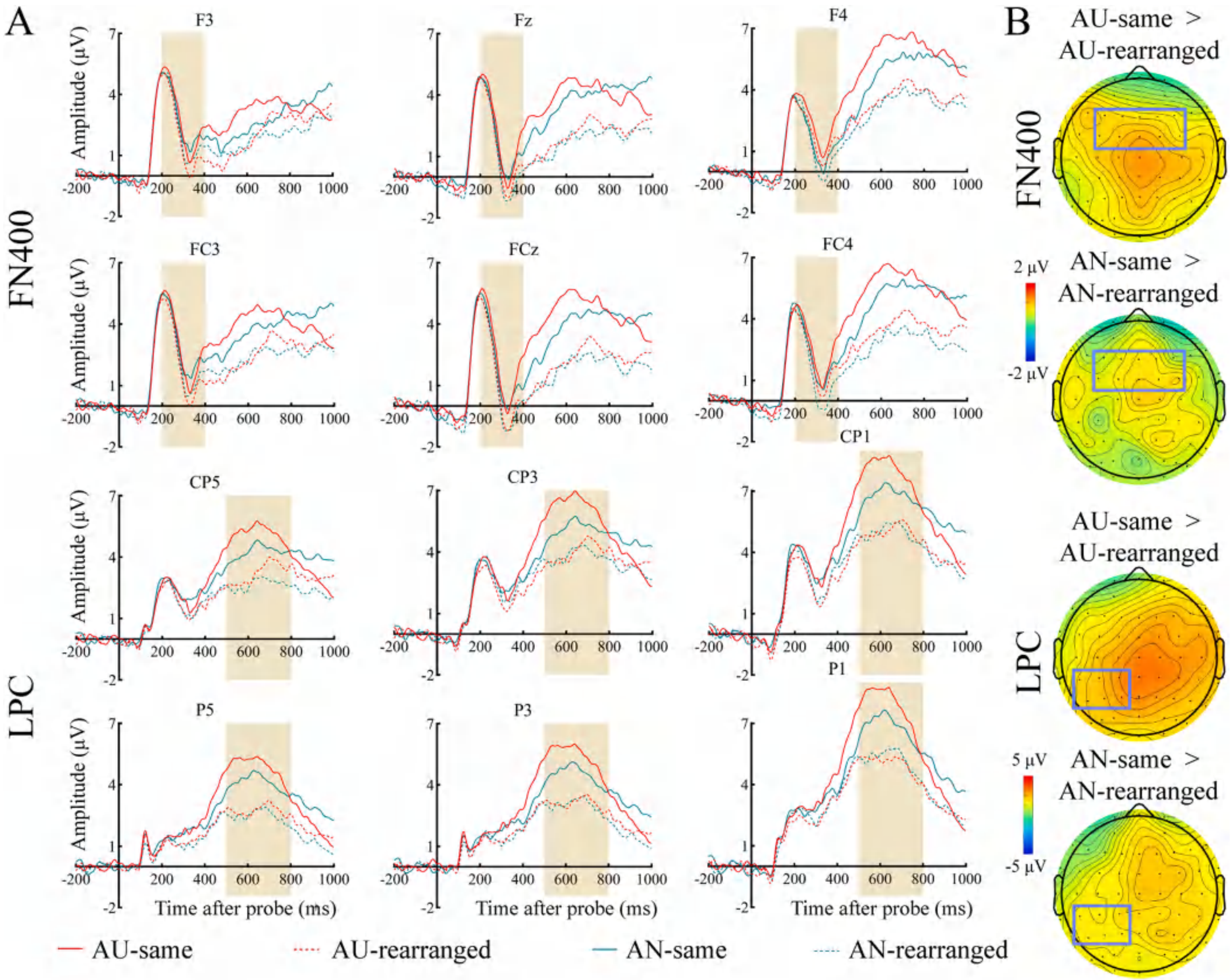


**Fig. 5.** Grand-average ERPs and topographical maps for associative recognition. A: Grand-average ERPs corresponding to AU-same, AU-rearranged, AN-same, and AN-rearranged character pairs at the mid-frontal electrodes (F3, Fz, F4, FC3, FCz, and FC4) and left parietal electrodes (CP1, CP3, CP5, P1, P3, and P5). B: Topographical maps of old/new effects within the time windows of 200 ~ 400 ms and 500 ~ 800 ms for the unitized and non-unitized conditions.

unitization, which involves binding two items into a unified representation. Specifically, participants created a Chinese compound character by combining two individual characters according to their established orthographic rules. Given that all the participants were proficient in Chinese, they were easy to integrate the presented pairs into compound characters. Additionally, the results from the learning phase indicated that all participants comprehended the instruction completely and made correct judgments within the required time.

