Order-memory and association-memory

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Abstract

Two highly studied memory functions are memory for associations (items presented in pairs, such as "SALT–PEPPER") and memory for order (a list of items whose order matters, such as a telephone number). Order- and association-memory are at the root of many forms of behaviour, from wayfinding to language to remembering people's names. Most researchers have investigated memory for order separately from memory for associations. Exceptions to this, "associative-chaining" models build an ordered list from associations between pairs of items, quite literally understanding association- and order-memory together. Alternatively, "positional-coding" models have been used to explain order-memory as a completely distinct function from association-memory. Both classes of model have found empirical support and both have faced serious challenges. I argue we need models that combine both associative chaining and positional coding. One such hybrid model, which relies on brain-activity rhythms, is promising, but remains to be tested rigourously. I consider two relatively under-studied memory behaviours that demand a combination of order- and association-information: memory for the order of items within associations (is it William James or James William?) and judgements of relative order (who left the party earlier, Hermann or William?). Findings from these underexplored procedures are already difficult to reconcile with existing association-memory and order-memory models. Further work with such intermediate experimental paradigms has the potential to provide powerful findings to constrain and guide models into the future, with the aim of explaining a large range of memory functions, encompassing both association- and order-memory.

Keywords: memory; order-memory; association-memory; models; electroencephalographic oscillations

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I would like to thank Kenichi Kato, Yang Liu and Chris Madan for helpful comments on the manuscript. Supported by the Natural Sciences and Engineering Research Council of Canada.

Introduction

Many of the outstanding puzzling questions in verbal memory research concern how we remember not just which items (stimuli such as words) we studied, but so-called relational memory, memory for associations— pairings of stimuli— and memory for serial order— the precise sequence in which the items appeared (Murdock, 1974). It is easy to come up with examples of everyday situations that demand memory for pairings (e.g., names belonging to faces, Edmonton–Alberta, Toronto–Ontario, famous couples like Michelle–Barack) or sequences (e.g., speeches, recipes, dance choreography). An important research question is whether there is a deep theoretical relationship between association- and order-memory. As an illustration, consider strategies people deliberately adopt to try to boost their memory functions. For example, to remember a particular pairing of words, such as Goat–Garden, an effective strategy is to make up a mental image that combines two words, such as a goat eating vegetables in a garden, known as interactive imagery (e.g., Bower, 1970b; Hockley & Cristi, 1996; Lowry, 1974; Paivio, 1969). To remember precisely ordered sequences of items, such as a list of unrelated words, or in the more famous, classical examples, concepts in a memorized speech or the seating order of dinner guests, there are three popular strategies: The method of loci, wherein one imagines a familiar environment such as one's own house, and places to-be-remembered items along an imagined path (Yates, 1966); the peg list method, wherein one first learns a standard list of "peg" words associated with numerals (1–bun, 2–shoe, etc.), and then associates each word in a new list to its corresponding peg word (e.g., Bugelski, Kidd, & Segmen, 1968; Bugelski, 1968; Bower & Reitman, 1972); and the link method, wherein one forms images combining each word in a list with the subsequent word (e.g., Roediger, 1980). There are plenty of things one might consider to be common between strategies used to learn sets of associations and serial-order information, such as the effectiveness of visual imagery. However, memory for associations and order have been, for the most part, investigated separately and even modeled separately, even by those who have formalized models that can handle both (e.g., Brown, Neath, & Chater, 2007; Humphreys, Bain, & Pike, 1989; Murdock, 1982). I suggest that this may be a bias specific to our recent tradition of research, that is not a particularly helpful conceptual distinction. Indeed, even considering the mnemonic strategies just mentioned: interactive images, used to support memory for associations, are also used in the link method, used to learn an ordered list of items. The peg-list method, used to learn ordered lists, is in fact built upon interactive images that combine a pair of words, one peg word with one target-list word. Similarly, the method of loci can be viewed like the peg-list method, as a way to learn a list of words by forming associations between each list-word and a location or landmark in the memorized environment (Bower, 1970a). These parallels suggest that a goal of memory research should be to investigate association- and order-memory together and to model these paradigms using common mechanisms. Moreover, thinking beyond the lab, there are many real-life situations in which both association- and order information may be required simultaneously, so some kind of synergy, or at least, compatibility, between order- and association-memory must exist, particularly in complex memory behaviours like spatial navigation. It is unclear exactly how to model association- and order-memory together. I suggest that new experimental designs may hold the key to guiding theory in the direction of unified models of relational memory.

I first summarize a major, ongoing, unresolved debate about whether or not the representation of serial lists is based on inter-item associations and argue that the polarized nature of this debate has exhausted its utility; rather, there is enough evidence for and against both classes of model, so we should consider hybrid mechanisms. I then review the current state of evidence for a specific hybrid model that has received considerable attention in neuroscience fields, based on neuronal population oscillations. Next, I discuss a surprising recent finding, that judgements of relative order produce different patterns of accuracy and response latency depending on how one asks the question, and show that this finding presents interesting challenges for both chaining and positional-coding models of serial-order memory, as well as potential hybrid models. Finally, I discuss hybrid paradigms, such as tests of the order of constituent items within associations, and their potential to guide model-development.

The debate between associative-chaining and positional-coding models

As a way to isolate association-memory, the most extensively investigated paradigm has been cued recall of paired-associates. Stimuli, most often words, are studied in pairs, and memory for those pairings is later tested by presenting one word (e.g., Goat) and asking for its target (Garden, in the example given above). Likewise, the most extensively investigated paradigm for understanding order-memory has been serial recall of lists. In serial recall, a participant studies a set of stimuli (often words), and then is asked to recall the just-studied list from start to finish, in order. If the goal is to understand association- and order-memory together, these two paradigms would therefore seem the most sensible place to start. Indeed, Ebbinghaus (1885/1913) suggested *associative chaining,* that people build memory of a serial list from associations between pairs of items (Figure 1a), an idea that also appealed to James (1890). After learning even just the associations between pairs of adjacent items, the participant could be able to retrieve the list in order: Starting with item A, retrieve the item it was paired with (like cued recall of a pair), which should be B. Once retrieved, item B can then serve as the cue for the next item, which should be C (B may also retrieve A, but it is plausible to assume that the participant can at least rule out the item just-recalled). Associative-chaining models can, in principle, include remote associations, which link non-neighbouring items, as well, but Lewandowsky and Murdock (1989) simulated an associative chaining model with only nearest-neighbour associations. This model successfully fit a broad range of well established empirical findings, including the large advantage in memory for items close to the beginning and smaller advantage at the end of the list, how this flips when participants recall the list in backward order, how memory changes as the number of items in the list increases and as the list is presented faster. Importantly, associative chaining, quite literally, implies that order- and association-memory have something in common.

