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Unitization and temporality in associative memory: Evidence from modulation of context effects

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ABSTRACT

It has been proposed that the formation of episodic associations between stimuli may involve different processes when memoranda are from the same or different perceptual domains, and when stimuli are experienced concurrently or sequentially. Such differences are postulated to determine the degree of unitization of memoranda, and are asserted to influence whether such associations are later retrieved via familiarity or recollection. In two experiments utilizing the context effects (CEs) paradigm, we examined effects on associative memory observed when unitization of memoranda is not readily achieved, due to domain differences between stimuli or to asynchronous presentation. In both cases, the standard associative-binding CE of better recognition of probes under contextual reinstatement (i.e., higher hit rates for pairs of repeated probes vs. re-paired probes) was only found when participants explicitly recognized the context stimuli. These results contrast with earlier findings that for concurrent encoding of same-domain stimuli, CEs are obtained even in the absence of explicit memory for contexts. The contrast supports the assertion that in the absence of unitization associative memory is dependent on recollection, while unitized associations may be supported by familiarity strength.

Introduction

Inherent in our most basic ideas about memory is its ability to represent not only discrete stimuli, but also the spatio-temporal relationships between them – i.e., episodic associations. Although episodic associations have been the topic of much research, numerous significant questions about this aspect of memory remain open. Two of the many extant questions are whether common cognitive processes and neural structures are responsible for the encoding, storage, and retrieval of all forms of episodic associations, and whether the same episodic associative process binds stimuli across separation in space and separation in time. In the current study, we attempt to address these two questions.

Stimuli perceived simultaneously may be experienced as independent entities or as a gestalt. *Unitization* refers to the perception and encoding of a number of discrete stimuli as a single unit (Graf & Schacter, 1989; LaBerge & Samuels, 1974). A recent taxonomy of episodic association has proposed that associative memory comprises three types of associations, reflecting differing degrees of unitization: intra-item associations, i.e., items that were unitized into one entity (e.g., two interactively encoded objects); within-domain associations, formed between similar kinds of items that are not remembered as one entity (e.g., two unrelated words); and between-domain associations, formed between different kind of items or modalities, such as faces and voices (Mayes, Montaldi, & Migo, 2007). Unitization is postulated to have manifold effects on associative memory. Yonelinas, Kroll, Dobbins, and Soltani (1999) proposed that unitized stimuli may be recognized via processes that rely on familiarity rather than recollection. Following up on that proposal, Bastin, van der Linden, Schnakers, Montaldi, and

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Mayes (2010) report that within-domain (face–face) associative recognition was mainly supported by familiarity, while between-domain (face–name) associative recognition required a major contribution of recollection. On the physiological level, event-related potential (ERP) measures of familiarity and recollection dissociate unitized and non-unitized associative representations for faces (Jäger, Mecklinger, & Kipp, 2006) and words (Bader, Mecklinger, Hoppstädter, & Meyer, 2010; Rhodes & Donaldson, 2007, 2008; Wiegand, Bader, & Mecklinger, 2010). In regard to neuroanatomy, Haskins, Yonelinas, Quamme, and Ranganath (2008) and Staresina and Davachi (2008), Staresina and Davachi (2010) have proposed that unitization enables associative representation formation by perirhinal cortex (PRh) independently of hippocampal processes. This notion dovetails with suggestions that have been made regarding PRh-supported "associative familiarity" (Mayes et al., 2007) and reports of the rapid encoding of single and unitized items (Henke, 2010). Furthermore, other studies have shown that unitization and associative strategies modulate aging effects on associative memory (Jäger, Mecklinger, & Kliegel, 2010; Naveh-Benjamin, Brav, & Levy, 2007). These anatomical, physiological, and behavioral findings indicate that distinctions between item and associative memory may be more parametric than binary, depending on the possibility of stimulus unitization.

A related crucial factor in the formation of episodic associations is *temporality*. The differences between associations of concurrently and sequentially experienced stimuli may be seen in forms of learning as simple as eyeblink conditioning, in which the hippocampus is required for trace conditioning in animals and humans (e.g., Cheng, Disterhoft, Power, Ellis, & Desmond, 2008). For declarative memory as well, binding concurrently experienced (*intra-temporal* association) and sequentially experienced (*inter-temporal* association) stimuli may depend on different processes and brain substrates. In studies of associative learning, most commonly stimulus pairs are presented simultaneously (e.g., word pairs – Buchler, Light, & Reder, 2008; Hockley & Consoli, 1999). In neuroimaging research, such as that tracking hippocampal involvement in associative encoding, most often stimuli are temporally concurrent though spatially distinct (e.g., Jackson & Schacter, 2004; Kirwan & Stark, 2004; Staresina & Davachi, 2006, 2008, and many other studies catalogued in Hales and Brewer (2010)). However, other studies have tracked brain activation during successful associative encoding of asynchronously presented stimuli (e.g., Hales & Brewer, 2010; Qin et al., 2007; Staresina & Davachi, 2009). Such studies report activity in bilateral frontal and parietal regions and hippocampi that is specifically predictive of subsequent memory for inter-temporal associative information. It remains to be determined to what degree these latter activation differences reflect fundamentally different cognitive processes for association formation between concurrent stimuli and between sequential stimuli.

Complementing these questions about type-diversity in the formation of episodic associations, there are various methods of assessing the strength of such associations. An important alternative to the more common cued recall and associative recognition tests is provided by measures of memory context effects (CEs). The basic CE is that target information is better retrieved at test in the presence of elements of the encoding context (e.g., Murnane, Phelps, & Malmberg, 1999; Smith & Vela, 2001; Vakil, Raz, & Levy, 2007). Models such as ICE (Item, Context, Ensemble; Murnane et al., 1999) or BIC (Binding of Item and Context; Diana, Yonelinas, & Ranganath, 2007) ground such phenomena in more general models of associative memory. The CE paradigm is reminiscent of source memory paradigms, in which memory for contextual information is directly queried (Johnson, Hashtroudi, & Lindsay, 1993), but has the advantage of assessing the strength of associative binding indirectly, through the impact of associated contextual information on the recognition of a target. This enables the detection of associative strength even in the absence of direct endorsement via cued recall or associative recognition. The robustness of this form of associative assessment has been shown by Cohn and Moscovitch (2007), who label it 'associative reinstatement', and demonstrate its resilience to retrieval manipulations (short response deadline, speeded recognition, and overlapping pairing) that reduced explicit associative recognition (which they call 'associative identification').

In one recent CE study (Levy, Rabinyan, & Vakil, 2008), participants studied pairs of simultaneously presented object pictures, with one object defined as a memory target and the other serving as background context. Later, they performed yes/no recognition judgments on targets and foils in the presence of the same or different background context stimuli. Probability of hits and false alarms was calculated as a function of whether the contextual pair-members were endorsed, i.e., judged as previously seen. Notably, the impact of context reinstatement on recognition persisted even when the associated pair-members of relevant probes were not explicitly recognized. These findings are in line with other studies documenting implicit memory influences on retrieval in Target-Context learning. For example, patients with closed-head injuries presumably involving frontal lobe damage, who exhibit general declarative memory impairments including deficits in direct source recollection, nevertheless benefit from context reinstatement at retrieval (Vakil, Openheim, Falck, Aberbuch, & Groswasser, 1997). Similarly, elderly individuals, whose source memory and other frontal-lobe based functions may be more impaired than their item memory relative to younger adults (e.g., Spencer & Raz, 1995), can nevertheless benefit equally from context reinstatement (Cohn, Emrich, & Moscovitch, 2008; Naveh-Benjamin & Craik, 1995; Vakil, Raz, & Levy, 2010).