Numerous prior studies have demonstrated that associative recognition can be supported by familiarity after unitization (Yonelinas et al., 1999; Jäger et al., 2006; Rhodes & Donaldson, 2007; Bader et al., 2010; Tibon & Levy, 2014; Tibon et al., 2014; Guillaume & Etienne, 2015; Li et al., 2019; Zhao et al., 2020). Our results are in line with these studies, despite the absence of an interaction between unitization and pair type for the FN400 component (because there was a marginal FN400 effect in the non-unitized condition), and therefore, we cannot conclude that familiarity is stronger in the unitized condition compared to the non-unitized condition. One possible explanation for the leakage of familiarity into non-unitized associative recognition is that characters in some non-unitized pairs may form a word in pronunciation or semantics, although they cannot form a compound character in orthographic rules. For example, consider the character pair "父" (*/fu4/*, father) and "友" (*/you3/*, friend), which cannot form a compound character but maintains semantic coherence (referring to the father's friend). Similarly, the word pair "分" (*/fen1/*, assign) and "哥" (*/ge1/*, brother)] do not constitute a compound character, yet their pronunciation aligns another word, "分割" (*/fen1, ge1/*, segmentation). When confronted a character pairs, participants tend to employ such strategies to connect them, thereby giving rise to familiarity-based associative recognition even under non-unitized conditions.

Therefore, many of the characters in our study could potentially be combined with other components to form a new character or a new word, even if they did not make up the current pair in the non-unitized condition. Overall, regardless of whether there was familiarity-based associative recognition in the non-unitized condition, there was indeed familiarity-based associative recognition after unitization, indicating that Chinese characters are effective in binding two items into a unit and that our study is comparable to previous research.

### 4.2. *The effect of unitization on item memory*

Despite the widely acknowledged effect of unitization on associative memory, there remains debate regarding its impact on item memory (Ahmad & Hockley, 2014; Parks & Yonelinas, 2015; Pilgrim et al., 2012;