In the latter half of the twentieth century, empirical findings emerged, that seemed to challenge chaining, and we will examine a few of these below (data from alternating lists, fill-in errors and the locality constraint). This motivated researchers to design models of serial recall that, by design, avoided direct associations between pairs of items, which we term *positional-coding* models[1] (e.g., Conrad, 1965; Brown, Preece, & Hulme, 2000; Brown et al., 2007; Burgess & Hitch, 1999; Henson, 1998; Lewandowsky & Farrell, 2000). In these models, an ordered list is remembered without item–item associations, by referencing items to a separate representation from which the order can be inferred (Figure 1b). After learning each list item by linking it to a position code, the model can read out the list in order by cueing with the code for position 1, and trying to retrieve the

[1] Note that modellers often argue that rather than a code with absolute position labels, a code with only relative "order" information is more realistic. Because here we focus primarily on the distinction between models with and without direct item–item associations, we collectively refer to position- and order-coding models as "positional-coding" models, but this should not be taken as an endorsement of position- over order-coding.

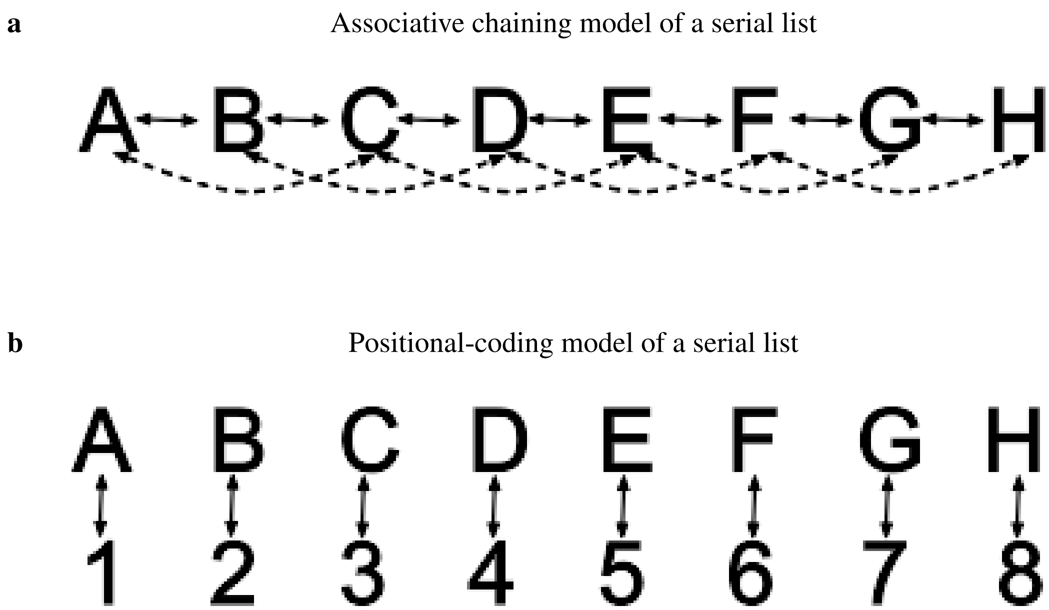

Figure 1. Schematic depictions of two classes of models of serial lists. **a,** An associative-chaining model that includes bidirectional associations between adjacent items, as well as remote associations that are weaker. **b,** A positional-coding model that is composed of (bidirectional) item–position associations but unlike associative-chaining, no direct item–item associations. Position codes are denoted with numbers for illustration only; specific positional-coding each make specific assumptions about what the ordered representation is. All such models assume that nearby position or order codes are similar, and therefore, confusable with one another. Note that both classes of model use some sort of associations; the important distinction is that in chaining, those associations are directly between items, whereas in positional-coding, inter-item associations are prohibited; rather, each item is association to a separate token from which order can be inferred.

item associated with it (A), then proceeding to cue with the next position (2), and so on. Positional-coding models have also been shown to fit a broad range of empirical benchmark findings in serial recall, including the advantage for items close to the beginning and end of the list and patterns of confusion people make, recalling an item out of order. The designers of these models have pointed out that, in most positional-coding models, recalling the current item is not influenced by whether or not the model could recall the prior item. In associative-chaining models, the retrieved item becomes the cue for the next item, so this could be a profound way in which the two classes of model differ, and the immunity of memory of a list item to memory of prior items may help positional-coding models fit certain findings (but see the discussion of alternating lists below). Granted, it is imprecise to say that positional-coding models do not rely on associations; memory of a list is built from associations between an given item and a corresponding position code. The key distinction that modellers have found to be important is that those associations are each between an item and a position-code, never directly between two items, as is done in an associative-chaining model.

Despite positional-coding having been proposed as an alternative to associative-chaining, positional-coding models do not strictly require memory for serial-order and associations to be

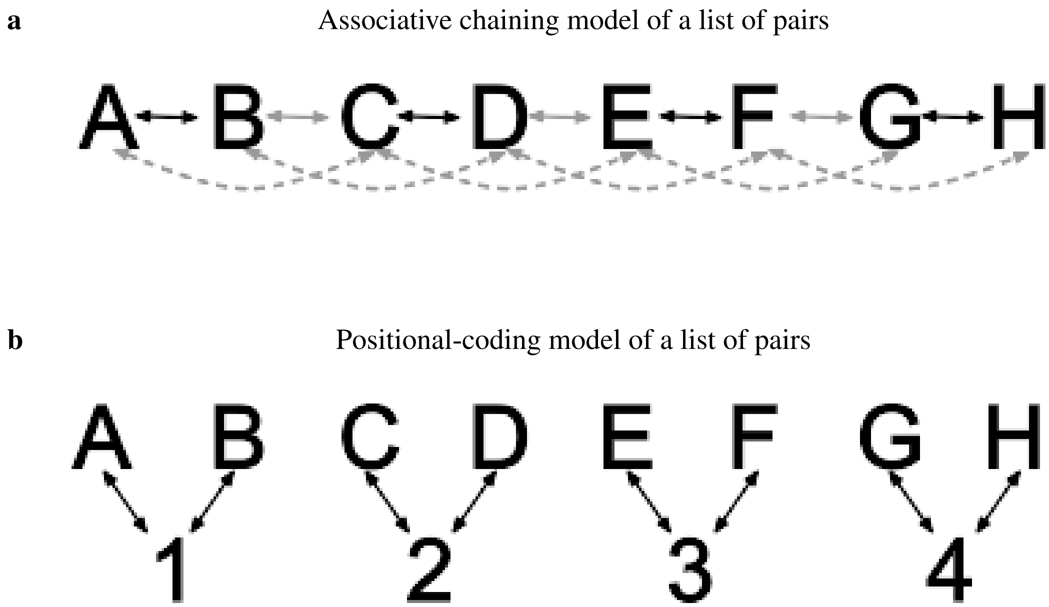

Figure 2. Schematic drawings of how the two classes of models of serial lists can be adapted to model memory for pairs, denoted AB, CD, EF, GH. **a,** An associative-chaining model that includes bidirectional associations between adjacent items, as well as remote associations that are weaker. The modification for pairs is that associations that cross from one pair to another are deliberately made very weak (depicted here in medium-gray). **b,** A positional-coding model that is composed only of (bidirectional) item–position associations. In this figure, items to be paired are linked to the same position code; however, it may alternatively be sensible to link items to different position-codes that are extremely close together (e.g., A associated with 1, and B with 1.1; C with 2, D with 2.1, etc.).