The formation of an association leading to CE can also take place when items are processed in temporal proximity (e.g., Malmberg & Annis, 2011; Schwartz, Howard, Jing, & Kahana, 2005). Schwartz et al. (2005) conducted a study aimed at assessing the fit of the Temporal Context Model (TCM), previously successfully applied to recall, to recognition memory (Howard & Kahana, 2002). TCM offers an explanation for the lag-recency effect – the finding that after recalling an item from a given serial position, the item recalled next tends to come from a nearby position

(Howard & Kahana, 1999, 2002). Testing recognition for scene pictures, Schwartz and colleagues (2005) found that participants were more likely to correctly recognize a picture if the preceding test item was studied in temporal proximity to it. However, the influence of such context reinstatement on picture recognition was found only when high-confidence recognition endorsements were made for the preceding test item.

Levy and colleagues (2008) proposed that the reason for the inconsistency regarding CEs on retrieval caused by unrecognized contextual information (i.e., found by Levy et al. (2008), but not by Schwartz et al. (2005)) was that the contextual structure used by Schwartz et al. (2005) was sequential, rather than concurrent. Similarly to the three levels of association type-relationship proposed by Mayes and colleagues (2007), different forms of associative binding might obtain for different temporal relationships. Items presented in temporal proximity may differ associatively from concurrently processed items: the former may yield inter-item associations, while the latter may yield intra-item unitized associations. Levy and colleagues (2008) suggested that conscious endorsement of the contextual information might be the boundary condition for the activation of non-unitized inter-item associations.

In the present study, we attempt to empirically test that proposal, and to better characterize the influence of domain and temporal effects on unitization of association between memoranda, in two experiments which utilize the CEs paradigm. In Experiment 1, we explore the parameters of unitization by manipulating the domains of the to-be-associated memoranda within trials, while maintaining simultaneous presentation at study. In contrast to our earlier studies which employed picture stimuli only, in this experiment object pictures were studied together with words. This represents the third type of domain relationship in the model of Mayes and colleagues (2007). Given the conventional depiction of unitization as the perception/encoding of discrete stimuli as a single unit (Graf & Schacter, 1989; LaBerge & Samuels, 1974), this combination arguably makes it more difficult to perform unitization at encoding than with two pictures presented simultaneously. To further examine the domain factor, we additionally manipulated the types of words employed, which could be either abstract or concrete. Concrete words may be characterized by dual-coding (Paivio, 2010), possibly leading to visualization which might allow some degree of unitization. We hypothesized that since pictures and words represent two different domains, even in the case of simultaneous encoding, CEs on recognition of picture probes caused by reinstatement of accompanying words would be dependent on endorsement of the word pair members. Furthermore, we expected that CEs on recognition of picture probes accompanied by abstract words would be more dependent on endorsement of the pair members than for pictures accompanied by concrete words. Additionally, although not directly comparable with the results of the previous experiments, we also examined the effects of reinstatement of pictures on recognition of the words that were encoded along with them.

Experiment 1

Materials and methods

Participants

Participants were 40 healthy young adults (12 males; mean age 24.25, *SD* = 2.15 years, range 21–30), with normal or adjusted-to-normal vision. All were undergraduate students who volunteered in return for academic requirement credit or payment. Informed consent was obtained from all participants for a protocol approved by the Interdisciplinary Center's Institutional Review Board. One participant was eliminated from the analyses due to her poor overall recognition performance (2 SD below group mean), so analysis was based on data from 39 participants.

Stimuli

Words. From the list of 863 concreteness-rated words provided by Henik, Rubinstein, and Anaki (2005), we selected 200 words that were rated 1–3.5 points (abstract class) and 200 words that were rated 3.5–7 points (concrete class). Words with lexical or orthographical ambiguity were excluded from the list. Ratings for familiarity (Henik et al., 2005), frequency (Frost & Plaut, 2001), and number of syllables were equated across the two conditions.

Pictures. From various internet sources, we obtained 200 color drawings of common objects, including fruits and vegetables, tools, sporting goods, electrical and electronic devices, animals, furniture, and clothing, each approximately 8 × 6 cm on-screen size. Pictures that matched the content of any of the word stimuli were excluded (e.g., if the word "lion" appeared in the word list, a picture of a lion was not used in the experiment).

Each picture was pseudo-randomly paired with an abstract and a concrete word. Words and pictures were never from the same domain (e.g., the word "cat" was not accompanied by a picture of a dog). In order to equalize levels of relatedness across experimental conditions, 11 participants were presented with the word–picture pairs (6 with concrete words and 5 with abstract words), and were asked to judge to what extent the stimuli were related, using a scale ranging from 1 (highly related) to 5 (highly unrelated). Examination of this data confirmed that levels of relatedness were equal across experimental conditions.

Procedure

We employed a mixed design, with the between-subjects factor instantiated via participants being randomly assigned to either the "concrete words" group or to the "abstract words" group. Prior to study, participants were told that in each trial a picture and a word would be presented together, and that their task would be to remember the words. Additionally, to encourage deep and interactive encoding, they were asked to judge whether the two stimuli were related to each other, on a scale ranging from 1 (highly related) to 5 (not related at all). The entire experiment was presented using e-Prime software (Psychology Software Tools, Inc.). During study, participants viewed a list of 120 pairs. Each pair appeared for 4 s. The disappearance of the pair triggered the appearance of the association scale. Responses were given by pressing the 1–5 keyboard keys. Most participants (37/39) used the entire range in their rating. Responses were self-paced, triggering a 500 ms blank screen, followed by the next trial. Five training trials were provided. A rest break of duration controlled by the participant was provided after half the study-pairs. During a 20 min delay period, participants performed a Trail–Making–Task (Lezak, 1995), and the Raven Progressive Matrices Test (Raven, Raven, & Court, 1996). Before the test, participants were told that they would see studied and unstudied words, accompanied by the same or different studied and unstudied pictures. They were instructed to indicate by key press if the probe stimuli had appeared at study (old) or not (new), irrespective of the other stimuli now accompanying it, and to guess if unsure. They then viewed 200 word-picture pairs in random order. Five types of picture pairs were presented at test, to generate the within-subjects factors of context reinstatement condition and material type:

1. 40 originally studied pairs (picture old, word old-same: Repeat condition);
2. 40 pairs of studied pictures with words seen at study as the pair member of other pictures (picture old, word old-different: Re-pair condition);
3. 40 pairs of studied pictures with new words (picture-old, word-new: POWN);
4. 40 pairs of new pictures with studied words (picture-new, word-old: PNWO);
5. 40 pairs of new pictures and new words (picture-new, word-new: PNWN).