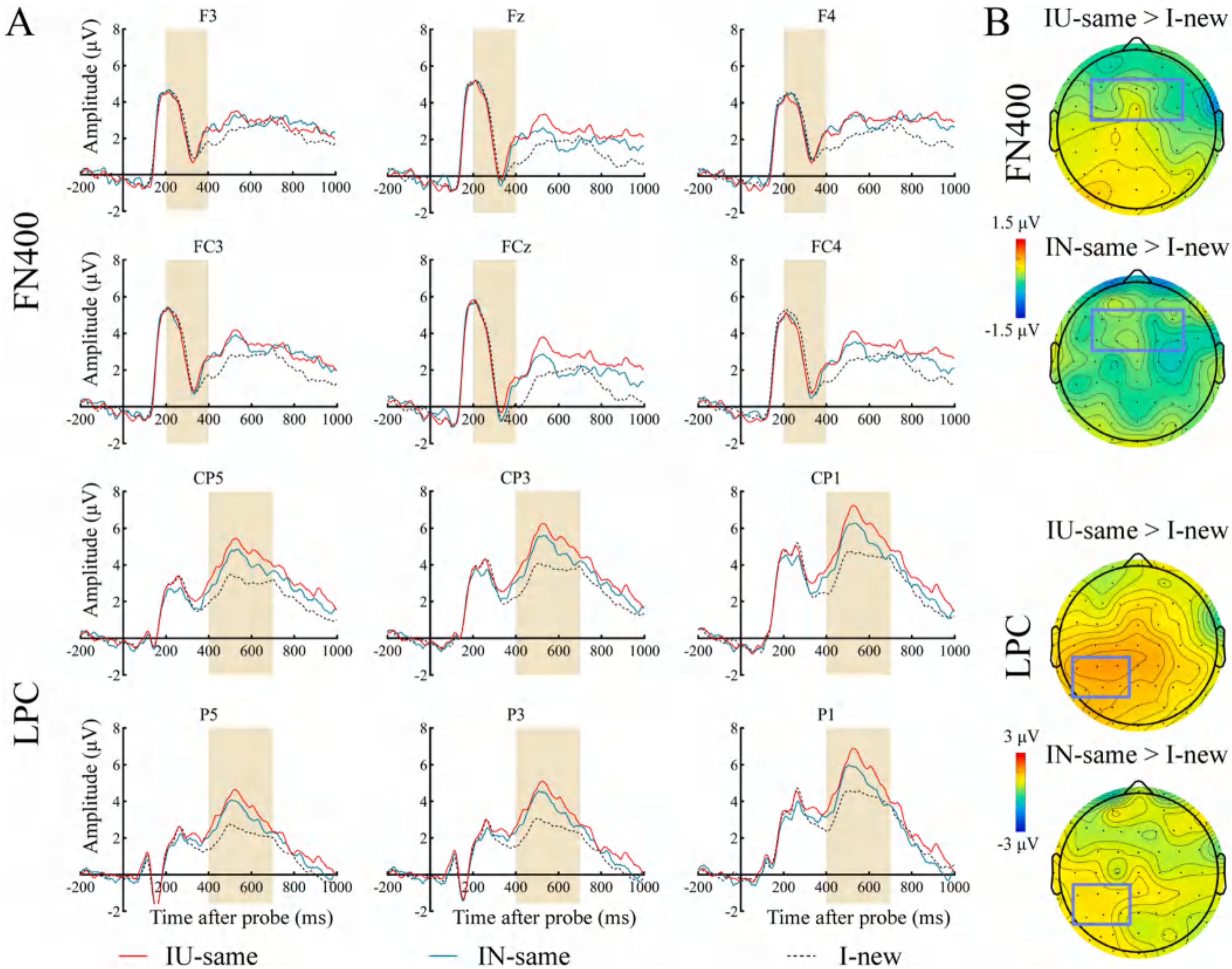


**Fig. 6.** Grand-average ERPs and topographical maps for item recognition. A: Grand-average ERPs corresponding to AU-same, AU-rearranged, AN-same, and AN-rearranged character pairs at the mid-frontal electrodes (F3, Fz, F4, FC3, FCz, and FC4) and left parietal electrodes (CP1, CP3, CP5, P1, P3, and P5). B: Topographical maps of old/new effects within the time windows of 200 ~ 400 ms and 400 ~ 700 ms for the unitized and non-unitized conditions.

Liu et al., 2020). Current behavioral evidence suggests that item memory in the unitized condition does not exhibit a decline compared to the non-unitized condition and even demonstrates improvement, supporting the perspective of “benefits-only”. Recent findings in the domain of working memory provide further support and a possible explanation for the improvement of item memory (Allen et al., 2021; Chung et al., 2022). By integrating disparate visual features into a meaningful entirety, researchers have observed enhancements in visual working memory capacity. They postulate that meaningful stimuli provide a scaffold to help maintain these items because it increases the distinctiveness and reduces interference between the items.

Regarding the cognitive and neural mechanisms underlying the enhanced item memory, the findings from TFR analysis provide some insights. Firstly, previous research has demonstrated the sensitivity of θ oscillation to discrimination of source memory, a process believed to be supported by recollection (Gruber et al., 2008). Furthermore, evidence suggests that hippocampal coordination of neocortical activity through θ-range synchronization is linked to recollection (Herweg et al., 2016). Building upon the observed increase in θ oscillation during item recognition in the present study, we propose that the enhancement of item memory is supported by recollection. Another line of evidence supporting the link between unitization and increased recollection-based item recognition arises from the results of ERP. Specifically, a marginally significant difference ($p = 0.07$) between conditions was observed for the LPC component during item recognition, indicating an increase in recollection after unitization, albeit under slightly relaxed criteria.