modeled separately; Caplan (2005) suggested positional-coding models could be used to model association-memory (Figure 2b). The idea is simple: instead of linking each item to a different position, link paired items to the same position (or alternatively, link pairs of items to extremely close positions. For example, item A could be given the position 1.0 and item B, 1.1; item C would then continue with a well-spaced position, 2.0, and so on). To do cued recall, the model is given the cue item (e.g., A), attempts to retrieve its positional-code (1), and then uses that retrieved position as a cue to retrieve the items associated with it (A and B, but A can be easily ruled out because it was the cue itself). A model like this should predict that errors in a paired-associate task should show a tendency to occur from nearby positions. Such adjacent intrusions have indeed been reported (Caplan, Glaholt, & McIntosh, 2006).

With or without the assumption that order-memory and association-memory have anything in common, the debate between chaining and positional-coding models of order-memory is still quite relevant to understanding both order- and association-memory. I briefly review and critique the current state of the debate between these two classes of models. For more insight into both sides of the debate, I refer the reader to the highly influential article by Henson (1998) and a more recent perspective by Hurlstone, Hitch, and Baddeley (2014), and to Farrell, Hurlstone, and Lewandowsky

(2013); Kahana, Mollison, and Addis (2010); Kahana (2012); Serra and Nairne (2000); Solway, Murdock, and Kahana (2012) for some recent findings that have challenged some of those arguments and have suggested associative-chaining should be given fresh consideration.

Relevance of a limited scope for the debate. One factor that may have led positional-coding models to seem better supported over associative-chaining than they are is that authors frequently begin by restricting their arguments to only a limited scope of experimental procedures. The main such boundary condition is short lists. Hurlstone et al. (2014), for example, contend that their review of the literature suggests associative chaining is ruled out for so-called "short-term memory" tasks, whereas at longer list lengths (beyond their scope), associative chaining may play a role. However, this boundary condition does not seem clear-cut. There is little consensus about which timescales qualify as "short-term memory" (e.g., Crowder, 1982). Many contemporary models are scale-invariant, assuming that common processes apply across a large range of list lengths (e.g., Brown et al., 2007; Howard & Kahana, 1999; McElree, 2006). Moreover, although some of the findings that are considered important by positional-coding advocates are found in short lists (e.g., 6-item lists alternating in phonological confusability; see next section), others are not so short. For example, the "interposition" results (also discussed below) are typically investigated with three "chunks" of three items each, nine items in total (Henson, 1998; Hurlstone et al., 2014; Ryan, 1969), which may very well be entering clear the presumed associative-chaining territory (e.g., Caplan, Madan, & Bedwell, in press; Solway et al., 2012). Many of the short lists used to provide support for positional-coding include end-of-list distractors. In the very influential debate about a related list-memory paradigm, free recall (remember a set of words without regard to their order), tasks that included an end-of-list distractor were considered "long-term" (Atkinson & Shiffrin, 1968; Bjork & Whitten, 1974; Brown et al., 2007; Crowder, 1982; Howard & Kahana, 1999; Nairne, 2002; Raaijmakers & Shiffrin, 1981). Thus, the limited-scope framing of the debate seems difficult to justify. A meaningful theoretical account of order-memory should be able to handle a broad range of list lengths.

We next consider some of the more compelling arguments that have been advanced in favour of positional-coding over associative-chaining models.

Alternating lists

One empirical finding that is often interpreted as support for positional-coding and against associative-chaining models comes from lists of consonants that differ in terms of whether the items are confusable (consonant-names that rhyme, like b, d, t) versus non-confusable (or less confusable, with names that do not rhyme, like k, r, q). As one might expect, lists composed entirely of confusable letters (we can write this pattern *CCCCCC* for a list of six different letters, where *C* indicates a confusable letter in a particular list-position) are recalled worse than those composed entirely of non-confusable letters (which we can write *NNNNNN*). The interesting result is what happens to non-confusable items when they are embedded in mixed lists that alternate between confusable and non-confusable items (patterned like *CNCNCN* or *NCNCNC*). The so-called "immunity" effect (Baddeley, 1968; Farrell, 2006; Henson, 1998; Henson, Norris, Page, & Baddeley, 1996) is the surprising, but much-replicated result that non-confusable items are recalled with nearly the same probability whether they are embedded in a pure list of non-confusable items (*NNNNNN*) or in an alternating list (e.g., *CNCNCN*). In other words, they appear to be immune to list-composition. This was thought to contradict associative-chaining models. The argument was that in a chaining model, one item, when retrieved, becomes the cue for the next item; thus, a non-confusable item in a pure list should be at an advantage, being cued by a (preceding) non-confusable item, than in a mixed list, where it is cued by a (preceding) confusable item. The claim was that the immunity effect rules out chaining, and that instead, confusability effects must occur at a very late stage (like red-integration, the stage when the participant takes the noisy representation they retrieved and "cleans up" this representation to decide on a valid response), following the main action of the model. This account was compatible with several positional-coding models, which included the assumption that the outcome of recall of one item does not affect retrieval of the next item.

However, there are problems with using the immunity result to support positional-coding and rule out associative-chaining. First, the immunity result itself is fickle; Farrell and Lewandowsky (2003) showed that immunity is very likely due to enhancement and impairment effects happening to approximately cancel. For example, as Farrell and Lewandowsky (2003) argued, there are fewer non-confusable items in alternating lists than in pure lists; this may make non-confusable items even more non-confusable, when the model selects its response, in alternating than pure lists. This means what looks like immunity in the data does not literally mean that non-confusable items are unaffected by list composition (pure or alternating). It may even be the case that recall of an item is in fact influenced by recall of the previous item, consistent with an associative-chaining model, which produces the expected disadvantage for non-confusable items in alternating lists, but this is then offset by other advantages for non-confusable items.

