Three-Way Bindings in Associative Recognition

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Abstract

To avoid interference among similar memory traces it is required to form complex memory structures that include multiple components of the event, which helps one to distinguish one event from another. In a laboratory setting, these complex binding structures have been studied through a paradigm where one has to form a memory structure that includes two items and the context together (i.e., three-way binding). However, despite the long history of the theoretical concept, its importance, and the existence of the laboratory paradigm, three-way binding structures have only been examined in recall paradigms. Moreover, not all memory models consider the ability to form three-way binding structures as a default. Therefore, the current study examined the use and formation of three-way binding structures in an associative recognition paradigm. Results provide evidence that three-way binding structures are used during recognition, which implies that it is critical for memory models to properly represent them.

Keywords: episodic memory; recognition; three-way binding

Introduction

LeSean McCoy is a running back in the National Football League (NFL) who started his career with the Philadelphia Eagles. After receiving several awards, and leading the team to the conference finals two times, McCoy was traded with Kiko Alonso, who was Buffalo Bills' linebacker with an "NFL Defensive Rookie of the Year" title. Knowing this fact, how would one later recall which team McCoy was playing before the trade? Even after restricting that there was a trade between McCoy and Alonso, simply recalling which team McCoy played for does not solve the answer since McCoy played for both the Eagles, and the Bills. Additionally retrieving the team that existed in the pre-trade period also does not help since both team existed before and after the trade. The only way to correctly retrieve this information is forming a coherent memory structure of [McCoy]-[Eagles]-[pre-trade] together, and later using the two cues together at retrieval (i.e., [McCoy] and [pre-trade]) as a compound cue.

Memory researchers call this kind of memory structure a three-way binding structure (Humphreys, Bain, & Pike, 1989), and controlled laboratory experiments using recall paradigms provide evidence that adults robustly form these memory structures (e.g., Postman, 1964). Binding structures in memory research have been mainly studied using a paired associate learning paradigm, where participants are given (usually two) lists of paired words to study, and are later tested. Especially the three-way binding structure could be examined when the word pairs in one list are repaired in another list (i.e., ABABr condition; Porter & Duncan, 1953). As in the notation, in an ABABr condition the words in one list (i.e., first two letters 'AB') are identical in the other list (i.e., second two letters 'AB') but paired differently (i.e., last letter 'r' representing that the words are re-paired). Therefore the structure creates a strong interference between the two lists when trying to retrieve a piece of memory as in the NFL trading example. To correctly retrieve which words were paired in which list, one needs to use a three-way binding structure that includes the context of a specific list, and the two words together (e.g., [list_1]-[word_1]-[word_2]).

Correctly retrieving information from an ABABr condition could be thought as an exclusive or (XOR) problem since the arrangement of the ABABr condition is similar to the XOR operation (Wiles & Humphreys, 1993). In the XOR operation, which is expressed by using the symbol $\veebar$, when zero is operated with zero the answer is one (i.e., $0 \veebar 0 = 1$), and zero operated with one is zero (i.e., $0 \veebar 1 = 0$). When one is operated with zero the answer is zero (i.e., $1 \veebar 0 = 0$), and one operated with one is one (i.e., $1 \veebar 1 = 1$). Considering the first two terms as the cues at test (i.e., first term as the context, and second term as the item cue), and considering the answer of the XOR operation as the to-be-retrieved target, the process of retrieving an answer from the ABABr condition becomes identical to the XOR problem. The solution of the XOR has been well known to be impossible within a two dimensional plane that has independent inputs (e.g., Minsky & Papert, 1969), and could be solved by increasing the dimension of the inputs such as using multiplicative (configural) coding of the inputs (Sloman & Rumelhart, 1992). Similarly, the ABABr condition could not be solved with a two-way binding structure, in fact not even with multiple two-way binding structures (e.g., Humphreys, Bain, & Pike, 1989), and requires a higher dimensional representation such as three-way binding structure.

Empirical evidence for the ability to form and use three-way binding structures implies that our memory system should be able to store three-way binding structures, and use compound cues when retrieving these structures. However, not all theoretical accounts of episodic memory, and their computational models consider three-way binding structures as a default.