With no significant FN400 effect or difference in γ oscillation observed between the unitized and non-unitized conditions during item recognition, the results are substantiated by moderate support from the Bayesian analysis. These findings imply a potential divergence from previous researches (Pilgrim et al., 2012; Liu et al., 2020), suggesting that the contribution of familiarity to item memory and its enhancement through unitization may be limited in our study. One possible explanation for these results is that the process of unitization involves the deformation of the original items, such as the deformation of the “禾” radical to the left side of the “秋” character. Although the old items presented during the testing phase were identical to those encountered during the learning phase, the features processed by participants' cognitive processes during the learning phase have undergone alterations. As a result, familiarity with the items is diminished during recognition. In other words, the excessive assignment of cognitive resources to encoding two items as a whole also compromises the encoding of the original item representation.

The continuous dual-process model (Wixted & Mickes, 2010) presents an alternative account for the absence of significant familiarity

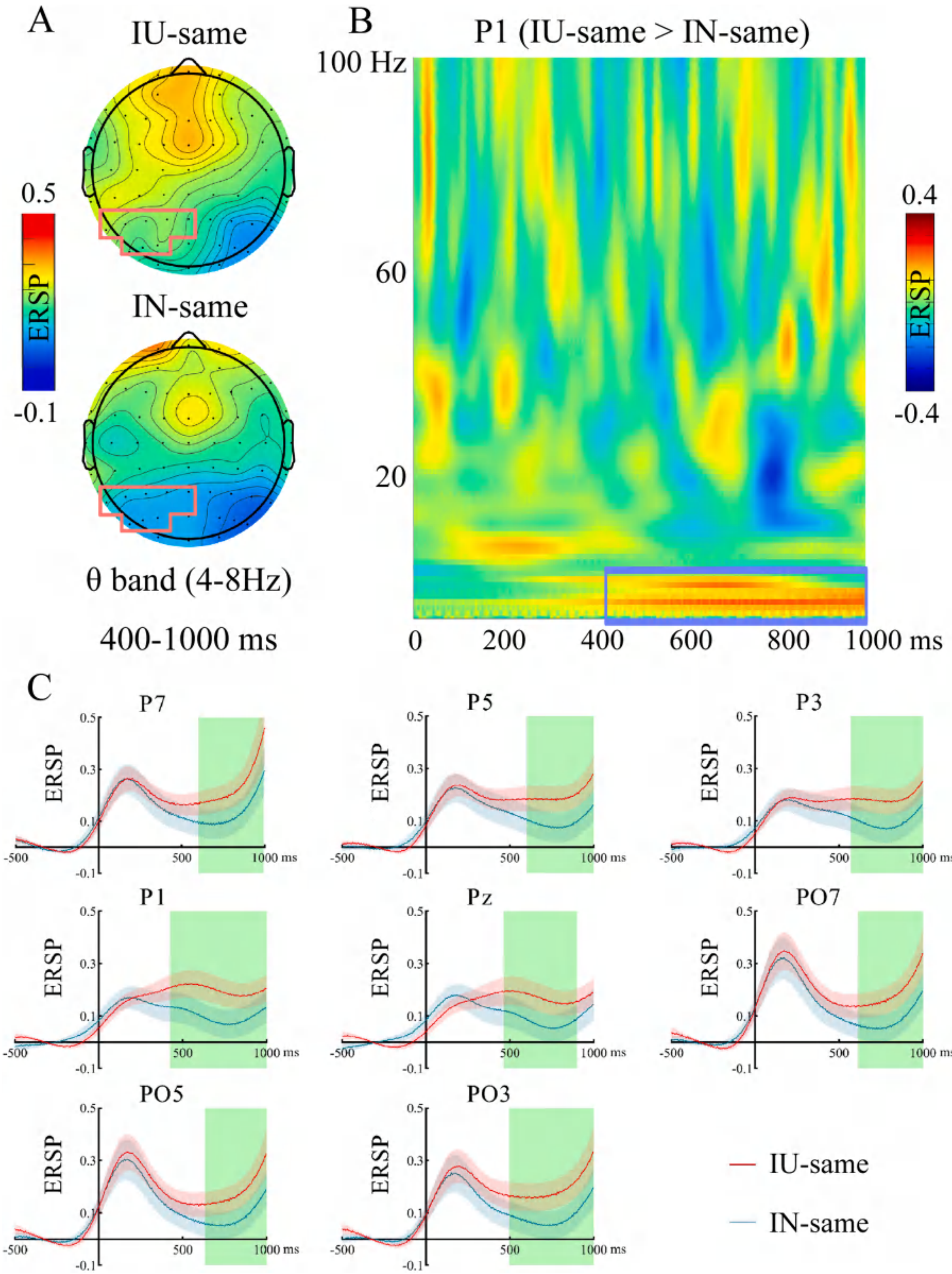


**Fig. 7.** Grand averaged results of time-frequency analysis. A: The group-level scalp topographies of θ-ERSP averaged for IU-same and IN-same. The red box represents the area where θ-ERSP was higher for IU-same than IN-same. B: TFR of one example channel (P1) obtained by subtracting IN-same from IU-same. The blue box marks the significant frequency band and time window. C: θ-ERSP for IU-same and IN-same as a function of time. The green shadow represents a significant time window after the cluster-based permutation test.

during item recognition. According to this model, familiarity and recollection are not always strictly assumed to be separated, and recognition depends on the combined signals of recollection and familiarity for a given item. Therefore, even if familiarity alone does not reach statistical significance, the sufficient level of recollection ensures accurate recognition, because the aggregated confidence of recollection and familiarity is substantial. Of course, reaching the recollection threshold does not imply the absence of familiarity during recognition. Further research is needed to empirically examine and validate this perspective.

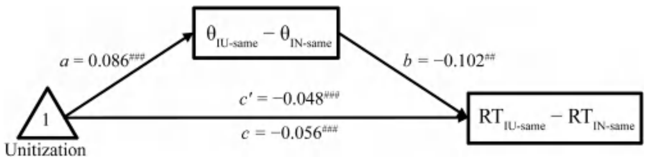