One would think that, whereas immunity effects in alternating lists are not easy to explain with chaining model, findings of a lack of immunity in lists alternating in some other item-property would be considered support for the presence of the item–item cueing expected by chaining models and in turn, challenging for positional-coding models that assume recall of one item does not affect the cue for the next item. This kind of result has been replicated with manipulations of word-frequency, referring to how common a word occurs in natural language (Hulme, Stuart, Brown, & Morin, 2003; Morin, Poirier, Fortin, & Hulme, 2006). Pure lists composed of high-frequency words were recalled better than pure lists composed of low-frequency words, but interestingly, lists alternating in word-frequency were recalled worse than pure-high- but better than pure-low-frequency lists. This is what one would predict based on associative-chaining. Caplan et al. (in press) replicated this finding and ruled out several positional-coding-friendly accounts. Thus, the immunity effect may be peculiar to phonological confusability, and to strictly alternating lists (Farrell & Lewandowsky, 2003).

Approximate-immunity may therefore be caused by some idiosyncratic strategy. An example is the so-called "streaming" account, the idea that participants can conceptualize an alternating list as two interleaved "streams" (sub-lists), one composed of confusable items and the other composed of non-confusable items (Fabiani & Donchin, 1995; Farrell & Lewandowsky, 2003; Hunt & Lamb, 2001). If item–item cueing effects were present in lists alternating in phonological confusability, streaming would obfuscate evidence of item–item cueing, because the retrieval of the chain(s) would be from item i to item $i+2$, which are of the same stimulus type in strictly alternating lists. Thus, lists alternating in phonological confusability may simply not be diagnostic of chaining versus positional-coding. Rather, word-frequency is a subtle enough item property. It is hard to imagine that participants could stream lists alternating in word-frequency. As just mentioned, word-frequency produces serial-position effects consistent with associative chaining. Imageability (referring to how easy participants find it to construct a visual image representing a word) might be conducive to streaming, and interestingly, Caplan et al. (in press) found evidence for both positional-coding-like and associative-chaining-like characteristics in lists alternating in imageability.

There is one final problem with the idea that the immunity effect supports positional-coding models. The argument was that the immunity effect suggests phonological confusability effects occur at the very last, redintegration stage of a model. It is clear that this account does not rely on associative-chaining. But, neither does it rely on positional-coding. That is because certain item-properties may make an item individually easier to produce as responses (e.g., precise spelling or phonology), but have no influence on how effective the item may be as a cue for the next item (e.g., features reflecting the deeper meaning of the item). A redintegration-locus mechanism could apply to an associative-chaining model as well, as long as the additional features provided at the redintegration stage do not contribute to the effectiveness of the item as a cue for the next item.

In sum, alternating-list data do not cleanly select between associative-chaining and positional-coding models. Rather, a close examination of alternating-list findings shows that they are compatible with associative-chaining, and in fact raise new challenges for positional coding models.

Fill-in errors

We next consider a type of error that has been thought to support positional-coding over associative-chaining models. A typical positional-coding model will go on to probe with each position in turn, regardless of the outcome of the previous position-probe. Sometimes the model will miss item i. That often happens because nearby position-codes are assumed, by design, to be similar to one another, and therefore confusable. When item $i+1$ is stronger than item i, the position-probes for i might instead retrieve item $i+1$. When this happens, the model proceeds to probe with the position of item $i+1$. However, item $i+1$ was just recalled, and as already mentioned, a standard assumption in most models is that models (and participants) are wise enough not to repeat the item they just recalled. Again, because the position of $i+1$ is similar to (aka confusable with) the position of i, the model is therefore very likely to next recall item i in response to position-probe $i+1$. Thus, if the list were ABCDEF, the model might recall ABDCEF, transposing C and D. These so-called "fill-in" errors are more frequent than so-called "in-fill" errors, wherein the participant continues on to recall item $i+2$ (ABDEF), possibly never returning to item i (Farrell et al., 2013; Henson, 1998; Page & Norris, 1998; Surprenant, Kelley, Farley, & Neath, 1999). Positional-coding modellers have further argued that associative-chaining models predict the opposite result: more in-fill than fill-in errors, because, once item i is skipped and item $i+1$ is retrieved, item $i+1$ will become the cue for the next item. A chaining model would thus continue to recall the chain in the forward order.

However, there is a problem with this logic. The overwhelming evidence is that associations are symmetric, termed "associative symmetry" (Asch & Ebenholtz, 1962; Kahana, 2002), and one of the more thoroughly studied chaining models includes this property (Lewandowsky & Murdock, 1989), because it relies on associations that are formed using a mathematical operation called "convolution" (Farrand & Jones, 1996; Lewandowsky & Murdock, 1989; Murdock, 1982). Assuming each item is represented by a vector (essentially, an ordered list of feature values), convolution is calculated from sums of products of features of a pair of items. As it turns out, the convolution of item A with item B is identical to the convolution of item B with item A (in mathematical terminology, convolution is commutative). Empirical evidence is consistent with the assumption that serial lists are built from associations that are either symmetrical in strength (Caplan et al., 2006; Caplan, Glaholt, & McIntosh, 2009), or nearly so (Kahana & Caplan, 2002). To move forward in a serial list without backtracking, a symmetric model must rule out the immediate-backward associates. This is usually handled with response suppression (Lewandowsky & Murdock, 1989): keeping track of recalled items and not considering them as further response candidates (see also Murdock, 1993, 1995). However, if item i is skipped when item $i+1$ is recalled too early, item i would not be suppressed, and thus will still be a candidate response when item $i+1$ is used as a retrieval cue; because the association from item $i+1$ to item i can be just as strong as from item i to item $i+1$, a symmetric chaining model would clearly predict a high rate of transitions from item $i+1$ back to the skipped item i— namely, fill-in errors. Clearly, then, findings of a high rate of fill-in errors do not pose seriously challenges to symmetric associative-chaining models.

Finally, Dennis (2009) proposed a variation on the typical chaining model: one in which the list is retrieved all at once, rather than one item at a time, and then proceeds to output the list one item at a time at at an approximately constant rate. In part due to recall being constrained by associations anchored to both the beginning and the end of the list at once, Dennis' model could produce the fill-in error pattern, as well as the alternating-list patterns (previous section) and serial-position-preserving prior-list intrusions, another finding that had been thought to support positional-coding and challenge chaining model (see end of the next section).

Order errors and the locality constraint

Related to fill-in errors, the so-called "locality constraint" (Henson, 1998) is the observation that items recalled out of order tend (including items mistakenly recalled from previous lists) to be recalled at nearby positions (Estes, 1972; Lee & Estes, 1977). For example, the item presented in position 4 would be more like to be recalled at position 5 than at position 6, and more likely at position 6 than position 7, and so on. This has been taken as evidence of positional coding, reflecting the built-in property that nearby position-codes are more confusable with one another than distant position-codes.