For example, the Search of Associative Memory (SAM; Gillund & Shiffrin, 1984; Raaijmakers & Shiffrin, 1981) theory does not consider three-way binding structures as a memory representation. The model assumes that memories are stored as association strengths between two components such as item and context, or item and item. Because these associations contain only two components, it is not possible to represent three-way bindings. On the retrieval side, SAM is unable to use compound cues when multiple cues are provided during retrieval. Rather it treats each cue independently and then combines the retrieved information of each cue by seeking overlapping information that are retrieved by each cue.

The Temporal Context Model (TCM) and its variants also do not employ three-way binding structures (Howard & Kahana, 2002; Lohnas, Polyn, & Kahana, 2015; Polyn, Norman, & Kahana, 2009; Sederberg, Howard, & Kahana, 2008). TCM employs a two-way binding between an item and the current context representation, which are stored in a matrix of item-context bindings. In TCM, the context is defined as a weighted sum of all past items where more recent items have a stronger weight in representing the current context. These assumptions even hold when word pairs are studied in a paired associate learning paradigm (e.g., Howard et al., 2009). TCM resembles SAM in that the representational structure is fundamentally restricted to two-way associations, and therefore cannot represent three-way bindings without extensive modification.

On the other hand, models that are capable of explaining the use and formation of three-way binding structures have slightly different assumptions. MINERVA 2 (Hintzman, 1984) encodes events as separate traces, in which context and item representations are concatenated into a single vector. Thus, items A (I_A) and B (I_B) in context 1 (C_1) could be represented as $C_1 \oplus I_A \oplus I_B$. Recognition decisions in the model are made by matching the cue vector to each memory trace and summing the similarities to produce a single index of memory strength that is then compared to a decision criterion.

MINERVA 2 is sensitive to three-way associations by virtue of a non-linearity at retrieval, where the similarity between a cue and a stored trace vector is raised to the third power. This enables the model to be more sensitive to conjunctions among studied elements, rather than the individual elements themselves. Consider if pairs A, B and C, D were studied in context 1 and pairs A, C, and B, D were studied in context 2. A foil such as $C_2 \oplus I_A \oplus I_B$ contains studied elements, but these were not all studied together. After the cubing process (increasing the similarity to the third power), the target $C_1 \oplus I_A \oplus I_B$ receives a stronger match than the sum of the partial matches to $C_2 \oplus I_A \oplus I_B$. Models in the Retrieving Effectively from Memory (REM; Criss & Shiffrin, 2005; Shiffrin & Steyvers, 1997) framework employ a similar idea, where instead of a cubing process at retrieval the likelihood of feature match is multiplied across each element in the vector to calculate a likelihood ratio that the trace was a studied item, producing stronger matches to conjunctions of studied elements than studied elements distributed across different memory traces.

The MATRIX model (Humphreys, Bain, & Pike, 1989; Osth & Dennis, 2015; Pike, 1984) has a slightly different assumption about its storage representation by using tensor representations. Items and contexts are represented as vectors and the vectors are bound together using outer products to form a third-order tensor (i.e., $C_1 \otimes I_A \otimes I_B$). Rather than having individual traces for each event, the MATRIX model sums all representations for each event into a single composite tensor. The tensor representation naturally allows the use of compound cues during retrieval by forming a second-order tensor (i.e., an outer product of an item and a context) to represent the compound cue. At retrieval, the cues are combined into a tensor and matched against the memory tensor using the dot product operation which produces a measure of memory strength that reflects how similar the combined cues match the contents of memory.

Interestingly, evidence for the use of three-way binding structures have only been examined with cued recall tasks (e.g., Porter & Duncan, 1953; Shimamura, Jurica, Mangels, Gershberg, & Knight, 1995; Yim, Dennis, & Sloutsky, 2013) where a context and an item is given at test as a cue to recall the paired item during study (e.g., what was the word paired with 'apple' in 'the first list'?). To our knowledge, no recognition paradigm examined the use of three-way binding structures. A number of studies have examined the role of inter-item bindings in recognition memory by using an *associative recognition* task, where participants study pairs of items such as A-B, C-D, and E-F in a single list. At test, participants have to make discriminations between *intact* pairs, which were studied on the list (e.g., A-B), and *rearranged pairs*, which are studied items but in a novel arrangement (e.g., C-F).