**Fig. 8.** The RT of item recognition was partially mediated by θ oscillation. # represents the statistic within a 95% CI; ## represents the statistic within a 97.5% CI; ### represents the statistic within a 99.5% CI.

After clarifying the effects of unitization on item memory and its cognitive neural mechanisms, attention can now be directed toward revealing the metacognitive processes accompanying item recognition. The mediation analysis showed that the θ oscillation partially mediates the reduction of RT, indicating that individuals with higher average θ activity tend to exhibit faster response times on average. While previous studies have linked faster RTs to high-confidence responses associated with recollection, and slower RTs to low-confidence responses associated with familiarity (Dewhurst et al., 2006; Gimbel & Brewer, 2011; Rotello & Zeng, 2008; Memel & Ryan, 2018), it is important to acknowledge that greater confidence does not necessarily indicate recollection, as high-confidence familiarity is also plausible. Hence, it is appropriate to confine the conclusion of the mediation analysis to the proposition that unitization, through recollection (reflected by θ oscillation), promotes high-confidence judgments during item recognition. It is important to consider a potential limitation in the interpretation of the mediation analysis, namely the cross-sectional nature of both the θ oscillation and the RT. Stronger θ oscillations do not necessarily lead to higher confidence judgments on a trial-to-trial basis. Instead, the findings suggest a tendency for individuals with higher average θ oscillation to exhibit faster reaction times on average.

### *4.3. The relationship between associative memory and item memory after unitization*

Comparing the results of familiarity during associative and item recognition under the unitized condition in this study with those under the non-unitized condition in previous studies (Haskins et al., 2008; Li et al., 2019; Liu et al., 2020; Liu et al., 2023; Rhodes & Donaldson, 2008; Zheng et al., 2015; Zheng et al., 2016), a dual effect of unitization can be observed, whereby unitization enhances familiarity of associative recognition, while concurrently reducing familiarity of item recognition. Prior studies have similarly proposed this trade-off by examining the impact of unitization on item memory from the perspective of information processing (Tibon et al., 2017). Unitization, which exploits inherent associations between the items (e.g., compound words or semantically related words), has the potential to enhance item memory because these built-in associations can facilitate unitization and conserve cognitive resources for item processing. Conversely, unitization achieved through explicit instructions (e.g., Imagining two unrelated images into a single image or linking two unrelated words with a novel definition) requires a greater allocation of cognitive resources to combine disparate pairs into a unit. Consequently, this increased resource demand during the encoding of associations comes at the expense of item processing, resulting in a decrease in item memory.