The first thing to note is that the locality constraint, as an empirical finding, may be over-estimated. Solway et al. (2012) showed that the locality effect appears more pronounced if one considers all recalls, because correct recalls have a distance of 0 (item i recalled in position i). When they restricted their analyses only to responses that followed the first order-error, they found the locality effect nearly vanished, even at list lengths as short as ten items.[2] Solway et al. (2012) took the in-fill argument (see previous section) further, arguing associative-chaining models should predict that after an order error, the next item recalled should cluster near the position of the out-of-order item rather than around the correct position. For example, suppose a model recalls AE. According to a positional-coding model, the next response should be cued by position 3, in which case C should be the most likely response. An associative-chaining model would instead assume that the next response will be cued by E, in which case D and F would be the most likely responses (assuming a model built upon symmetric associations). This pattern of errors clustering around the position of the erroneously recalled item rather than the response-position, had been reported by Klein, Addis, and Kahana (2005) and was replicated by Solway et al. (2012). This finer-grained look at locality constraints actually argues in favour of chaining models.

The four data sets that Solway et al. (2012) analyzed showed little evidence for the kinds of errors expected based on positional-coding (errors clustered around the correct recall position), but Hurlstone et al. (2014) suggested this could be due to participants not having an easy way to skip output positions. The Caplan et al. (in press) study discussed above did allow participants to

[2]Hurlstone et al. (2014) misconstrued this in their footnote #3, asserting that Solway et al.'s lists contained 19 items, whereas they actually analyzed data sets with 10, 13 and 19 items.

skip positions, by typing the word “PASS” any number of times. Interestingly, with a relatively short list length (eight words), there were indeed high levels of errors clustered around the correct position (Figure 3a,b), in line with Hurlstone et al.’s logic, even when conditionalizing as prescribed by Solway et al. (2012); but there were also high levels of errors clustered (nearly symmetrically) around the position of the out-of-order item (Figure 3c,d). This composite finding makes it seem quite plausible that both associative-chaining and positional-coding operate even within the same task.

Solway et al.’s flat distance functions may be incompatible with strict positional-coding models (Burgess & Hitch, 2006), but with a modification, positional-coding models may be able to accommodate even the pattern of greater temporal clustering around the serial-position of error-responses— namely, by assuming that when an item is retrieved, it retrieves its position code, and that retrieved position code becomes part of the cue for the next item. The notion of retrieved position, formally suggested by Caplan (2005) for serial-recall (and see Brown et al., 2000; Rehani & Caplan, 2011), bears resemblance to the notion of retrieved context, which is a central concept in the design of the Temporal Context Model as it has been applied to free recall (Howard & Kahana, 1999)[3]

Other findings related to the locality constraint include intrusions (items not on the current list) from prior lists tending to cluster around their original position (so-called “protrusions”), and items in grouped lists tending to be recalled in the wrong group, but in the correct within-group position (so-called “interpositions”) might be evidence in favour of positional-coding, but it is a mistake to infer that these findings argue against the simultaneous presence of associative chaining. A model that *only* includes associative chaining seems untenable— as is a model that only includes positional coding. Collectively, the lack of resolution to the debate between positional coding and associative chaining makes hybrid models quite plausible.

“Hybrid” models

If, as I argue, the evidence points to hybrid models, the challenge becomes figuring out how associative-chaining and positional-coding should be combined to approximate human behaviour. Some modellers have already attempted this. One particular hybrid model has become popular in behavioural and cognitive neuroscience. It is based on the idea that theta oscillations, rhythmic neural-population activity in the range of 4–8 Hz (but sometimes more generously defined to span 3–12 Hz), can serve to store and retrieve relative-order information. The idea, termed phase-coding, is that if a set of item representations is activated in sequence, each item will be active at a different point (phase) of a cycle of the rhythm. Thus, phase information can be used to infer order. Early evidence for this notion came from rat hippocampal recordings, which suggested that a brief moving-window sub-sequence of a rat’s path through space was activated as the rat ran around an environment, and with a consistent (and consistently evolving) relationship to theta-rhythm phase (O’Keefe & Recce, 1993). Lisman, Idiart and Jensen developed computational models that exploited theta-phase coding (e.g., Jensen & Lisman, 2005; Lisman & Idiart, 1995), assuming that faster, gamma-band oscillations ($>$ 30 Hz) were multiplexed within the slower theta rhythm, and each gamma cycle reflected the activation of a population-coded item (Figure 4). In their model,

[3]Such a modification would need to be pursued with caution, because positional-coding models have been sold in part due to their *lack* of dependence of one item on the outcome of the previous recall, so there is some danger that retrieved context could undermine some of what have been considered strengths of positional-coding models.