In each trial, word–picture pairs were presented for 1 s, followed by two serial screen displays for each pair, in which the word–picture pair remained presented. In the first screen, the picture was flanked by the legends "appeared" (in a green font) and "did not appear" (in a red font) on either side, and participants were instructed to respond using keys marked in corresponding colors and sides. In the second screen, the legends flanked the word and a second response was required, using the same red/green marked keys on the corresponding sides in a lower row of the keyboard. Screen order randomly varied across trials. Test trials were self-paced, with responses triggering a 500 ms blank screen, followed by the next probe screen or trial. Eight practice trials were provided at the beginning of the test session.

Results

Recognition of studied object pictures and words

Since we have shown in several prior studies (Levy et al., 2008; Vakil et al., 2007, 2010) that context reinstatement may increase bias as well as recognition, we performed separate analyses for hits and false alarms (FAs). For hits, we performed a two-way repeated measures analysis of variance, with factors of context reinstatement condition (Repeat vs. Re-pair vs. POWN/PNWO) and material type (picture vs. word) as repeated factors, and with word category (concrete vs. abstract words) as a between-subject factor. In addition to main effects of context reinstatement condition, $F(2,74) = 131.81$, $p < .01$, $\eta^2 = .78$, and material type, $F(1,37) = 193.41$, $p < .01$, $\eta^2 = .84$, the analysis revealed a significant key three-way interaction between context reinstatement condition, material, and word category, $F(2,74) = 5.54$, $p < .01$, $\eta^2 = .13$. Following up this three-way interaction revealed that for pictures (Fig. 1A), there was a main effect of context, $F(2,74) = 16.21$, $p < .001$, $\eta^2 = .31$, and of word category, $F(1,37) = 5.51$, $p < .05$, $\eta^2 = .13$, with no significant interaction, while for words (Fig. 1C), there was a main effect of context, $F(2,74) = 127.36$, $p < .001$, $\eta^2 = .78$, a main effect of word category, $F(1,37) = 5.54$, $p < .05$, $\eta^2 = .128$, and a significant interaction, $F(2,74) = 4.46$, $p < .05$, $\eta^2 = .108$. This interaction can be seen in Fig. 1C, which shows that hit rates for concrete words were higher in general than for abstract words, except in the Repeat condition. Given that interaction, we conducted repeated measures ANOVAs and repeated contrasts for words, separately for the abstract words group and for the concrete words group. Those tests revealed significant Repeat > Re-pair effects (all $ps < .01$) for both types of material in both groups, but no Re-pair > PNWO effects (all $ps > .1$). The same pattern was obtained for pictures. Therefore, in the endorsement analysis directed towards the question of interest, we focused on the Repeat > Re-pair effects.

False alarms for object picture and word foils

For FAs, our initial analysis comprised within-subjects factors of context reinstatement condition (PNWO/POWN vs. PNWN) and material type (pictures vs. words), and a between-subject factor of word category (concrete vs. abstract words). This yielded a significant effect of material type, $F(1,37) = 25.78$, $p < .01$, $\eta^2 = .41$, with the false alarm rate for words about twice that of pictures. Regarding context effects, there was an interaction between context reinstatement condition and material, $F(1,37) = 7.93$, $p < .01$, $\eta^2 = .18$. Follow-up paired samples *t*-tests revealed that across word categories, context reinstatement (the PNWO–PNWN contrast) led to more foil picture FAs, $t(38) = 2.21$, $p < .05$, but that for word foils of both categories, the POWN–PNWN difference in FAs was not significant, $t(38) = -1.81$, $p = .08$. As our prime concern was with the effects of unitization on veridical recognition, we conducted further analyses on the hit rate data only.

Endorsement modulation of context effects

To investigate the role of explicit memory for context in CE in cross-modal associations that do not readily enable unitization, for each participant, we calculated the conditional probabilities of hits on probes as a function of whether their pair-members were endorsed or not endorsed. For instance, to calculate probability of picture (P) hits if their accompanying context word (W) was endorsed, we used $\text{pPHIT} \cap \text{WHIT}/(\text{pPMISS} \cap \text{WHIT} + \text{pPHIT} \cap \text{WHIT})$ for Repeat and Re-pair conditions (see Levy et al., 2008 for full description of this analysis). Those conditional probabilities were the dependent measure in a repeated-measures ANOVA with material (picture vs. word), pair-member endorsement (pair-member endorsed vs. pair-member not endorsed), and context reinstatement