Moreover, associative recognition tasks with the ABABr condition have been used in other studies with different purposes (e.g., Aue, Criss, & Fischetti, 2012; Criss & Shiffrin, 2005; Postman & Stark, 1969). However, the design and goal of the studies do not focus on the use of three-way binding structures, mostly by not testing the word pairs from both lists together. This is especially relevant because the role of context has been generally neglected in models of associative recognition. For instance, the TODAM2 model of Murdock (1997) did not bind context to inter-item bindings due to an assumption that context was not employed in associative recognition as it was not relevant to the goal of the task.

Therefore, the current study examined whether three-way binding structures are used during recognition using a associative recognition task with the ABABr condition. We constructed an ABABr condition by presenting pairs in different contexts, such as A-B and C-D in context 1 and A-D and C-B in context 2. At test, participants are given a pair and a context cue and asked if the pair occurred in the particular context. Successful discrimination in ABABr conditions would suggest a memory structure that is capable of representing three-way bindings. Demonstration of such bindings in both recognition and recall tasks would provide further evidence that memory models need to consider such representations.

Experiment

The experiment tested whether people use three-way binding structures in an associative recognition paradigm. In addition to the ABABr condition, which requires a three-way binding structure for a correct recognition, we used an ABAC, and ABCD condition. In the ABAC condition, as in the notation, one item from each pair in the first context (i.e., A in 'AB') overlap with an item from each pair in the second context (i.e., A in 'AC') which results in a moderate overlap between the two contexts compared to the ABABr condition. At the minimum, it is required to form two two-way binding structures (i.e., item-to-item, and context-to-item) for a correct retrieval (Humphreys, Bain, & Pike, 1989). Using the same scheme, in the ABCD condition there are no overlapping items between the contexts which results in two contexts with unique items. Since there is no overlap between the two contexts, a correct retrieval only requires a single item-to-item binding at the minimum (i.e., item-item, or cue-target binding). Therefore the level of overlap increases from the ABCD condition to the ABABr condition. Moreover, a more complex binding structure is required for a correct retrieval at test as the level of interference increases. Previous studies using a recall paradigm showed a negative correlation with the level of interference and performance (e.g., Yim, Dennis, & Sloutsky, 2013). Therefore, the additional two conditions will serve as a reference point for the performance on the ABABr condition.

As part of the design, we defined context as the identity of the speaker that presents the word pair instead of using the temporal order of the 'list' (i.e., first list, and second list) as in previous studies. Embedding the context in the trial enables us to intermix different context in the study phase, and prevents the participants from using the temporal cue. A weakness of previous ABABr designs which use two successive study lists as their contexts is that the first list is naturally expected to have weaker memory strength than the second list. This enables participants to infer that an item is from the first list due to its weaker memory strength even with a two-way binding structure (e.g., Lohnas, Polyn, & Kahana, 2015). By eliminating the memory strength confound, our design ensures that participants require a three way binding structure to achieve above chance performance in the task.

Methods

Participants Forty-three undergraduate students at The University of Newcastle participated for course credit (36 females, M = 25.12 years, SD = 9.87).

Materials The stimuli were video clips of a speaker saying a word. There were nine female and nine male speakers, and each speaker had its own unique background scene (see Figure 1A). All words were high frequency words consisting of 54 adjectives, and 63 nouns. Most of the words were selected from the MacArthur-Bates Communicative Development Inventory through the Wordbank repository (Frank, Braginsky, Yurovsky, & Marchman, 2016).

Procedure Participants were tested individually in the laboratory. There were nine blocks where each block had a study phase followed by a retention interval and a test phase. In the study phase, participants were told that they will be seeing two speakers each presenting different word pairs one at a time. They were also told to exactly remember who said which words together since they will be tested later. Each trial started with a fixation cross for 500 msec followed by a blank screen of 500 msec and a video clip presenting a word pair, which lasted for approximately 3400 msec (see Figure 1B). In all blocks, one of the speakers was always a female, and the other a male. Also, the video clips were presented on one side of the screen throughout the experiment depending on the speaker's sex (e.g., female on the left side, male on the right side), but was randomized across participants. There were eight trials in each study phase consisting of the ABCD, ABAC, and ABABr structures (see Table 1 for an example). The first word was always an adjective and the second word was always a noun. The presentation order of the eight trials corresponding for each structure were randomized every block.