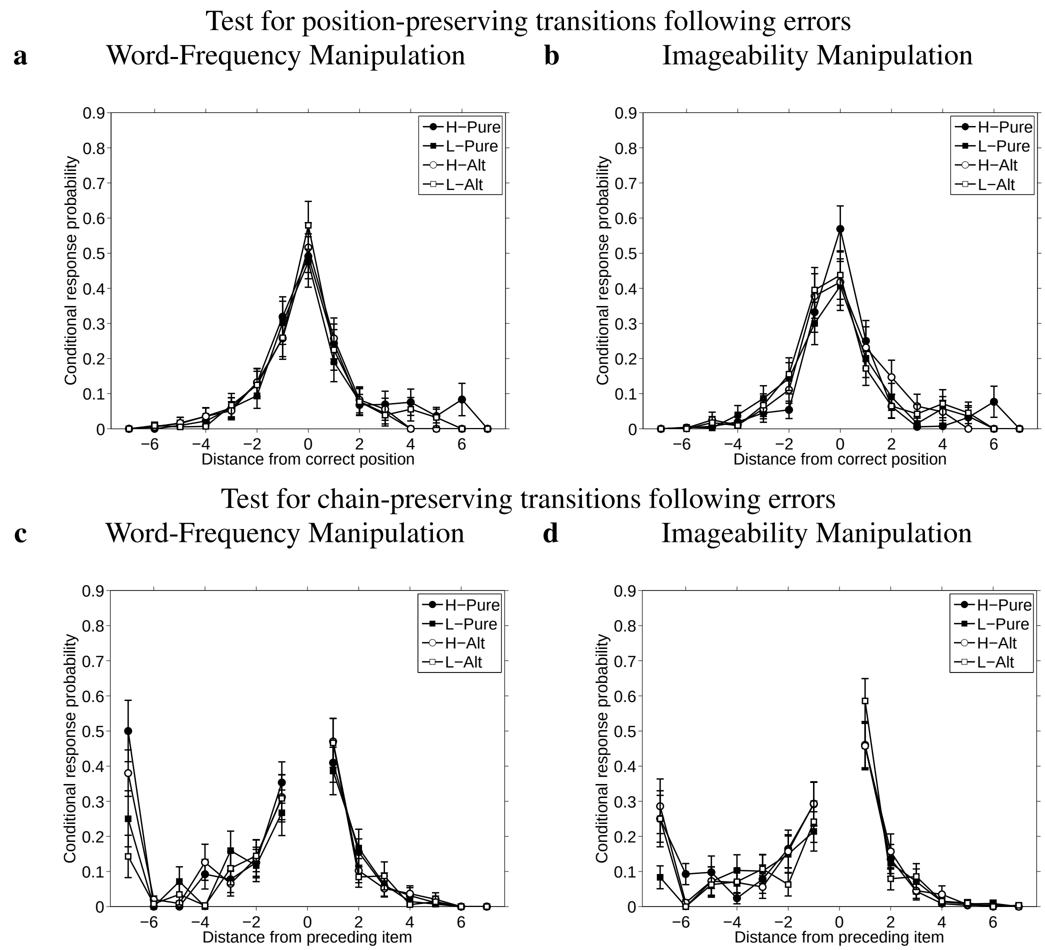

Figure 3. Conditional-response probability functions, for responses following the first order-error (following Solway et al., 2012), based on data reported by Caplan, Madan and Bedwell (2014), for manipulations of word-frequency (a,c) and imageability (b,d). **a,b,** Positional distance functions, plotting conditional response probability as a function of lag from the item's correct position. Distance=0 are responses of items in their correct position, and nearby lags may be taken as evidence of positional-cueing. **c,d,** Temporal distance functions, plotting conditional response probability as a function of lag from the prior item's serial position. Legend abbreviations refer to list conditions, as follows. H-Pure, L-Pure: Pure lists of high or low (frequency/imageability) words, respectively. HL-Alt, LH-Alt: Alternating lists starting on a high or low item, respectively. Error-bars are 95% confidence intervals based on standard error of the mean. Panels a and b are reprinted from Caplan, Madan, and Bedwell (2014), with the permission of the Psychonomic Society

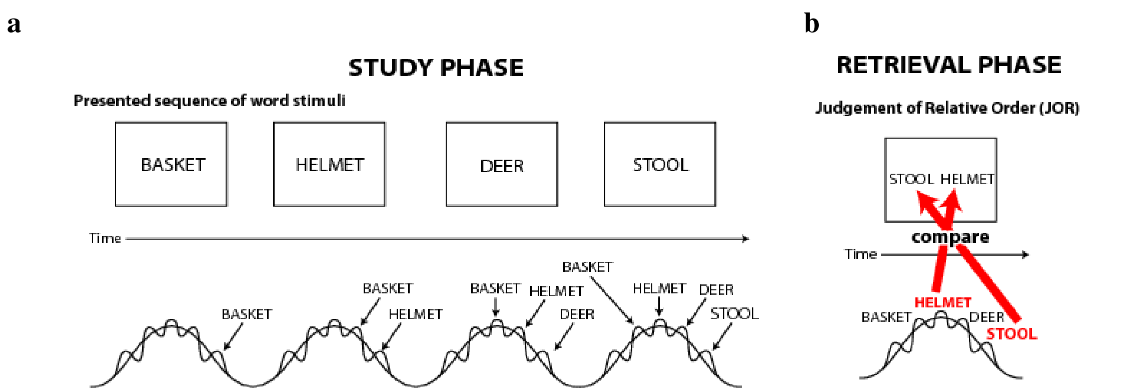

Figure 4. Illustration of theta/gamma multiplexing models (e.g., Jensen and Lisman, 2005). Each list item is presumed to be activated within a single, faster, gamma cycle. As the participant learns or recalls the list, using a given item as the cue, the next few items activate in a sequence of a few gamma cycles. *Not depicted*, they assumed that the items were stored within an associative network; thus, in serial recall, the sequence is read out by chaining, but theta-phase provides and accompanying position-code. Absolute or relative positions of list items can thus be inferred by reading off the theta-phase at which a given item activates. The left panel illustrates a hypothetical study phase, during which a sequentially presented list is encoded alongside a theta rhythm. Serial recall would proceed similarly, with an item cue starting the recall sequence. The right panel illustrates how this model could be used to do the judgement of relative order task, reading off the phases of two list items, and then comparing them.

they assumed these item-representations were stored in an associative network; thus, when one item was retrieved, it would then cue the next item (hence, chaining-like). When activated along with a theta rhythm in the local field potential, the phase at each a particular item activated could be "read off" (Jensen, 2001), so absolute or relative position could be inferred (resembling a positional code).

Such ideas led other researchers to test for the presence of theta activity during relational memory tasks requiring participants to judge contextual features (reviewed by Nyhus & Curran, 2010), and has been reported in virtual navigation tasks, which presumably place high demands on relational (spatial) memory (Caplan, Kahana, Raghavachari, & Madsen, 2001; Caplan et al., 2003; Cashdollar et al., 2009; de Araújo, Baffa, & Wakai, 2002; Ekstrom et al., 2005; Kahana, Sekuler, Caplan, Kirschen, & Madsen, 1999). And, theta oscillations have been observed broadly during memory tasks even when no relational memory is required (e.g. Klimesch, 1999; Nyhus & Curran, 2010; Raghavachari et al., 2001). One study found more direct support for the idea that theta oscillations are instrumental in supporting relational memory. Caplan and Glaholt (2007) recorded oscillations while participants studied pairs of words (associations) as well as word-triples (brief sequences of three items), and were later tested with directional cued-recall probes. Theta oscillations, detected over fronto-central electrodes and left centro-parietal electrodes, covaried with memory outcome: participants with more theta oscillations had higher accuracy and faster response times. This result is consistent with theta rhythms contributing to the effectiveness of memory for both associations and order.