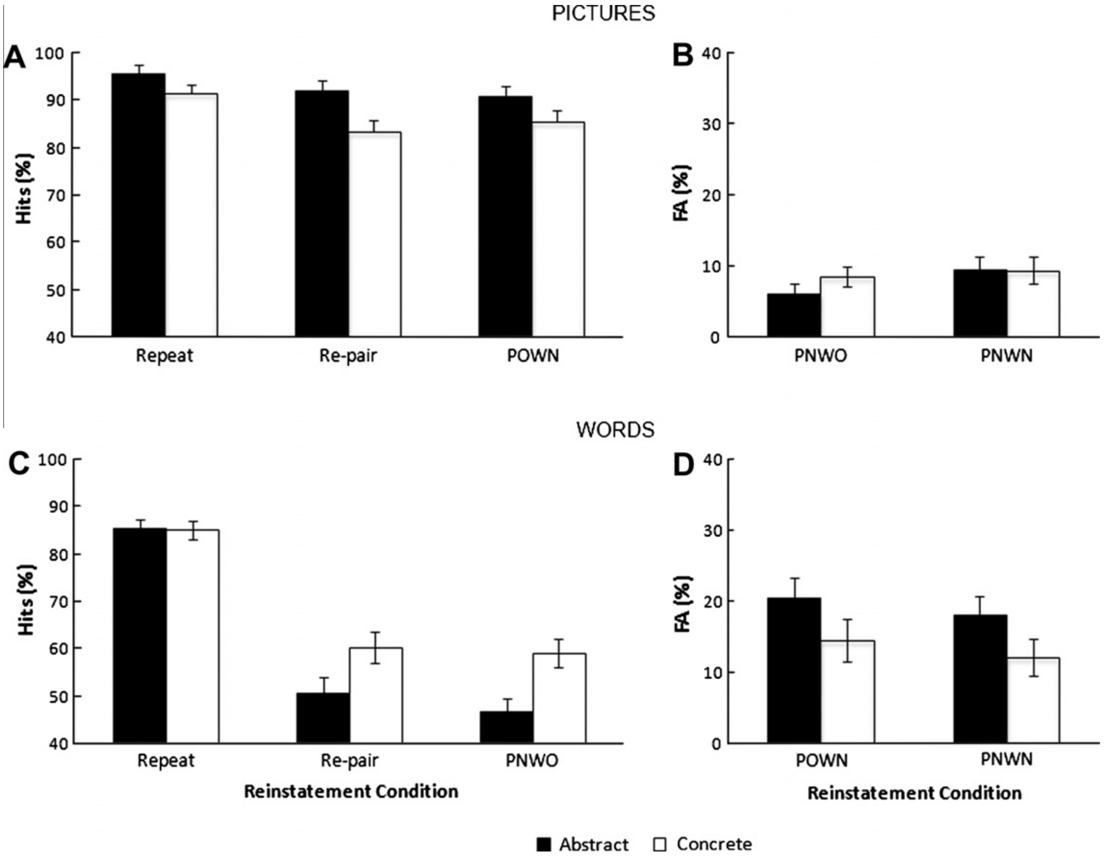

Fig. 1. Recognition memory for object pictures (A, B) and words (C, D) in various probe and context reinstatement condition combinations. (A) Percentage of hits for picture probes in the Repeat, Re-pair and POWN (picture old, word new) context reinstatement conditions, when accompanied by abstract words (black bars) or concrete words (white bars). (B) Percentage of false alarms for foil picture probes in the PNWO (picture new, word old) and PNWN (picture new, word new) context reinstatement conditions, for pictures accompanied by abstract words (black bars) or concrete words (white bars). (C) Percentage of hits for abstract word (black bars) or concrete word (white bars) probes in the Repeat, Re-pair and PNWO (picture new, word old) context reinstatement conditions. (D) Percentage of false alarms for abstract word (black bars) or concrete word (white bars) foil probes in the POWN (picture old, word new) and PNWN (picture new, word new) context reinstatement conditions.

condition (Repeat vs. Re-pair; the POWN/PNWO condition was not included since we found no Re-pair > POWN/PNWO CE) as within-subjects factors, and word category (concrete vs. abstract) as a between-subject factor. Our initial analyses showed that there was no main effect of word category and no significant interactions involving the effects of word category and endorsement; we therefore collapsed the data across word categories. In the resulting ANOVA, all main effects and all interactions were significant. In order to allow a comparison with Experiment 2, in which only images were used, and as the main effect of material was considerable ($F(1,38) = 102.33$, $p < .01$, $\eta^2 = .73$), we then conducted two separate ANOVAs, one for pictures and one for words, with the repeated factors of pair-member endorsement and context reinstatement condition.

For pictures (Fig. 2A), this analysis revealed an effect of pair-member endorsement, $F(1,38) = 12.38$, $p = .01$, $\eta^2 = .25$, and an interaction between pair-member endorsement and context reinstatement condition, $F(1,38) = 12.8$, $p = .01$, $\eta^2 = .25$. Further exploration of the interaction showed that probe hits were higher in the Repeat condition than in the Re-pair condition when pair-member was endorsed, $t(38) = 5.15$, $p < .01$. However, in the absence of pair-member endorsement, the opposite pattern was found, $t(38) = -2.1$, $p < .05$. For words (Fig. 2B), this analysis revealed an effect of pair-member endorsement, $F(1,38) = 30.89$, $p < .01$, $\eta^2 = .45$, an effect of context reinstatement condition, $F(1,38) = 20.06$, $p < .01$, $\eta^2 = .35$, and an interaction between these factors, $F(1,38) = 18.53$, $p < .01$, $\eta^2 = .33$. Further exploration of the interaction revealed that when pair-member was endorsed, probe hits were higher in the Repeat condition than in the Re-pair condition, $t(38) = 10.9$, $p < .01$. However, when pair-member was not endorsed, there was no difference between the two context reinstatement conditions. Thus, for both pictures and for words, when unitization at encoding is not readily performed, recognition memory CEs based on associative binding are dependent on conscious memory for the contextual information.

Although in this experiment we did not find a CE of Re-pair > POWN/PNWO, the effect revealed by last analysis of Exp. 2 (see below) suggested that we should examine possible endorsement-related reasons that the effect was

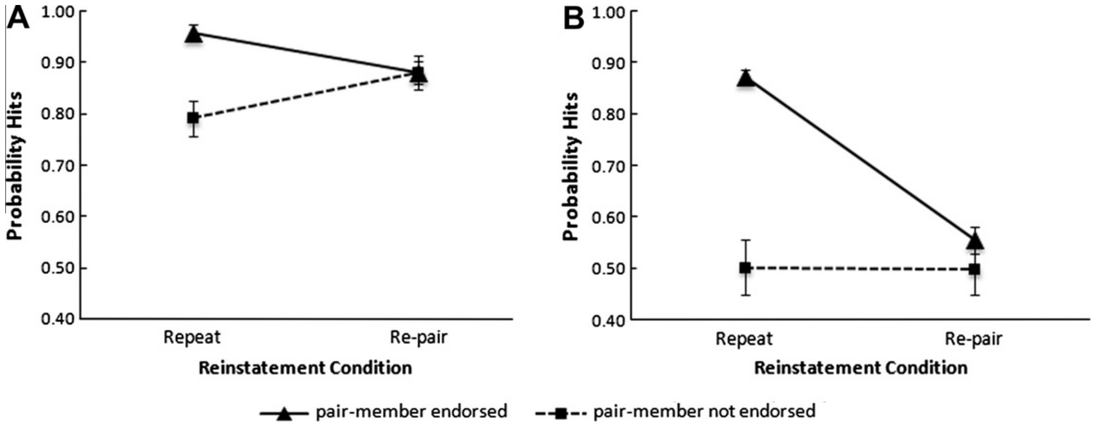

Fig. 2. Mean conditional probabilities of recognition in various context conditions, for pictures (panel A) and words (panel B). The data points represent the probabilities that a probe is correctly endorsed (hit) if its accompanying pair member was correctly endorsed (solid line) or not endorsed (dashed line).

not obtained. Accordingly, we compared the hit rate for Re-pair condition picture targets for which accompanying old words were not endorsed (88.1%) with the hit rate for POWN condition picture targets for which the new accompanying words were correctly rejected (73.0%), and the hit rate for Re-pair condition word targets for which accompanying old pictures were not endorsed (49.7%) with the hit rate for PNWO condition word targets for which accompanying old pictures were correctly rejected (49.5%). We performed a repeated measures ANOVA with factors of context condition (Re-pair vs. POWN/PNWO) and stimulus type (picture vs. word). This revealed a main effect of context condition, $F(1,38) = 8.04$, $p < .01$, $\eta^2 = 0.20$, a main effect of stimulus type, $F(1,38) = 86.8$, $p < .01$, $\eta^2 = 0.70$, and a significant interaction, $F(1,38) = 9.80$, $p < .01$, $\eta^2 = 0.21$. We explored the interaction with paired samples *t*-tests, which revealed a Re-pair > POWN effect even when pair members were not endorsed, $t(38) = 6.23$, $p < .01$, but no Re-pair > PNWO effect when pair members were not endorsed, $t(38) = 0.05$, $p > .9$. Thus, although Re-pair vs. POWN/PNWO CE in general was not found in this experiment, it did emerge in the specific case of pictures for which accompanying words were not endorsed. The significance of this finding is assessed in the "General Discussion".

