A COMMON REPRESENTATION OF SERIAL POSITION IN LANGUAGE AND MEMORY

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Abstract

Speaking, spelling, and serial recall require a sequence of items to be produced one at a time in the correct order. The representations that underlie this ability, at a minimum, contain information about the identities and positions of the items in the sequence. This chapter summarizes a series of studies that investigate whether similar principles underlie how position is represented in different cognitive domains. In each domain, a variety of hypotheses have been proposed for how the position of an item is represented. An analysis framework has been developed that allows for controlled cross-domain experimentation that considers a common set of hypotheses. Careful analysis of the patterns of errors produced by neuropsychological case studies and unimpaired adults in a range of tasks support a both-edges representation of position, a scheme in which each item's position is represented both by its distance from the beginning of the sequence and its distance from the end of the sequence. The fact that a similar scheme is used to represent position across a range of cognitive domains suggests that serial order processing may rely on some domain-general representational principles. I discuss implications of this pattern of results for situating language processing in domain-general mechanisms and propose some tentative hypotheses as to why this edge-based representation of position is so prevalent.

Our ability to process language relies heavily on our ability to process sequences of linguistic items and their order. Individual words are composed of sequences of segments in spoken language and letters in written language. Sentences are composed of sequences of words. The capacity to track the order of items is clearly critical for language processing. Switching the order of letters or phonemes in a word make *lemons* and *melons* indistinguishable. Sentences with the same words, but in different orders, can have radically different meanings.

Language is not unique in its dependence on serial order processing. We dial 10-digit telephone numbers from memory, and understand the consequences dialing the numbers out of order. When following navigation directions, we need to keep track of the order of left and right turns or else we will end up far from our intended destination. As Karl Lashley pointed out many decades ago, the problem of how we represent and process the serial order of items and events is central to many aspects of cognition (Lashley, 1951).

The fact that serial order is critical in both language and non-language domains naturally leads to the question of whether there are common representations and processes for serial order that cut across domains. This question fits in the context of a larger debate over the role of domain-general and domain-specific processes in language, with extensive debate over the role of domain-general cognitive control (e.g. Nozari & Novick, 2017), working memory (e.g., Tan et al., 2017, Tan & Martin, 2018) or learning mechanisms (e.g. Aslin & Newport, 2012) in language processing. In these debates, domain-generality is taken to mean a variety of things. Language and non-language domains could rely on common capacities with a common neural resource, or the processes in language and non-language domains could rely on similar computational principles, though not necessarily a common neural resource (see Nozari and Novick, 2017 for discussion). The logic of the contribution of serial order processing to these debates is as follows: language relies on the ability to represent not only the items in a sequence – with the items being the letters that form words in written language, the phonemes that form words in spoken language and the words that form sentences – but also the ability to represent the position of those items in a sequence. But the need to represent both the items in a sequence and their positions is not unique to language. It is clear that items for linguistic sequences are unique to language. Phonemes, letters and words are the inventories that make up languages. The way that we represent the position of those items need not be language specific. There may be general schemes for representing position that are observed for sequences of different types; that is, there might be similar computational principles for how serial order is represented across domains. If so, then we will have evidence that our ability to process language depends on a domain-specific item representations of items paired with domain-general position representations of positions.

In the remainder of this chapter, I will argue that these types of general principles of position representation exist. First, I will lay out a series of hypothesis for how position might be represented, which referred to as the set of position representation schemes. The strategy of this research has been to consider as a wide of a variety of different position representation schemes as could be imagined. Then, I will describe a general method that can be used to pit each these different position representation schemes against each other, by analyzing corpora of errors produced in different of domains, in order to identify how position is represented for those different types of sequences. Following that, I will describe the results of a series of studies that apply this analysis to sequences that are core to language processing – letters in reading and writing, phonemes in spoken production – and sequences that are thought to be outside of language processing – immediate serial recall experiments with both verbal and nonverbal items. Strikingly, there is a convergence across most of these experiments that indicate a common scheme for representing position, specifically, one in which the order of items is defined by its distance from both the beginning and the end of the sequence. This pattern suggests that this both-edges based representation of position is a cognitive primitive that is critical not only for language but also for other domains (see also Endress, Nespor and Mehler, 2009 for a similar proposal). Finally, I will pose some additional questions for future research based on these findings.

Position Representation Schemes

Sequence representations contain information both about the identity of the items, as well as their position. The position of an item in a sequence could be defined using a variety of methods. Consider the position of the E in the word NEST. It could be represented as the second letter from the beginning of the word or as the letter after the N. In the first case, the position of the E is defined relative to a word beginning anchoring-point. In the second case, the position of the E is defined relative to the letter that precedes it.

Many of the same schemes could be used for difference types of sequences. In a verbal short-term memory experiment, a participant could be asked to recall the list “flour, hitch, zebra, clash” in order. The position of the word “zebra” could be represented as the third word in a sequence, defined relative to the beginning of the sequence. Or it could be the word after the word “hitch”, defined by the word that precedes it. Furthermore, because the same schemes could be used to represent position in either domain, a beginning-based scheme or a preceding-item scheme could be a general principle of position representation that applies broadly across cognitive domains.