The present study is in line with this theoretical framework. Participants performed Chinese character unitization based on their inherent orthographic rules, conserving cognitive resources that could be allocated to encode the constituent items. We posit that the preserved cognitive resources were employed to process the relationship between the items within an association and the relationship between the item and the association. For instance, the compound character "叶" (*/ye4/*, leaf), the constituents "口" (*/kou3/*, mouth) and "十" (*/shi2/*, ten), have vastly different meanings. Therefore, during unitized encoding, the items can be linked with a greater variety of semantics. During retrieval, participants can identify the character "口" as the same not only through recalling "叶" but also through recalling "十". This interpretation is consistent with the theory of encoding variability (Martin, 1968).

Regarding the relationship between associative memory and item memory, while findings related to familiarity demonstrated a "benefit-cost" pattern (consistent with Pilgrim et al., 2012), the current study still supports the "benefits-only" viewpoint as the behavioral performance and recollection of item memory have not decreased, and even improved (consistent with Liu & Guo, 2019; Zhao & Guo, 2023). These results suggest that unitization enhances recollection for item recognition although it reduces familiarity. These items in an association have not been disregarded, but have instead been processed more precisely and accurately after unitization.

## 5. Conclusion

By employing Chinese characters as a manipulation of unitization, our findings demonstrated the positive impact of unitization on both associative memory and item memory. Additionally, the analysis of EEG data revealed that unitization augments item memory through recollection, ultimately resulting in heightened confidence judgments. The current study presents empirical evidence demonstrating an observed enhancement in the precision and accuracy of item processing after unitization.


## Funding

This work was supported by the project of the National Natural Science Foundation of China (32271091).

## Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

## Data availability

Data will be made available on request.


## References


Ahmad, F. N., & Hockley, W. E. (2014). The role of familiarity in associative recognition of unitized compound word pairs. *The Quarterly Journal of Experimental Psychology, 67*(12), 2301–2324.

Allen, M.G., Destefano, I., & Brady, T.F., (2021). Chunks are not "content-free": Hierarchical representations preserve perceptual detail within chunks. In: Proceedings of the annual meeting of the cognitive science society (Vol. 43, No. 43).

Bader, R., Mecklinger, A., Hoppstädter, M., & Meyer, P. (2010). Recognition memory for one-trial-unitized word pairs: Evidence from event-related potentials. *Neuroimage, 50*(2), 772–781.

Chung, Y.H., Brady, T.F., & Störmer, V.S. (2022, March 28). No fixed limit for storing simple visual features: Working memory capacity for colors is increased when remembered as parts of realistic objects. https://doi.org/10.31234/osf.io/bg4r5.

Curran, T., & Hancock, J. (2007). The FN400 indexes familiarity-based recognition of faces. *Neuroimage, 36*(2), 464–471.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open-source toolbox for analysis of single-trial eeg dynamics including independent component analysis. *Journal of Neuroscience Methods, 134*(1), 9–21.

Diana, R. A., Yonelinas, A. P., & Ranganath, C. (2010). Medial temporal lobe activity during source retrieval reflects information type, not memory strength. *Journal of Cognitive Neuroscience, 22*(8), 1808–1818.

Gimbel, S. I., & Brewer, J. B. (2011). Reaction time, memory strength, and fMRI activation during memory retrieval: Hippocampus and default network are differentially responsive during recollection and familiarity judgments. *Cognitive Neuroscience, 2*(1), 19–26.

Giovanello, K. S., Keane, M. M., & Verfaellie, M. (2006). The contribution of familiarity toassociative memory in amnesia. *Neuropsychologia, 44*(10), 1859–1865.