Discussion

In Experiment 1, we sought to assess the effects of unitizability on associative binding, as expressed in context effects on recognition of object pictures by reinstatement or switching of accompanying words, which requires association of non-unitizable stimuli. Importantly for the question of interest, the Repeat > Re-pair CE was only obtained when the studied word pair member of the Repeat condition picture probe was recognized. In fact, if their studied pair-members were not recognized, Repeat condition picture probes were less likely to be recognized compared to Re-pair probes. The dependence of the Repeat > Re-pair CE on conscious endorsement of the accompanying pair member was true of Repeat > Re-pair CE of pictures on words as well, though not to the point of reversal in the absence of endorsement. Endorsement expresses explicit memory for the context of the encoding episode for which the recognition judgment is made, which is the essence of recollection. Thus, these data suggest that in the absence of the possibility of unitization, processes related to recollection appear to be more important for associative memory as expressed through CEs than familiarity-based processes.

Reserving discussion of the broader implications of these results for the General Discussion, we will here focus on the specific questions raised by the experiment. Contrary to our prediction, there were no significant endorsement-related CE differences between picture-word pairs comprising abstract words and those comprising concrete words, either as targets or as contexts. This indicates that the verbal aspect of the stimulus was the important factor in impacting on CE, and the possibility of forming visual images for the concrete words was not sufficient to enable unitization.

The finding that hit rates were generally higher and false alarm rates lower for concrete words than for abstract words is not surprising, being in line with classic concreteness effects attributed to dual-coding (recently revisited by Paivio (2010)). The exception, found in the Repeat condition, might be a testimony to the ability of strong context reinstatement to boost recognition to the point of overcoming differences in encoding strength. The results of Experiment 1 also show the classic picture superiority effect in the pattern of the mirror effect (i.e., the hit rate is greater and the false alarm rate less for pictures compared to words).

Finally, although as predicted there was a CE of studied words increasing FAs for foil picture probes, there was no CE of studied pictures increasing FAs for foil probes for words of either category. The reason for this specific absence of CE for word FAs, which is robustly found in other CE studies (e.g., Levy et al., 2008; Vakil et al., 2007, 2010) is not evident.

Having demonstrated the effects of domain differences on unitizability for expressions of recollection and familiarity in associative memory, in Experiment 2 we proceeded to explore the impact of temporality effects on unitization. Using a different variation on the aforementioned learning paradigm, we designed a sequential target-context learning paradigm directly comparable to the concurrent target-context learning paradigm of Levy and colleagues (2008), which allows direct comparison between the nature of associative binding of temporally different contextual structures. Participants studied pairs of object picture sequentially, with the first picture serving as context for a following target object picture, and were subsequently asked to make an old-new judgment for each pair-member. The data was analyzed together with the data gathered by Levy and colleagues (2008), in order to directly address the question of whether associations formed between concurrently and sequentially presented stimuli differ in their dependence on explicit memory of the contextual information.

Experiment 2

Materials and methods

Participants

Twenty-two students (six males, mean age 22.45 years, *SD* = 2.08, range 19–26) participated in return for academic credit. Informed consent was obtained from all participants for a protocol approved by the Bar-Ilan University Institutional Review Board.

Stimuli

480 drawings of common objects used in our lab in previous studies (Levy et al., 2008). Each object was approximately 8 × 6 cm in size on-screen. 240 pictures were paired to form 120 study-pairs. Additional 240 pictures supplemented them to form various test-pairs combinations.

Procedure

Participants were told that in each trial two objects would be presented sequentially. They were instructed to remember the target-object, which was always the second object presented, further marked as the target by a 2-cm blue border. Additionally, to encourage deep and interactive encoding, they were asked to judge whether the pair of portrayed objects were likely to be found in the same location under normal circumstances. The experiment was presented using e-Prime software (Psychology Software Tools, Inc.). During study, participants viewed a list of 120 pairs. The first object appeared for 2 s, with 0.5 s blank inter-stimulus interval, followed by the second object, which also appeared for 2 s. Yes/no responses were given by pressing corresponding keys after the disappearance of the objects, revealing the next set. Four training trials and a self-paced break were provided.

During a 20 min delay period, participants performed a Trail Making Task (Lezak, 1995), and the Digit Span subtest from the WAIS III (Wechsler, 1997). Next, participants were told that they would see studied and unstudied target pictures, accompanied by the same or different studied and unstudied context pictures. They were instructed to indicate if the probe picture had appeared at study (old) or not (new), irrespective of the other picture now accompanying it. They then viewed 240 picture pairs in random order. Pairs of successive objects appeared for 1 s each, with 0.2 s blank inter-stimulus interval. The second probe was marked by a 2-cm blue border. Five types of picture pairs were presented:

1. 40 originally studied pairs (Repeat);
2. 40 pairs of studied target pictures with pictures seen at study as the context of other targets (Re-pair);
3. 40 pairs of studied target pictures with new pictures in context-positions (target-old, context-new; TOCN);
4. 40 pairs of new target-position pictures with pictures seen at study as contexts (target-new, context-old, TNCO);
5. 80 pairs of new object pictures in both target and context positions (target-new, context-new, TNCN).

After disappearance of the pictures, to query recognition of the context-position stimulus, the legends "first object appeared" (in green) and "first object didn't appear" (in red) were shown, and participants responded using the corresponding keys. The response triggered the appearance of the next legends, to query the target position stimulus, stating "second object appeared" (in green) and "second object didn't appear" (in red), to which participants gave a second response, triggering the next set. Eight training trials and three self-paced breaks were provided. During performance of the task, magneto-encephalographic (MEG) measurements were recorded, in order to assess patterns of neural activation associated with other aspects of temporal CEs (not reported here).

In order to examine differences in associations between sequentially and concurrently processed stimuli, we contrasted the data from the current experiment with those gathered by Levy et al. (2008). In that experiment, participants were drawn from the same pool as the present experiment, and stimuli were identical or highly comparable to the ones employed in this experiment. Additionally, the task and the experimental procedure were similar, but with one key difference, related to our factor of interest: in the previous study, picture pairs were presented at study and test simultaneously (in contrast to the sequential presentation of the current study). Additionally, in the previous study 180 stimulus pairs were employed, while in the current study, the list was of 240 pairs. However, the relative proportion of items in each test category was the same in both experiments. Finally, in the previous study participants performed a verbal fluency task during the delay period, while in the current study participants performed the Trail Making Task (Lezak, 1995).