One puzzle is why theta oscillations appear to be present during item-memory tasks that should place very little demand on relational memory (e.g., Doppelmayr, Klimesch, Schwaiger, Stadler, & Röhm, 2000; Düzel et al., 2003; Guderian, Schott, Richardson-Klavehn, & Düzel, 2009; Klimesch, 1999; Raghavachari et al., 2001; Rizzuto et al., 2003; Rizzuto, Mamelak, Sutherling, Fineman, & Andersen, 2005). Because brain-activity is observed during a task, but not experimentally manipulated itself, it is always possible that even behaviour-related activity is a spectator process, present during the behaviour, but not contributing directly to the behaviour. Chen and Caplan (in preparation) tested this possibility. Theta oscillations have been found to differentiate effective study of an item, being more prominent while participants study items that are later recalled versus items that are later forgotten; this is known as a "subsequent-memory effect." Similarly, theta oscillations have been found to differentiate successful (activity during "hits") from unsuccessful (activity during "misses") trials during the recognition-memory test, known as a "retrieval-success effect." Chen and Caplan replicated both of these effects. They then reasoned, if theta oscillations were important to recognition-memory behaviour, those effects should also explain *individual differences* in performance on the task. In other words, a participant who has more of a difference in theta oscillations between later-remembered and later-forgotten items should thus be performing better on the task than a participant who has less such difference. However, theta oscillations only explained within-subjects memory effects, and fell far from significantly covarying with individual differences in recognition-memory performance. Meanwhile, alpha oscillations ($\sim$10-Hz rhythms over the vision regions in the back of the head, thought to reflect visual inattentiveness) passed both tests, explaining both within- and between-subjects differences in memory outcome, suggesting that the experiment was not simply underpowered. Chen and Caplan (in preparation) reasoned that theta oscillations may be present during item-memory tasks not because of the item-memory demands. Instead, theta oscillations may be boosting memory in relational ways, which would be seen if association- or order-information were tested (as in Caplan & Glaholt, 2007). In the case of a simple item-recognition experiment, perhaps theta oscillations during study, and even test, support relational memory retrieval that is never tested— in other words, preparing the participant to do a memory task that never comes. This may also explain why some studies have even reported reduced theta activity related to subsequent memory as tested with free recall (Long, Burke, & Kahana, 2014).

Evidence for gamma oscillations reflecting item-memory is more challenging to evaluate, because scalp-muscle artifacts have a large amount of power in the gamma band, and what's more, gamma-band signal is severely attenuating due to the low-pass filtering action of the skull (e.g., Luck, 2005; Schomer & Lopes da Sliva, 2011). Intracranial EEG, which records EEG from contacts placed just over the cortical surface (pia) or from depth electrodes that are driven through brain tissue, bypass muscle artifact and the skull, and are much closer to their sources, so they can pick up gamma oscillations that are unlikely to synchronize over large distances across the brain. Intracranial EEG findings are indeed suggestive that gamma oscillations play a role in item-memory (Howard et al., 2003; Long et al., 2014; Sederberg, Kahana, Howard, Donner, & Madsen, 2003) but gamma oscillations appear to have a complex specific relationship to memory (Burke et al., 2014) that goes beyond the theta/gamma model.

In sum, there is some very rudimentary support for theta and gamma oscillations contributing to memory for associations and serial lists, but this evidence is not specific enough to support the theta/gamma hybrid model over alternative notions of the possible cognitive functions of theta and gamma oscillations. Although this model should continue to be investigated, other ways of building hybrid models should also be pursued. For example, hybrid models have been developed to explain how participants identify words (in other words, thinking of a word as a sequence of letters). These models, coincidentally, are built on associations that are implemented with convolution, both between "items" (letters) and between items and vectors representing position-codes (Chubala & Jamieson, 2013; Cox, Kachergis, Recchia, & Jones, 2011; Hannagan, Dupoux, & Christophe, 2011). With care, these models might be extended to model episodic memory for serial lists.

The congruity effect in judgements of relative order and constraints on models

Nearly all the evidence informing the debate between associative-chaining and positional-coding as representations of order in memory comes from procedures derived from serial recall. However, serial recall confounds item-memory with order-memory (Healy, 1974). After all, how can one remember an item in its correct position without being able to remember the item itself? A similar point has been made about cued-recall confounding item- and association-memory (Criss, Aue, & Smith, 2011; Madan, Glaholt, & Caplan, 2010). In the serial-reconstruction procedure (Healy, 1974), the participant is given all items at time of test, but in a shuffled order. The participant has to simply reconstruct the order of the list, but is not responsible for producing (recalling) the items themselves (e.g., Farrand & Jones, 1996; Healy, 1974). However, the probe in reconstruction has an order to it, so even the reconstruction technique may be more complicated than it first seems.

Less explored, and arguably simpler, are procedures wherein the experimenter asks the participant directly to make judgements of position or order, which were traditionally called judgements of absolute and relative recency (Hacker, 1980; Muter, 1979; Yntema & Trask, 1963). In these procedures, the participant is asked to judge items' positions on a target list of single- (absolute judgements) or two-item (relative judgements) probes. A parsimonious account would be to have a single model that could simultaneously explain serial recall (and reconstruction) as well as judgements of order.

Taking the example of judgements of relative recency (JORs), positional-coding models could provide a parsimonious account of order-memory by adding the (testable) assumption that the representation of order used in serial recall is the same as is used to make order-judgements. Brown et al. (2007) proposed just this, that JORs should be thought of just as comparative judgements more generally, and that accuracy should be determined by the discriminability of item-presentation times. They proposed that this would enable their model, SIMPLE, to produce the standard benchmark findings (e.g., Yntema & Trask, 1963) of bowed serial-position effects and a distance effect (relative-order probes are easier the larger the temporal distance between them). However, it is unclear how SIMPLE could handle judgements of relative order in short lists, which appear to depend relatively little on discriminability; rather, short-list JORs resemble a strategy of sequential, self-terminating search (Chan, Ross, Earle, & Caplan, 2009; Hacker, 1980; McElree, 2006; Muter, 1979).

Alternatively, chaining models may be more easily adapted to support sequential, self-terminating search, and fit the short-list JOR data better. That is because chaining models (with the exception of Dennis, 2009) already assume sequential readout of a list. However, it is unclear how a chaining model could handle long-list JOR data, which better resembles direct-access models, where the positions are retrieved and directly compared (Liu, Chan, & Caplan, 2014; Yntema & Trask, 1963).

Even if a chaining model or a positional-coding model can be shown to fit JOR data, Chan et al. (2009) found that JOR behaviour depends on how the participant is asked to respond. Participants asked to choose the item that came earlier in the list responded faster at early serial positions, whereas participants asked to choose the item that came later in the list were faster at late serial positions. This is despite the fact that both instructions are logically equivalent: in a two-item probe, the item that is not the later item must be the earlier item, and vice-versa. This "congruity effect" was found both in short lists, 3–6 items, with response time as the dependent measure (Chan et al., 2009), and in longer lists, up to 10 items, in error rates as well (Liu et al., 2014), and even in judgements of a very long, overlearned, semantic-memory list: the English alphabet (Liu & Caplan, in preparation), suggesting that the congruity effect is quite general.

