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Evidence for the use of three-way binding structures in associative and source recognition

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ABSTRACT

Avoiding interference among similar memory traces may be helped by forming complex memory structures that include multiple components of the event. In a laboratory setting, these structures have been studied through list learning paradigms, where the pairs in one list are swapped in another list (i.e., ABABr condition), and one has to form a memory structure that includes items and context together (i.e., three-way binding). However, despite the long history of the theoretical concept, and its importance, three-way bindings have only been examined in recall paradigms. Moreover, not all memory models consider the ability to form three-way binding structures as a default. The current study, therefore, examined the use of three-way binding structures in associative and source recognition. Results indicate that three-way binding structures are used during recognition, thus challenging memory models that are not capable of representing such structures.

Introduction

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

Memory researchers call this kind of memory structure a three-way binding structure (Humphreys, Bain, & Pike, 1989). In a three-way binding structure, the three components are not simply bound by multiple pairwise associations but in a three-way configural fashion. This three-way configural coding reduces interference among events of overlapping elements, whereas multiple two-way bindings would be vulnerable to the interference. For example, consider that the trading example above was stored by multiple pairwise bindings (or two-way bindings) such as [**player**]-[**team**] bindings and [**context**]-[**team**] bindings (see Fig. 1A). When asked the question "*Which team was McCoy playing for before the trade?*" [*McCoy*] will cue structures such as [*McCoy*]-[*Eagles*], and [*McCoy*]-[*Bills*], while [*pre-trade*] will cue structures such as [*pre-trade*]-[*Eagles*], and [*pre-trade*]-[*Bills*]. Even when taking the intersection of these structures, both [*Eagles*] and [*Bills*] are retrieved, which does not ensure a correct answer. On the other hand, if the example situation was stored by three-way bindings such as [**player**]-[**team**]-[**context**] as a coherent structure (see Fig. 1B), the use of the compound cue (i.e., [*pre-trade*]-[*McCoy*]) leads to the correct response (i.e., [*Eagles*]).

In a controlled laboratory experiment, three-way binding structures have been examined using the ABABr condition in paired-associate learning paradigms (Porter & Duncan, 1953). In a paired-associate learning paradigm, participants are given lists of paired words and are later tested. The ABABr condition manipulates the word pairs in the lists, where words in one list are identical to the other list but paired differently (e.g., A-B, C-D in list1 and A-D, C-B in list2). The ABABr condition resembles the trading example mentioned above when list1 and list2 are substituted with pre-trade and post-trade, and the items A, C with the players (i.e., McCoy and Alonso) and B, D with the teams (i.e., Eagles and Bills).

Not all theories and computational models are capable of representing three-way bindings. Computational models such as Search of Associative Memory (SAM; Gillund & Shiffrin, 1984; Raaijmakers & Shiffrin, 1981), and variants of the Temporal Context Model (TCM; Howard & Kahana, 2002; Lohnas, Polyn, & Kahana, 2015) assume only

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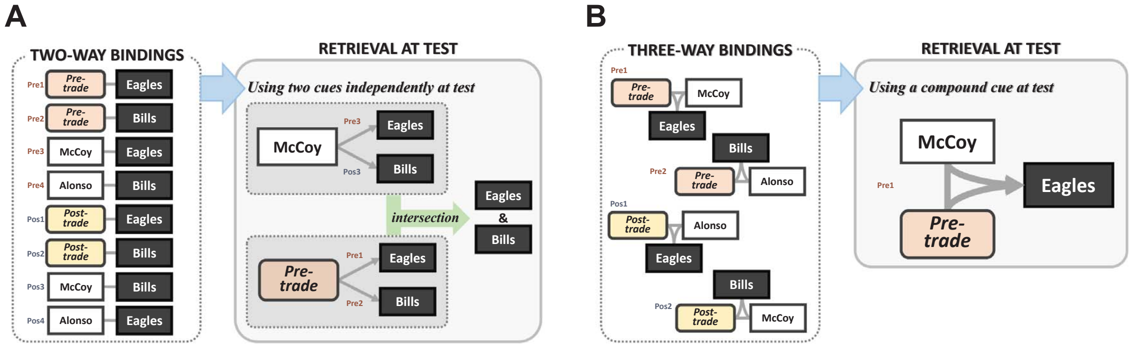

Fig. 1. An illustration of the difference between forming two-way binding structures and three-way binding structures in the NFL trading example. In each panel, the left side shows how the events would be stored, and the right side shows how information could be retrieved when cued with *"Which team was **McCoy** playing for **before the trade**?"* (A) When only two-way binding structures are formed (e.g., [player]-[team] or [context]-[team]), and an intersection of these structures is taken at test (i.e., two two-way bindings) both 'Eagles' and 'Bills' are retrieved and the bindings do not ensure a correct response. (B) However, when forming a three-way binding structure, the use of the compound cue leads to an unambiguous response (i.e., Eagles).