Results

Recognition of studied pictures

As in Experiment 1, CEs were analyzed separately for hits (Fig. 3A) and false-alarms (FAs; Fig. 3B). For hits, we performed a two-way repeated measures analysis of variance (ANOVA) and repeated contrasts, with factors of context reinstatement condition (Repeat vs. Re-pair vs. TOCN/TNCO) and encoding role (target vs. context) as repeated

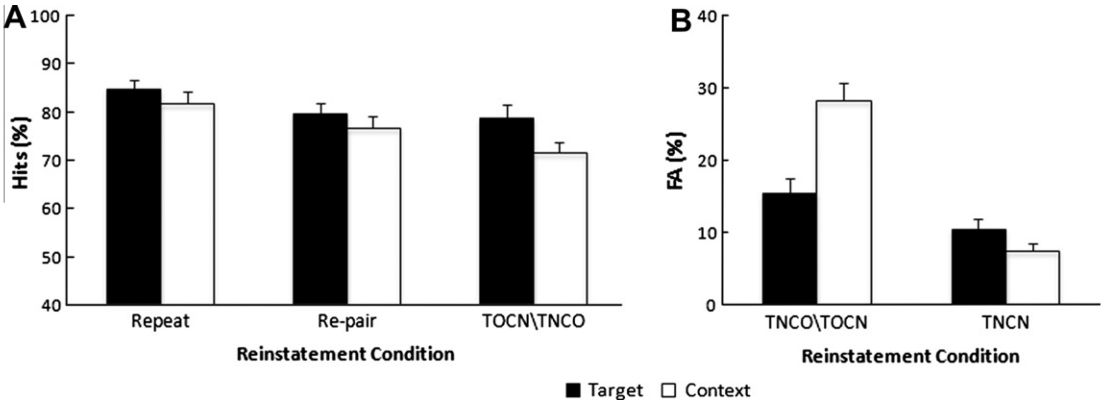

Fig. 3. Recognition memory for object pictures in various probe and context reinstatement condition combinations. (A) Percentage of hits for target (black bars) and context (white bars) probes in the Repeat, Re-pair and TOCN (target old, context new)/TNCO (target new, context old) conditions. (B) Percentage of false alarms for target and context position foil probes in the TNCO (target new, context old)/TOCN (target old, context new) and TNCN (target new, context new) conditions.

factors. This revealed an effect of context reinstatement condition, $F(2,42) = 13.69$, $p < .01$, $\eta^2 = .4$, an effect of encoding role, $F(1,21) = 7.72$, $p = .01$, $\eta^2 = .27$, and no interaction between these effects. Further analysis revealed that the hit rate for target-position probes was higher than for context-position probes, $F(1,21) = 7.72$, $p = .01$, $\eta^2 = .27$. Additionally, repeated contrasts revealed that hits in the Repeat condition were higher than in the Re-pair condition, $F(1,21) = 16.64$, $p < .01$, $\eta^2 = .44$, and hits in the Re-pair condition were marginally higher than in the TOCN/TNCO condition, $F(1,21) = 3.36$, $p = .08$, $\eta^2 = .14$.

False alarms for new foil pictures

For FAs, the analysis revealed an effect of reinstatement condition, $F(1,21) = 63.63$, $p < .001$, $\eta^2 = .75$, an effect of test position (foils in the target vs. context positions), $F(1,21) = 6.4$, $p < .05$, $\eta^2 = .23$, and an interaction between these effects, $F(1,21) = 28.92$, $p < .01$, $\eta^2 = .58$. Examination of this interaction using repeated contrasts revealed that while for target-position test probes, FA rates in the TNCN condition were lower than in the TNCO/TOCN condition, $F(1,21) = 9.67$, $p < .01$, $\eta^2 = .32$, this difference was even more pronounced for context-position test probes, $F(1,21) = 61.98$, $p < .01$, $\eta^2 = .75$. As our prime concern was with the effects of unitization on recognition judgments directed towards the studied materials, as in Experiment 1, we conducted further analyses on the hit rate data only.

Endorsement modulation of context effects

To investigate the role of explicit memory for context in CE, we used the same method of computing conditional probabilities of endorsement employed in Exp. 1 (see above). Next, we conducted a repeated-measures ANOVA with factors of encoding role (target vs. context), pair-member endorsement (pair-member endorsed vs. pair-member not endorsed), and context reinstatement condition (Repeat vs. Re-pair). The results of these analyses are portrayed in Fig. 4, Panel A. The ANOVA revealed an effect of pair-member endorsement, $F(1,21) = 40.86$, $p < .01$, $\eta^2 = .66$, and an interaction between reinstatement condition and pair-member endorsement, $F(1,21) = 11.29$, $p < .01$, $\eta^2 = .35$. Exploration of the interaction using repeated contrasts showed that in the event of pair-member endorsement, probe hits were higher in the Repeat condition than in the Re-pair condition, $F(1,21) = 17.52$, $p < .01$, $\eta^2 = .46$. However, in the absence of pair-member endorsement, probes in the Repeat condition were actually less likely to be recognized than probes in the Re-pair condition, $F(1,21) = 4.86$, $p < .05$, $\eta^2 = .19$.

Effects of unitization on endorsement modulation of context effects

In order to examine differences in associations between sequentially and concurrently processed stimuli, we combined the data from the current experiment with those gathered by Levy et al. (2008), portrayed in Fig. 4, Panel B. We then performed repeated measures ANOVA with all the factors described above, and an additional between-subject factor of encoding design (sequential vs. concurrent). This analysis revealed that overall recognition accuracy rates did not differ between sequential and concurrent experimental designs. Furthermore, as expected, hit rates for target probes were higher compared to those for context probes, $F(1,48) = 10.66$, $p < .01$, $\eta^2 = .18$, while no interactions were found between encoding role and any other factors. These findings allowed us to further interpret the results of the analyses, assuming that difficulty levels were similar in both designs, while collapsing across the levels of the encoding role factor. In addition to an effect of pair-member endorsement, $F(1,48) = 58.21$, $p < .01$, $\eta^2 = .55$, and an effect of context reinstatement condition, $F(1,48) = 6.49$, $p < .05$, $\eta^2 = .12$, the analysis revealed a key three-way interaction between reinstatement condition, pair-member endorsement and design, $F(1,48) = 4.91$, $p < .05$, $\eta^2 = .09$. Further exploration of this interaction showed that while the effect of pair-member endorsement differed across reinstatement conditions in the sequential-learning design of the current study, in the concurrent-learning design of Levy et al. (2008) the effect of pair-member endorsement was similar in the Repeat and Re-pair condition, as indicated in Fig. 2B. Thus, explicit memory for context is required for associative-memory

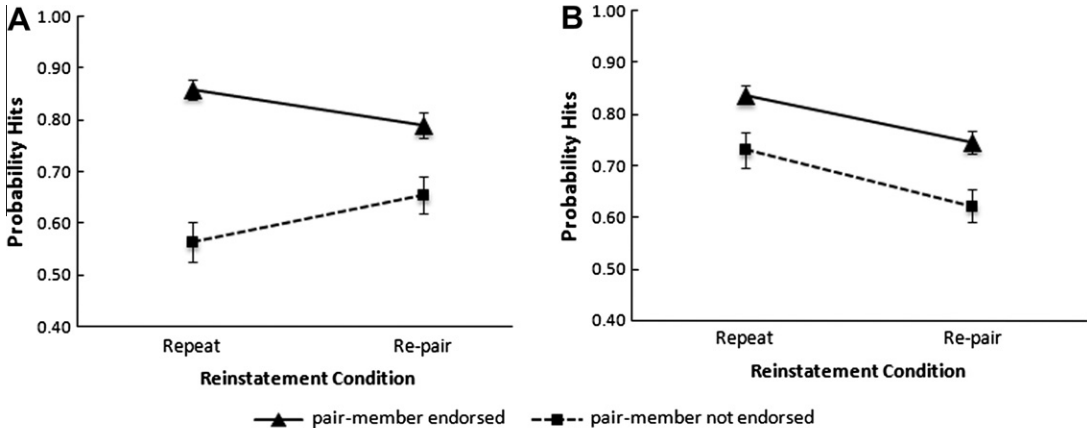

Fig. 4. Mean conditional probabilities of recognition in various context conditions, for sequential processing (panel A) and concurrent processing (panel B; based on data from Levy et al., 2008). The data points represent the probabilities that a probe is correctly endorsed (hit) if its accompanying pair member was also correctly endorsed (solid line) or not endorsed (dashed line).