Table 1: An example of the eight trials in each study phase. Each triplet in the *Trials* column represents the speaker's sex (M: male, F: female), first word (adjective), and second word (noun) in order. There are four trials for the ABABr structure, two trials each for the ABAC and ABCD structures.

Condition	**Trials**	
ABABr	[M] – *green – hand* [M] – *hot – toy*	[F] – *green – toy* [F] – *hot – hand*
ABAC	[M] – *empty – cat*	[F] – *empty – shoe*
ABCD	[M] – *tall – rain*	[F] – *quiet – ball*

During the 60 second retention interval participants were presented with two groups of dots on each side of the screen, and were told to choose the side that had more dots. After a 500 msec fixation (+++) the two groups of dots were presented for 250 msec followed by a random color dot mask, which was presented until a response was made. The number of dots varied between 10 and 40 where the ratio of the two numbers were randomly chosen among the following range:

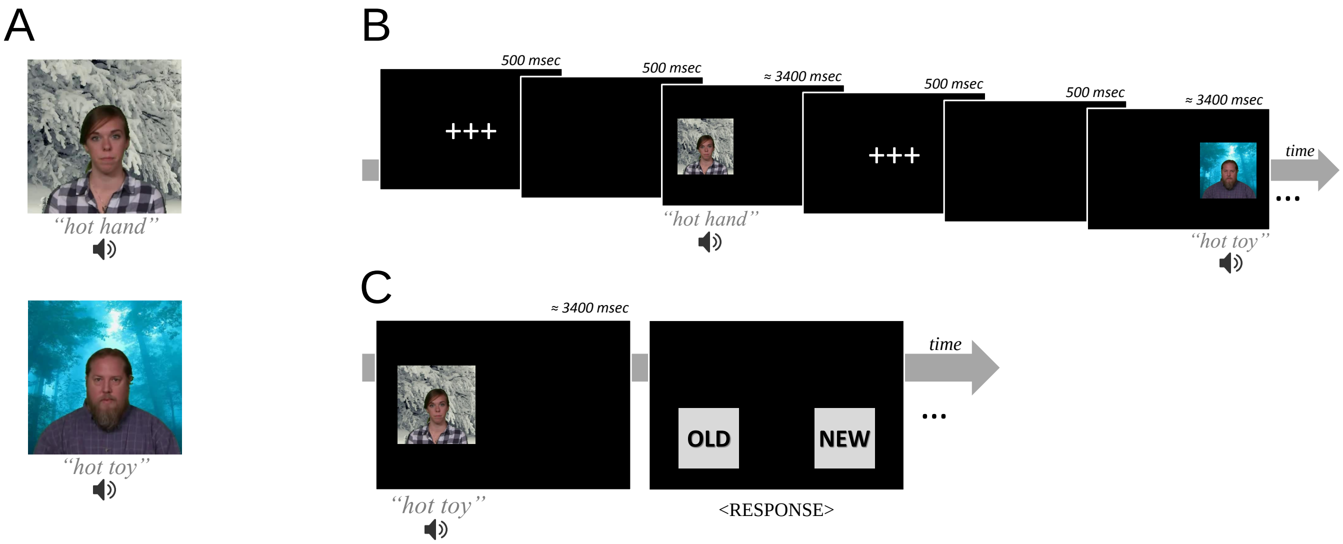

Figure 1: Design and stimuli used in the experiment. (A) an example of the videos used in the experiment, (B) an example of the study phase, (C) an example of the test phase.

1.0991-1.1915, 1.1915-1.2917, 1.3302-1.4421, and 2.2906-2.4833 (adapted from Halberda & Feigenson, 2008).

In the test phase, participant were presented with a video clip as in the study phase and were asked whether it was an old video that they saw during the study phase (i.e., same speaker saying the exact same word pair), or a new one (see Figure 1C). Responses were collected using a computer mouse by clicking the corresponding image on the screen. There were 18 test trials consisting of eight old videos, eight new videos that had the speaker swapped (re-arranged pairs), and two new videos that had a new word pair spoken by the female speaker and the male speaker (lure pairs). The words in the lure pair did not appear in the study phase, and the trials were randomized every block.