Graf, P., & Schacter, D. L. (1989). Unitization and grouping mediate dissociations in memory for new associations. *Journal of Experimental Psychology: Learning Memory & Cognition, 15*(5), 930–940.

Gruber, T., Tsivilis, D., Giabbiconi, C. M., & Müller, M. M. (2008). Induced electroencephalogram oscillations during source memory: Familiarity is reflected in the gamma band, recollection in the theta band. *Journal of Cognitive Neuroscience, 20*(6), 1043–1053.

Guillaume, F., & Etienne, Y. (2015). Target-context unitization effect on the familiarity-related FN400: A face recognition exclusion task. *International Journal of Psychophysiology, 95*(3), 345–354.

Hanslmayr, S., Staresina, B. P., & Bowman, H. (2016). Oscillations and episodic memory: addressing the synchronization/desynchronization conundrum. *Trends in Neurosciences, 39*(1), 16–25.

Haskins, A. L., Yonelinas, A. P., Quamme, J. R., & Ranganath, C. (2008). Perirhinal cortex supports encoding and familiarity-based recognition of novel associations. *Neuron, 59*(4), 554–560.

Herweg, N. A., Apitz, T., Leicht, G., Mulert, C., Fuentemilla, L., & Bunzeck, N. (2016). Theta-alpha oscillations bind the hippocampus, prefrontal cortex, and striatum during recollection: Evidence from simultaneous EEG–fMRI. *Journal of Neuroscience, 36*(12), 3579–3587.

Herweg, N. A., Solomon, E. A., & Kahana, M. J. (2019). Theta oscillations in human memory. *Trends in Cognitive Sciences, 24*(3), 208–227.

Hockley, W. E., & Cristi, C. (1996). Tests of encoding tradeoffs between item and associative information. *Memory & Cognition, 24*(2), 202–216.

Jäger, T., Mecklinger, A., & Kipp, K. H. (2006). Intra-and inter-item associations doubly dissociate the electrophysiological correlates of familiarity and recollection. *Neuron, 52*(3), 535–545.

Li, B., Han, M., Guo, C., & Tibon, R. (2019). Unitization modulates recognition of within-domain and cross-domain associations: Evidence from event-related potentials. *Psychophysiology, 56*(11), Article e13446.

Liu, Z., & Guo, C. (2019). Unitization improves item recognition through less overall neural processing. *Neuroreport, 30*(13), 882–886.

Liu, Z., Li, X., Li, X., Yuan, J., & Guo, C. (2023). From encoding to retrieval: Change in level of unitization resolves debate about Unitization's effect on associative recognition. *Psychophysiology, 60*(2), Article e14161.

Liu, Z., Wu, J., Wang, Y., & Guo, C. (2020). Unitization does not impede overall item recognition performance: Behavioral and event-related potential study. *Neurobiology of Learning and Memory, 167*, Article 107130.

Lu, B., Liu, Z., Wang, Y., & Guo, C. (2020). The different effects of concept definition and interactive imagery encoding on associative recognition for word and picture stimuli. *International Journal of Psychophysiology, 158*, 178–189.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of eeg- and meg-data. *Journal of Neuroscience Methods, 164*(1), 177–190.

Martin, E. (1968). Stimulus meaningfulness and paired-associate transfer: An encoding variability hypothesis. *Psychological Review, 75*(5), 421–441.

Memel, M., & Ryan, L. (2017). Visual integration enhances associative memory equally for young and older adults without reducing hippocampal encoding activation. *Neuropsychologia, 100*, 195–206.

Memel, M., & Ryan, L. (2018). Visual integration of objects and scenes increases recollection-based responding despite differential MTL recruitment in young and older adults. *Hippocampus, 28*(12), 886–899.

Montoya, A. K., & Hayes, A. F. (2017). Two-condition within-participant statistical mediation analysis: A path-analytic framework. *Psychological Methods, 22*, 6–27.

Murray, B. D., & Kensinger, E. A. (2012). The effects of emotion and encoding strategy on associative memory. *Memory & Cognition, 40*(7), 1056–1069.

Nyhus, E., & Curran, T. (2010). Functional role of gamma and theta oscillations in episodic memory. *Neuroscience & Biobehavioral Reviews, 34*(7), 1023–1035.