two-way binding representations. These bindings could be in a form of an item-to-item binding, an item-to-context binding, or a combination of the two where the format is not obviously extendable to represent three-way bindings. On the other hand, models such as TODAM (Murdock, 1982), MINERVA 2 (Hintzman, 1984), models in the Retrieving Effectively from Memory (REM; Criss & Shiffrin, 2005; Shiffrin & Steyvers, 1997) framework, and the MATRIX model (Humphreys et al., 1989; Osth & Dennis, 2015) can represent three-way bindings. Although three-way bindings have been only explicitly discussed in the MATRIX model, the other three models (i.e., TODAM, MINERVA 2, and REM) have representation structures that could be easily extended to accommodate three-way binding structure such as simply concatenating additional elements or adding an extra dimension. These models have different mathematical assumptions about how the structures are formed and retrieved and detailed predictions could slightly vary. However, the models are identical in showing above chance performance in the ABABr condition through accuracy or discriminability by combining the matches of the three elements multiplicatively. For illustration, we focus on the MATRIX model, which represents three-way bindings as a mode-three tensor product (i.e., item-item-context).

In Fig. 2 we illustrate that the three-way binding is required to achieve above chance performance in the ABABr task. On the top panel (i.e., STUDY) we assume a simple ABABr condition where A-B, C-D were each studied in context 1, and A-D, C-B in context 2. The next panel shows how these are stored in memory. The left side demonstrates two-way bindings (i.e., item-item, and context-item), while the right demonstrates three-way bindings. The last panel (i.e., TEST) assumes two test trials in an associative recognition task – an intact trial, which comprises a studied pair, and a rearranged trial, which comprises two studied items in a novel arrangement. For both binding structures, global matching is employed at retrieval; the probe at test is compared to all memories and the summed similarity is the basis of judgment. Higher similarity values are assigned to matching cues relative to non-matching cues; the example assigns an arbitrary value for match (i.e., .9) and non-match (i.e., .1). The matches within each trace are multiplied to obtain a probe-to-trace similarity, and the similarities are subsequently summed together. As shown in the figure, using the two-way binding (i.e., left side), the summed similarity between the intact trial and the rearranged trial both produce a value of 3, which makes the model unable to distinguish between the two trials. On the other hand, using the three-way binding (i.e., right side), the intact trial gains higher value (i.e., .756) than the rearranged trial (i.e., .244). Therefore, under this reasoning, two-way bindings are insufficient to distinguish between the two test trials, and the difference can only be created by utilizing three-way bindings where the cues are combined multiplicatively (or in a configural fashion). It is possible that both two-way and three-way bindings could be formed during study. In this case, both kinds of information will be retrieved at test, where signals from the two representations will be merged. Since the signals from the two-way bindings cannot distinguish between the studied and rearranged trials, it will only serve as noise while the discriminating signal will only come from the three-way binding structures.

As shown in the above demonstration, models that only assume two-way binding structures (e.g., SAM, TCM) would predict chance level performance in the ABABr condition. It is not that these models simply did not extend their machinery to test the ABABr condition. Instead, these models would require a major modification in order to explain above chance level performance in the ABABr condition. The modifications would not only be limited to adding a representation structure that could incorporate three-way bindings, but also include control/retrieval mechanisms that are involved, which is beyond a simple extension of the models. For example, in TCM, the representation structure could be modified into an outer product of context-itemA-itemB, similar to the MATRIX model. Then the retrieval process must assume a cue that is comprised of the current context at test and a previous itemA in order to retrieve the paired itemB from the stored representation. Adding such a mechanism could have significant consequences for the results of previous TCM simulations.

Interestingly, evidence for the use of three-way binding structures has mainly been examined with cued recall tasks (e.g., Porter & Duncan, 1953; Shimamura, Jurica, Mangels, Gershberg, & Knight, 1995; Yim, Dennis, & Sloutsky, 2013) where a context of a list and an item is given at test as cues to recall the paired item during study (e.g., what was paired with the word apple in the first list?). Previous studies that used recognition tasks with the ABABr condition did not employ a design that properly tests for three-way bindings. First, studies did not cue both contexts at test and only one context was consistently cued (e.g., Aue, Criss, & Fischetti, 2012; Criss & Shiffrin, 2005; Postman & Stark, 1969; Weeks, Humphreys, & Hockley, 2007). If only one context is constantly cued during test, it is possible for participants to ignore the context that is not cued, which will prevent them from forming binding structures in the uncued context. Consequently, there will be no interference between the two contexts and correct retrieval will be possible without forming three-way bindings.

Another weakness of prior experiments that employ the ABABr condition is that the two contexts were defined as two temporally separated study lists (e.g., first list and second list). This makes it possible for participants to achieve above chance ABABr performance with two-way bindings if memories from the first list are weaker, enabling the participant to infer that weak memories are more likely to be from the first list and stronger memories are from the second list (e.g., Lohnas et al., 2015). Therefore, these previous studies could not provide evidence of using three-way bindings during recognition.