Presentation of all stimuli was controlled using MATLAB with Psychtoolbox-3 (Kleiner, Brainard, & Pelli, 2007) equipped with a 22 inch monitor, and an individual headphone. The combination of the word pairs, and speakers were randomized across participants.

Results

We analyzed and compared each condition regarding hit rate (HR), false alarm rate (FAR), d', and correct reaction time (RT). As shown in Figure 2A, HR was the highest for the ABAC condition (M = .76, SD = .14) followed by the ABCD condition (M = .71, SD = .15) and ABABr condition (M = .67, SD = .11). A linear mixed-effects model[1] with subject as a random factor (random intercept model) supported the effect of Condition ($\chi^2(2) = 16.70$, $p < .001$), while a Tukey post-hoc test only provided evidence for the difference between the ABAC condition and the other two condition (ABAC - ABABr: $p < .001$; ABAC - ABCD: $p = .057$; ABCD - ABABr: $p < .001$). Similarly, the FAR measured by the re-arranged pairs was the highest for the ABABr condition (M = .40, SD = .15) followed by the ABCD (M = .25, SD = .16), ABAC (M = .23, SD = .15), and the lures (M = .17, SD = .16; see Figure 2B). A linear mixed-effects model with subject as a random factor supported the effect of Condition ($\chi^2(2) = 94.62$, $p < .001$), while a Tukey post-hoc test provided evidence for the difference between the ABABr condition and the other conditions ($p < .001$), and between the lures and the ABAC ($p = .046$) and ABCD conditions ($p = .001$). There was no evidence for a difference between the ABCD and ABAC conditions. Unlike previous studies using a recall paradigm, where the ABCD condition shows a better performance than the ABAC condition, the current results show a higher HR and lower FAR for the ABAC condition than the ABCD condition.

We measured discrimination using d' by comparing old pairs against rearranged pairs ($d'_{rearranged}$). As shown in Figure 2C the ABABr condition showed the lowest (M = .74, SD = .64), followed by the ABCD condition (M = 1.30, SD = .71), and ABAC condition (M = 1.53, SD = .80). Also, all conditions showed an above chance performance ($ts(42) > 7.60$, Bonferroni adjusted $ps < .001$, Cohen's $d > 1.16$), as evidenced by d' scores above zero in each condition. A linear mixed-effects model with subject as a random factor supported the effect of Condition ($\chi^2(2) = 59.12$, $p < .001$), while a Tukey post-hoc test provided evidence for the difference between the ABABr condition and the other two conditions (ABAC: $p < .001$; ABCD: $p < .001$), and between the ABAC and the ABCD condition ($p = .028$).

[1] All mixed-effects models here and hereafter were implemented using the lmer4 package in R (Bates, Mächler, Bolker, & Walker, 2015), and all effects were calculated by a likelihood-ratio test against the null-model that only had the random effect of subject (random intercept model).

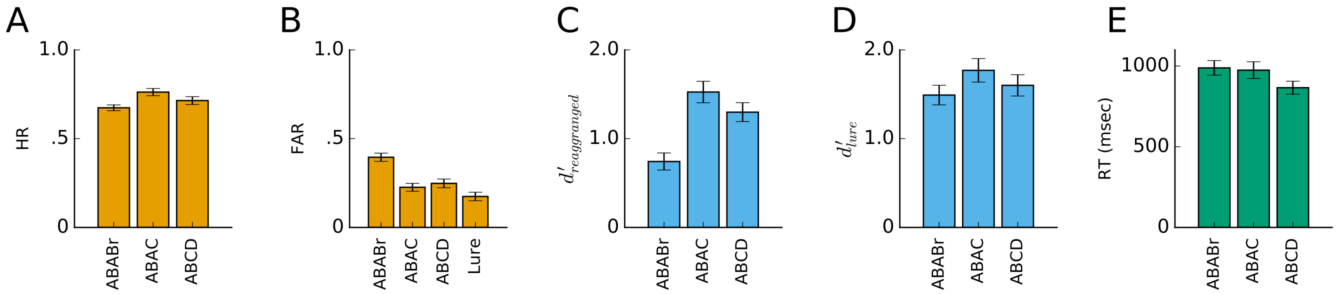

Figure 2: Results of the Experiment. (A) hit rate (HR), (B) false alarm rate (FAR), (C) d' of distinguishing the re-arranged pairs from studied (old) pairs ($d'_{rearranged}$), (D) d' of distinguishing the lures from non-lures (d'_{lure}), and (E) correct reaction time (RT). *Error bars represent* ± 1 *SEM*.