CEs when stimuli are learned sequentially, but not when they are learned concurrently.

A final analysis concerned the dependence of the Re-pair > TOCN/TNCO CE on endorsement of the relevant contextual stimulus. For this purpose, for target-position probes, we compared the hit rate for Re-pair condition targets for which accompanying pair members were not endorsed (71.0%) with the hit rate for TOCN condition targets for which the new contexts were correctly rejected (64.2%). For context-position probes, we compared the hit rate for Re-pair condition contexts for which accompanying pair members were not endorsed (59.9%) with the hit rate for TNCO condition contexts for which the new target-position stimuli were correctly rejected (60.5%). We performed repeated measures ANOVA with factors of condition (Re-pair vs. TOCN/TNCO) and encoding role (target vs. context). There was no main effect of condition ($p = .36$), a significant main effect of encoding role, $F(1,21) = 6.68$, $p < .05$, $\eta^2 = 0.24$, and a marginal interaction, $F(1,21) = 3.41$, $p = .08$, $\eta^2 = 0.24$. We explored the marginal interaction with paired samples t-tests, which revealed a Re-pair > TOCN effect even when pair members were not endorsed, $t(21) = 2.13$, $p < .05$, but no Re-pair > TNCO effect when pair members were not endorsed, $t(21) = -0.12$, $p > .9$.

Discussion

In this experiment, we sought to determine how associative binding modulated by the temporal structure of learning – i.e., whether stimuli are processed concurrently or sequentially – affects memory CEs. For object pictures studied sequentially, we once again found the manifold effects of study context reinstatement on retrieval that we have demonstrated for concurrently studied stimuli (Levy et al., 2008; Vakil et al., 2007): a hit rate pattern of Repeat > Re-pair > TOCN/TNCO and a FA pattern of TOCN/TNCO > TNCN, for probes drawn from both encoding target and encoding context positions. However, unlike our earlier findings (Levy et al., 2008), the Repeat > Re-pair CE was only found when the studied pair-member of the Repeat condition probe was also recognized. In fact, if their studied pair-members were not recognized, probes were *less* likely to be recognized, compared to Re-paired probes. This was true for probes in both encoding roles, i.e., those encoded as targets for remembering and those encoded as contexts of those targets. In contrast, the Re-pair > TOCN CE were obtained regardless of whether the Re-pair condition pair member was also recognized (though that effect did not obtain for context position Re-pair stimuli relative to TNCO).

These results confirm the view that memory CEs are multifactorial (Vakil et al., 2007). In the current study, we found that following sequential encoding, explicit memory for contextual information is vital for the emergence of Repeat > Re-pair CE, which is based on associative binding. In contrast, for Re-pair > TOCN/TNCO CE, which is posited to be based on additive familiarity, i.e., increased global activation resulting from the summation of activation of encoded events representations (Murnane & Phelps, 1994; Vakil et al., 2007), the same CE obtains whether the studied pair-member is endorsed or not (though, as noted above, this effect was not found for Re-pair > TNCO). As we will propose below (see General Discussion), these findings suggest that when stimuli cannot be unitized during encoding, as in the current case of study asynchrony of the two stimuli, memory for the association requires recollection (hence Repeat > Re-pair, but only with endorsement). In contrast, summation of memory strength for individual items can lead to greater recognition endorsement driven by familiarity (hence Re-pair > TOCN, regardless of endorsement). It must be noted, though, that since this experiment did not manipulate the extent to which the pairs of items were treated as single units, it is not conclusive that the sequential/concurrent differences necessarily reflect unitization.

The current findings concord with the report that CEs caused by temporal proximity at encoding are obtained only when the relevant contextual stimulus is recognized at test with a high degree of confidence (Schwartz et al., 2005). The direct contrast with the findings of Levy et al. (2008) enabled by the present results strongly suggests that both these results and those of Schwartz and colleagues (2005) are a direct function of the temporal asynchrony of the stimuli at encoding.

Our results also concord with the findings of Humphreys (1978) who showed that the probability of failing to recognize both words in an intact (repeated) study pair did not differ from the probability of failing to recognize two words in a rearranged (re-paired) pair. We have suggested that the discrepancy between those findings and those of Levy et al. (2008) is due to the fact that in Levy et al. (2008) stimulus pairs underwent deep and interactive encoding, while in Humphreys (1978), encoding was shallow and independent – which affected the nature of the ensemble representation supporting subsequent CEs. In the current study, encoding was both deep and interactive, but perhaps the strength of the association was limited by the sequential presentation, leading to results that parallel those of Humphreys (1978).

One unexpected result of both experiments was that hit rates for Repeat condition probes with unendorsed pair members were actually lower than those for Re-pair condition probes with unendorsed pair members – i.e., a reverse CE (in Experiment 1, this was only found for pictures, not for words). One possible explanation of this effect is that incorrect rejection of the studied context pair member for Repeat trials may reflect poor encoding of some trials, resulting in correlated encoding strength of the two items, and a lower hit rate for the target probes as well. In contrast, since in Re-pair trials the test pair member was not studied together with the target probe, lack of context endorsement does not suggest poorer encoding of the encoding trial in which the probe stimulus was studied (a similar suggestion, referred to as "good" vs. "bad" encoding, is made by Schwartz et al. (2005)). However, in our prior study (Levy et al., 2008), in which stimuli were studied concurrently, such that even stronger correlation of encoding strength would be expected, this "reverse CE" did not occur. An alternative understanding of this reverse CE occurring specifically in the conditions of the present experiments is that in the absence of unitization (either because of inter-modality as in Exp. 1 or inter-temporality as in Exp. 2), dependence of the CE on recollection can sometimes lead to a process in which the rejection of a Repeat condition test pair member leads to further judgments of the other member of the ensemble as being new as well. This is akin to a "recollect-to-reject" process (Clark & Gronlund, 1996), but in this case the failure of recollection of the probe item seems to inhibit endorsement of the other ensemble member that was studied with it. Since in unitization conditions context reinstatement is postulated to affect the recognition judgment of the probe even without recollection (as we have shown), recollection-based inhibition does not occur.