The congruity effect, although previously overlooked in memory research, is quite clearly expected (Liu et al., 2014; Liu & Caplan, in preparation) if one considers JORs a type of comparative judgement (Brown et al., 2007). That is because in comparative judgement research, congruity effects are quite common (although rare with error-rate measures). Interestingly, if one looks at the data reported by Chan et al. (2009) and Liu et al. (2014), one can see that error rates are fairly low (around 10%) for short lists, but then begin to rise around list-length 6–8, quite close to Miller's estimate of the capacity of participants to make judgements along a single continuous stimulus-property (Miller, 1956). In the case of judgements of relative order, that stimulus dimension (time or position) may thus function very much like any other stimulus dimension, as Brown et al. (2007) proposed.

Liu et al. (2014) found that the congruity effect could be well fit by a self-terminating search model (Hacker, 1980; McElree, 2006) if it could switch directions depending on the instruction (searching the list in the forward direction for the "earlier" instruction and in the backward direction for the "later" instruction), but only at short list lengths. They noted that the Hacker (1980) sequential, self-terminating search model saved response time when list-items were "unavailable" in memory, but they could find no published model that would actually save any time in this way. As for longer list lengths, discriminability-based direct-access models (as was suggested for SIMPLE) might fit the congruity effect well, but remain to be tested.

JOR findings, including the congruity effect, present serious challenges to models of serial-order memory, particularly if one seeks to connect order-memory as measured by JORs to the ability to reconstruct presentation order of a list in serial-recall and reconstruction. Thus far, however, models have made relatively little use of JOR findings as potential constraints, perhaps because there has not been a large amount of empirical work with this procedure. On the one hand, current findings are already challenging, as just discussed. On the other hand, the JOR procedure may provide even more fruitful findings to constrain future models.

When forms of memory collide: Memory for order within associations

Just as positional-coding advocates have emphasized findings that suggest that positional information is stored directly in list-memory (and not only derived from inter-item associations, as it would have to be in a pure associative-chaining model), models of association-memory should speak to data on whether or not memory for associations themselves include position- or order-information about their constituent-items (e.g., is it William James or James William?). Although models to date have not been designed with within-pair order in mind, each model of association-memory does in fact lead to a clear prediction (Rehani & Caplan, 2011). Convolution-based association models such as TODAM (Murdock, 1982), which uses the same basic association-memory operation as in the associative-chaining model discussed above (Lewandowsky & Murdock, 1989), store no directionality information. Thus, memory for A–B is exactly equivalent to memory for B–A. In a typical cued-recall task, a participant is given the A item and asked for B, or vice-versa, so whether the participant remembers A–B or B–A, they could equally well produce the correct associate. However, if one were to demand that participants be able to distinguish A–B from B–A, convolution-based models would make the extreme prediction that such judgements should be no better than chance. In contrast, the many models based on matrix outer-product, another mathematical operation that is computed from pairwise products of item feature-values (e.g., Anderson, 1970; Humphreys et al., 1989), without additional explicit assumptions, store associations in order. In these models, if the association is remembered, it is remembered in perfect order. Surprisingly, there is only a small amount of published data that could speak to this question. Two studies compared associative recognition with intact versus reversed probes (Greene & Tussing, 2001; Kounios, Bachman, Casasanto, Grossman, & Smith, 2003), and found better-than-chance accuracy, but these studies did not have enough conditions to determine whether or not order is a necessary property of associations. Rehani and Caplan (2011) got at this question indirectly; in their double-function pair procedure, participants had to disambiguate pairs sharing a common item, but because the position of the common item varied between pairs (A–B vs. B–C), within-pair order information could be used to resolve this ambiguity. Participants performed moderately well on this task, suggesting that both convolution- and matrix models make too-extreme predictions. Positional-coding models applied to lists of pairs (Figure 2b) might provide a good account of the moderate level of memory for order within pairs, because one can assume that paired items are stored at slightly differing position values (Caplan, 2005; Rehani & Caplan, 2011), but such models have not yet been systematically tested.

In sum, memory for order within associations, and other procedures that demand both association and order information at the same time, should be further investigated to produce empirical findings that could constrain models and guide future model-development.

Conclusion

The broad question I considered in this article is whether memory for order and associations should be understood as relying on associative-chaining or positional-coding or both. Because the dichotomous debate seems to continue to be unresolvable, it seems quite likely that associative-chaining and positional-coding processes co-exist, and I argued that several specific empirical results suggest this. Such a hybrid model is challenging for researchers, because it increases the complexity of models; a larger number of degrees of freedom means that model fits to data are very likely to be under-determined, so some creative work needs to be done to figure out what meaningful questions one can ask about hybrid models. Specific empirical phenomena, however, may turn out to be produced exclusively via the associative-chaining portion of a hybrid model, or exclusively via the positional-coding portion, or by neither (as may be the case with phonological confusability in alternating lists).

As a special-case model, the theta/gamma multiplexing model can be viewed as a hybrid associative-chaining+positional-coding model. Some broad hypotheses inspired by this model have been confirmed, but the model has not yet been sufficiently rigourously tested.

New experimental paradigms may hold the keys to designing accurate hybrid models of serial-order and association-memory behaviour. Already, the earlier- vs. later- target congruity effect in judgements of relative order presents a new challenge to models, and can help guide model-development. Order within associations has been largely a blind spot in behavioural (and neuroscience) research, but may prove to be a major constraint for models.

The recent dominance of positional-coding model may be in part due to there being a relative lack of serious consideration and updating of associative-chaining models. The last truly systematic investigation of an associative-chaining model was by Lewandowsky and Murdock (1989), which is now somewhat dated. Since that time, there have been several attempts to develop positional coding models of various kinds to the point that they could handle an up-to-date range of keystone empirical phenomena (e.g., Brown et al., 2000, 2007; Burgess & Hitch, 1999; Henson, 1998; Page & Norris, 1998). The responses have been sporadic, responding to specific arguments (Caplan et al., in press; Dennis, 2009; Kahana et al., 2010; Serra & Nairne, 2000; Solway et al., 2012), but not yet comprehensive. To adequately evaluate chaining mechanisms, there is a dire need for modelling work that brings associative chaining up to date, adding features such as remote associations, a distinction between features that cue items versus features that are only helpful for the final stage of selecting the response, and some imperfect coding of directionality. Such a model should then be evaluated on the keystone findings that have been thought to be diagnostic of associative-chaining versus positional-coding.

Finally, well known mnemonic strategies, such as the peg-list method and the method of loci, at least superficially resemble positional-coding models, whereas other strategies, such as the link method, resemble associative chaining. Between-subjects manipulations of instructed strategies such as these, with sufficient experimental control (Legge, Madan, Ng, & Caplan, 2012), could help us check whether particular empirical findings are in fact diagnostic of associative-chaining versus positional-coding processes.

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