Discriminability of lures (new pairs) from intact pairs (d'_{lure}) was also calculated (see Figure 2D). The ABABr condition showed the lowest d'_{lure} (M = 1.49, SD = .73), followed by the ABAC condition (M = 1.77, SD = .88), and ABCD condition (M = 1.60, SD = .79), while all conditions showed an above chance performance (ts(42) $>$ 13.18, Bonferroni adjusted ps $<$ .001, Cohen's $d > 2.01$). A linear mixed-effects model with subject as a random factor showed supported the effect of Condition ($\chi^2(2)$ = 17.87, $p < .001$), where evidence for difference was found between the ABAC condition and the other two conditions (Tukey post-hoc test, ABABr: $p < .001$; ABCD: p = .022), but not between the ABABr and ABCD conditions (p = .198).

RT was first pre-processed by taking the median value of each condition for each participant. RT was the slowest for the ABABr condition (M = 988 msec, SD = 299 msec) followed by the ABAC condition (M = 974 msec, SD = 344 msec), and ABCD condition (M = 866 msec, SD = 267 msec; see Figure 2E). A linear mixed-effects model with subject as a random effect showed a statistically significant effect of Condition ($\chi^2(2)$ = 9.11, p = .011), where a Tukey post-hoc test provided evidence for the difference between the ABCD condition and the other two conditions (ABAC: p = .035; ABABr: p = .015), but not between the ABAC and ABABr conditions ($p > .25$).

General Discussion

In the current study we examined whether three-way binding structures are formed and used in a recognition task. Even though three-way binding structures are crucial in everyday life since items could be easily re-paired in different contexts, previous studies have only examined the structure with recall paradigms. The results most importantly showed that participants reliably use three-way binding structures during an associative recognition task. Based on both $d'_{rearranged}$, and d'_{lure} measures, participants showed robust above chance level performance in the ABABr condition, which indicates that three-way bindings were formed and used. The overall pattern was similar to previous findings using recall tasks (e.g., Yim, Dennis, & Sloutsky, 2013) where the ABABr condition showed above chance accuracy while less accurate than the other two conditions, and required more time to respond due to greater interference. Our results also extend on previous studies by using two contexts that are inter-mixed within a single list. Past studies which have employed two temporally separated study lists allow for the possibility that participants could infer list membership on the basis of a difference in memory strength between the two lists.

One interesting difference from previous results was the performance in the ABAC condition. Previous studies show a better performance in the ABCD structure compared to the ABAC condition since there are less interference in the ABCD condition. However, the ABAC condition showed the best performance in the current results. One possible explanation could be a speed-accuracy trade off since it took longer to respond in the ABAC condition than in the ABCD condition while the accuracy was higher. However, it will be hard to disentangle the cause with only relying on the current data set.

The evidence of using three-way binding structures in both recall and recognition tasks implicate that models that do not represent three-way binding structures should be re-examined (e.g., Gillund & Shiffrin, 1984; Howard & Kahana, 2002; Lohnas, Polyn, & Kahana, 2015). Our results also cast doubt on the proposal that the associative recognition task does not employ a context representation (Murdock, 1997). However, future work may be needed to discriminate between the existing classes of models that are capable of predicting above chance ABABr performance. For instance, our results do not discriminate between multiple trace models such as MINERVA 2 (Hintzman, 1984) and REM (Shiffrin & Steyvers, 1997) which can predict above chance ABABr performance by virtue of their non-linear similarity metrics at retrieval, and the class of tensor models (Humphreys, Bain, & Pike, 1989; Osth & Dennis, 2015) which employ explicit three-way bindings as third-order tensors. Another interesting possibility for future work concerns the time course of when three way bindings are accessible. Although there are studies showing that associative information arrives after information (e.g., Gronlund & Ratcliff, 1989), further research should examine these possibilities with three-way bindings.

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