General discussion

In two experiments, we have demonstrated that context effects on recognition, which offer an indirect but robust assessment of associative memory, are sensitive to both unitizability and simultaneity at the time of study of memoranda. In both cases, increased recognition of memory probes caused by the reinstatement of identical encoding context (the Repeat > Re-pair effect) only occurred when the contextual information itself was remembered. A similar pattern of results was observed in both experiments, despite the differences in type of challenge to unitization (inter-modality vs. inter-temporality) and some procedural differences in the study task. This overall finding contrasts with previous reports that for simultaneous encoding of similar and potentially unitizable stimuli, context reinstatement increases recognition even when the contextual stimuli themselves are not remembered.

While these results were obtained using a context effects paradigm, their implications are relevant to associative memory in general. The need for conscious endorsement of contextual information for the emergence of associative binding-based Repeat > Re-pair CEs in the absence of unitization and simultaneity suggests that in such cases, recognition judgments are influenced by recollection of the conjunction of the stimuli at encoding (or lack thereof). Taken together with prior findings that when unitization is possible, Repeat > Re-pair CEs do not require endorsement of context stimuli, these results support the suggestion that familiarity as well as recollection may contribute to associative memory when unitization is possible (Bastin et al., 2010; Mayes et al., 2007; Yonelinas et al., 1999), but that in the absence of unitization, associative recognition must be recollective. The additional contribution of this study is the finding that in the absence of unitization, familiarity is insufficient to support not only direct associative recognition judgments, but even indirect expression of memory for associative binding. It is important to note that since recollection and familiarity were not directly assessed in the current CE paradigm, the attribution of the effects of unitization to familiarity and recollection can only be inferred, not demonstrated directly. Nevertheless, the use of the CE paradigm is valuable, as it provides confirmation of the unitization principle that is not dependent on subjective report of the participant, on which the ROC (e.g., Quamme, Yonelinas, & Norman, 2007), Remember-Know (e.g., Hockley & Consoli, 1999) or familiarity-only procedure (Bastin et al., 2010) paradigms are based.

The findings obtained with the current CE paradigms suggest another potential distinction between types of associations and their cognitive and neural substrates. The Repeat > Re-pair CE is based on the specific associative binding of two stimuli. The Re-pair > new-context CEs are based on what we have called additive familiarity (Vakil et al., 2007). The additive familiarity CE does not require memory for the specific stimulus pair-binding, but it does require memory that two stimuli were experienced in the same episodic event frame. Such association is of the type often assessed in source memory assessments (Johnson et al., 1993), in which individuals are asked to indicate in which condition or time period specific information was acquired or a particular stimulus was experienced. In two cases (for pictures in Exp. 1 and Re-pair > TOCN in Exp. 2), we found that conscious endorsement of the context stimulus was not required for the additive familiarity CE to emerge. Seemingly, in these two cases, the familiarity strength of the context stimulus affected the recognition judgment of the probe, despite not being sufficient for the participant to endorse the context itself as old in direct judgment. This suggests that while specific associative binding memory is recollective unless unitization is possible, diffuse episodic association across episodes may be supported by familiarity strength, even in the absence of unitization. Thus, in addition to the three levels of associative relationships proposed by Mayes and colleagues (2007), consideration should be given to the existence of a fourth level, "within-episode association", for which both familiarity and recollection might contribute to associative memory.

The concept of "within-episode association" brings to mind Kahana and colleagues' Temporal Context Model (TCM) of memory. Our current findings indeed support TCM, and the extension of the model to recognition memory (Howard & Kahana, 2002; Schwartz et al., 2005). One prediction of TCM is that if a stimulus is proximally paired with some event during study, then memory for that stimulus will be better if the event is repeated. Experiment 2 provides evidence that the lag-recency effect described by TCM is not only true for serial lists, but also for pair-associate recognition. As other aspects of mnemonic processes, such as associative asymmetry, might differ between pairs and lists (for review see Kahana, 2002), this confirmation of the TCM's predictions is noteworthy.

The ramified dissociation between associative-binding processes suggested by the results of these studies resonates with recent proposals regarding divisions of mnemonic function within the medial temporal lobes (MTLs). For example, Howard, Fotedar, Datey, and Hasselmo (2005) have suggested that temporal CEs are mediated by hippocampal processing. In their model, entorhinal cortex supports a gradually changing representation of temporal context, while the hippocampus itself enables retrieval of those contextual states. Another model, offered by Norman and O'Reilly (2003), asserts that the perirhinal cortex mediates unitized and within-domain associations, by using a pattern-generalization algorithm that identifies common features, while the hippocampus mediates between-domain associations using a pattern separation algorithm that makes distinct memory representations. These views have accrued support from behavioral, lesion and functional imaging evidence (reviewed by Mayes et al. (2007), to which may be added: Qin et al., 2009; Staresina & Davachi, 2010). Our data may support the proposed divisions, possibly reflecting the distinction between explicit contextual binding dependent on the hippocampus, and implicit contextual binding that may be supported by other MTL regions. One prediction of this view is that patients with limited hippocampal lesions might show diminished effects of temporal context reinstatement, but intact CEs for temporally unitized associations (as was shown for compound-word unitization in left-temporal lobe damage patients by Quamme et al. (2007)), while more extensive MTL damage would impair all kinds of CEs.

The notion of unitization is related to a long-standing debate about the possible differential contributions of sub-regions of the medial temporal lobes (MTL) to item vs. associative memory formation (recently surveyed by Konkel and Cohen (2009)). Initial evidence supported the view that different MTL sub-regions play different mnemonic roles. PRh is asserted to support discrete item encoding promoting familiarity at retrieval, whereas the hippocampus is seen as supporting associative memory formation, which also gives rise to subsequent recollection (Aggleton & Brown, 1999; Eichenbaum, Yonelinas, & Ranganath, 2007[1]; Mayes et al., 2007). This anatomical distinction is in line with the distinction between item and associative-memory characterizes many theoretical models of memory (e.g., Murnane et al., 1999).

That simple item-association distinction and related anatomical dissociation has been challenged by more recent data showing episodic associative encoding effects in PRh (Ford, Verfaellie, & Giovanello, 2010; Jackson & Schacter, 2004; Staresina & Davachi, 2006, 2008, 2010). A more fine-grained approach is suggested by the report that associative memory is relatively spared in patients with selective hippocampal damage if the to-be-associated information is processed in a unitized manner (Giovanello, Keane, & Verfaellie, 2006; Quamme et al., 2007). Thus, rather than a discrete dual-process model involving parallel dissociations of item/association, familiarity/recollection, and PRh/hippocampus, episodic processes might be best described as a continuum, reflecting the degree of unitization and simultaneity between the elements of a given representation. The behavioral evidence offered by the studies herein reported support the continuum approach, suggesting that more fine-grained distinctions between types of associations and their parameters should be sought.

In conclusion, this study documents important differences between memory for associations that depend on the temporal relationship and the potential for unitization of the component stimuli. The differences in CEs on recognition memory following these various types of encoding conditions hint to multi-dimensional dissociations in the nature of the associations that are formed, and possibly in their neural substrates.

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[1] Eichenbaum et al. (2007) extend the dissociation into a three-component model in which the parahippocampal cortex contributes to associative memory by coding contextual information, while the perirhinal cortex supports single-item memory, and the hippocampus supports associative memory by binding item(s) with relevant contextual information.

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