The research approach has been to consider a large number of possible position representation schemes. These schemes divide broadly into context-independent schemes, context-dependent schemes, and, some domain-specific position representation schemes. The full set of schemes that have been considered in the analyses are included in Table 1. For context-independent schemes, position is defined relative to some anchoring point, like the beginning of the sequence, the end of the sequence, the midpoint of the sequence, either the beginning or the end of the sequence, whichever is closer, or with a multidimensional code in which position is defined relative to both the beginning and end of the sequence. For context-dependent schemes, position is defined relative to the other items in the sequence. At its simplest, position is defined relative to the immediately preceding item. More complex versions of context-dependent schemes define position relative to the following item, both the preceding and following item, or the set of items that precede the current item, not just the immediately adjacent one. Versions of context-dependent position representations have been referred to as chaining theories or open bigram theories in different corners of cognitive science. Finally, language-specific representations of position have also been considered, specifically schemes in which position is defined syllabically have been considered for the sequences of letters and phonemes that make up words.

Proposed position representation schemes differ on other dimensions as well. One large point of contention is the difference between discrete and graded position representations. Classic examples of a discrete position representation include the slot-based schemes used to code letter position in computational models of reading, like the interactive activation model (McClelland & Rumelhart, 1981) and the dual-route connectionist model (Coltheart et al., 2001). The interactive activation model includes four pools of twenty-six letter units, with each pool representing a single letter position, such that the P in the word POST is represented by a totally different unit than the P in the word SPOT. In discrete schemes, position representations are either the same or different, with no similarity among non-identical positions, such that there is no way of coding the fact that the position of the P in POST is closer to the P in SPOT than it is to the P in STOP. In contrast, more recent computational models of reading have eschewed these slot-based position representations in favor of graded representations of position, in which nearby positions are represented more similarly (e.g. Gomez, Ratcliff & Perea, 2008; Norris & Kinoshita, 2012). Different answers to the question of “relative to what is position defined?” and “are nearby positions similar to each other?” yield a wide set of possible position representation schemes.

A general method for contrasting schemes

In many cognitive domains – speech production, reading and verbal short-term memory – there has been extensive debate over which of these schemes is used to represent position. Table 1 includes a non-comprehensive sample of papers that propose different position representation schemes for written language, spoken language and short-term memory, focusing only on the “relative to what is position defined?” question. Clearly, methods are needed that directly contrast these different position representation schemes empirically.

Below I present the outline of a method that can be used to accomplish this goal. A more thorough description of the method can be found in a number of recent papers that have applied it to adjudicate domain-specific debates about position representation (e.g., Spelling: Fischer-Baum, McCloskey & Rapp, 2010; Short-term memory: Fischer-Baum & McCloskey, 2015; Reading: McCloskey, Schubert & Fischer-Baum, 2013). The method relies on the fact that a clear way to distinguish these position representation schemes is to ask which items are in the same position in two different sequences. Consider the question: which letter in the word CANDY is in the same position as the E in NEST? As discussed above, for different schemes, the E in NEST could be described as the second letter or the letter after the N. If the E is the second letter in the word NEST, then the A in CANDY is in the same position as the E in NEST. If the E is the letter after the N in the word NEST, then the D in CANDY is in the same position as the E in NEST.

The analysis approach focuses on corpora of errors in which participants produce responses in which the sequence contains an intruded item and that intruded item appears in a recent response, what is called in the clinical literature a perseveration error (Cohen & Dehaene, 1998). This approach builds on the psycholinguistics tradition of analyzing speech errors to investigate the nature of the representations and processes that underlie language production (Dell, 1995). The logic is that the mistakes that we make when speaking are not totally random and carefully analyzing them reveals rich linguistic structure. While error analyses are likely most familiar to psycholinguists, careful analysis of errors in other parts of cognitive science similarly provide insights into the nature of cognitive representations (Short-Term Memory: Henson et al., 1996; Visual Cognition: Gregory & McCloskey, 2010). For the current analysis, corpora of errors can be collected from different sources. The papers using this method have investigated patients with acquired language disorders following stroke, neurotypical undergraduates participating in working memory studies in the lab, and deaf high school students producing signed responses. With each of these corpora of errors, the analysis remains exactly the same. Table 2 shows an example of this type of error, in a series of two spelling trials produced by a patient with acquired dysgraphia (Fischer-Baum, McCloskey & Rapp, 2010). The second response contains an error in which the word “edge” is misspelled as ERGE. The R is an intrusion error, it appears in the response but not in the target. As shown in the table, the intruded letter was present in the response immediately preceding the error (FRENCE), raising the possibility that the R is a perseveration, produced in ERGE because it was previously produced in FRENCE, what I call the source response.