Parks, C. M., & Yonelinas, A. P. (2015). The importance of unitization for familiarity-based learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*(3), 881–903.

Pilgrim, L. K., Murray, J. G., & Donaldson, D. I. (2012). Characterizing episodic memory retrieval: Electrophysiological evidence for diminished familiarity following unitization. *Journal of Cognitive Neuroscience, 24*(8), 1671–1681.

Quamme, J. R., Yonelinas, A. P., & Norman, K. A. (2007). Effect of unitization on associative recognition in amnesia. *Hippocampus, 17*(3), 192–200.

Rhodes, S. M., & Donaldson, D. I. (2007). Electrophysiological evidence for the influence of unitization on the processes engaged during episodic retrieval: Enhancing familiarity based remembering. *Neuropsychologia, 45*(2), 412–424.

Rhodes, S. M., & Donaldson, D. I. (2008). Electrophysiological evidence for the effect of interactive imagery on episodic memory: encouraging familiarity for non-unitized stimuli during associative recognition. *Neuroimage, 39*(2), 873–884.

Robey, A., & Riggins, T. (2017). Increasing relational memory in childhood with unitization strategies. *Memory & Cognition, 46*(1), 100–111.

Rotello, C. M., & Zeng, M. (2008). Analysis of RT distributions in the remember-know paradigm. *Psychonomic Bulletin & Review, 15*(4), 825–832.

Rugg, M. D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences, 11*(6), 251–257.

Shao, H., & Weng, X. (2011). Unitization benefits associative recognition whereas impairs item recognition. *Proceedings of the 2011 third international conference on multimedia information networking and security* (pp. 314–317). IEEE (November).

Tibon, R., Ben-Zvi, S., & Levy, D. A. (2014). Associative recognition processes are modulated by modality relations. *Journal of Cognitive Neuroscience, 26*(8), 1785–1796.

Tibon, R., Gronau, N., & Levy, D. A. (2017). Associative unitization via semantic relatedness benefits episodic recognition of component elements. *PsyArXiv*. https://osf.io/preprints/psyarxiv/cjxse/.

Tibon, R., & Levy, D. A. (2014). The time course of episodic associative retrieval: electrophysiological correlates of cued recall of unimodal and crossmodal pair-associate learning. *Cognitive Affective & Behavioral Neuroscience, 14*(1), 220–235.

Tulving, E. (1972). Episodic and semantic memory. In E. Tulving, & W. Donaldson (Eds.), *Organization of memory* (pp. 381–403). New York: Academic Press.

Wagenmakers, E. J. (2007). A practical solution to the pervasive problems of p values. *Psychonomic Bulletin & Review, 14*(5), 779–804.

Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., & Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review, 25*, 58–76.

Wixted, J. T., & Mickes, L. (2010). A continuous dual-process model of remember/know judgments. *Psychological Review, 117*(4), 1025.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory & Language, 46*(3), 441–517.

Yonelinas, A. P., Kroll, N. E., Dobbins, I. G., & Soltani, M. (1999). Recognition memory for faces: When familiarity supports associative recognition judgments. *Psychonomic Bulletin and Review, 6*, 654–661.

Zhao, C., & Guo, C. (2023). The relationship between associative encoding and item encoding in the multiple-component character unitization and compound word unitization. *Acta Psychologica Sinica, 55*(4), 513–528.

Zhao, M. F., Zimmer, H. D., Fu, X., & Zheng, Z. (2020). Unitization of internal and external features contributes to associative recognition for faces: Evidence from modulations of the fn400. *Brain Research, 1748*, Article 147077.

Zheng, Z., Li, J., Xiao, F., Broster, L. S., & Jiang, Y. (2015). Electrophysiological evidence for the effects of unitization on associative recognition memory in older adults. *Neurobiology of Learning & Memory, 121*, 59–71.

Zheng, Z. W., Li, J., Xiao, F. Q., Ren, W. C., & He, R. Q. (2016). Unitization improves source memory in older adults: An event-related potential study. *Neuropsychologia, 89*, 232–244.