The analysis tests whether the R appears in the same position in the error as it did in the source response, comparing the rate at which the position matches between the two responses with a rate expected by chance, calculated by a Monte Carlo procedure that randomly selects other responses in the corpora that are distant from the error being analyzed. The answer to that question depends on position representation scheme being considered. According to the beginning-based scheme, the R in ERGE is in the same position as the R in FRENCE as they both are the second letter. But the R in ERGE is not in the same end-based position (third from last vs. fifth from last), the same immediately-preceding item position (after an E vs. after an R) or even the same syllabic position (coda of the 1st syllable vs. onset of the 1st syllable).

When looking at the whole corpus of errors, it is frequently the case that the intruded letters appear in the same position in the error as it did in the source response more often than would be expected by chance for all of the position schemes considered. This observation is unsurprising because the same error can count as a position match for multiple schemes. For example, in the error “under” spelled as UNDEL, with the source response MOTEL, the L appears in the same position of the two responses for many schemes (beginning-based, end-based, midpoint-based, preceding-item, syllabic position). An additional set of analyses has been devised to pit these different position schemes against each other, essentially partialling out the errors accounted for by one scheme (e.g. the beginning-based scheme) and then asking whether the remaining perseveration errors match position by a different scheme (e.g. the end-based scheme) more than would be expected by chance. In applying this process iteratively, the analysis method identifies the position representation scheme or combination of schemes that best accounts for the pattern of perseveration errors observed in the corpus.

There are many strengths of this analysis approach for answering the question of whether there are domain-general properties of serial position representation. First, there is a clear way to contrast position representation schemes, including a statistical analysis that can determine which position representation scheme best accounts for the data. Second, the same set of position representations can be compared in different domains, so the conclusion about which position representation scheme best accounts or the data will be derived from the same hypothesis space. Third, the exact same method can be applied to sequences from different domains. As long as a corpus of errors can be collected in which participants produce responses in which intruded items perseveration from recent response more frequently than would be expected by chance, I can analyze whether those perseverations maintain position, and ask position defined how. Taken together, this approach provides an apples-to-apples comparison across domains that can reveal general principles of how position is represented.

Experimental Findings

This flexible analysis technique has been applied to a number of different domains already. Fischer-Baum, McCloskey and Rapp (2010) reported two individuals with acquired spelling problems following stroke, whose spelling errors largely consisted of letter perseveration errors. A third patient who produced similar patterns of spelling errors was reported in Fischer-Baum (2011; Chapter 5). McCloskey, Fischer-Baum and Schubert (2013) reported a single case study of a brain-damaged individual who made a similar type of error, except in reading. For example, this patient would read the word SAILOR as “sailog” immediately after correctly reading the word “flag.” In Fischer-Baum (2011; Chapter 6), I reported a single case study of an individual who makes similar errors, except in spoken production, for example producing the response “hahlo” in response to a picture of an arrow, with many of the immediately preceding responses – house, hat – containing the intruded /h/ (a more detailed case report of this patient is available in Olson, Romani & Halloran, 2007). For each of these case studies, large corpora of perseveration errors were collected by testing the participants extensively over a long period of time. For example, the reading patient was given approximately 30,000 words and nonwords to read aloud, both in the lab and at home. These 30,000 words included approximate 12,000 perseveration errors that were included in the position analyses. While the sample of data from the reading patient was by far the largest, but large corpora were collected from the other patients – between 1500 and 3700 perseveration errors – as well. These large numbers of errors made it possible to have the power to contrast the large set of position representation schemes described above.

In the language domain, the analyses focused on errors produced by brain-damaged patients because neurotypical individuals rarely produce perseveration errors in single word tasks. In short-term memory, however, it is easy to get participants to produce perseveration errors, as participants often intrude items from previous lists into the response to the current list in immediate serial recall tasks (e.g., Conrad, 1960; Estes, 1991; Henson, 1999). Fischer-Baum and McCloskey (2015) reported three verbal immediate serial recall experiments with neurotypical participants that differed in the lengths of the lists presented and the modality of input and output, and Miozzo et al. (2016) presented a similar experiment with deaf participants, recalling sequences of finger-spelled letters. Fischer-Baum (2011; Chapter 9) reported three non-verbal serial recall experiments, two experiments in which participants had to remember sequences of spatial locations and one in which participants were shown sequences of the same object presented at different orientations, and had to recall the sequences of orientations. Each of the seven samples generated a corpus of around 1,500 perseveration errors to analyze, ranging from 800 to 3000 depending on the experiment.

The goal of the current chapter is not to provide a detailed analysis of each of these datasets, but to look at the overall pattern of results across experiments. The results are summarized in Table 3. However, I will walk through the analysis of one dataset – the spelling patient LSS reported in Fischer-Baum, McCloskey and Rapp (2010) – to provide further insight into how conclusions about positions representation scheme are drawn from these analyses. The analysis of LSS included approximately 2,300 perseveration errors. Of these errors, 47% matched on beginning-based position and 54% matched on end-based position, both of which exceed what would be expected by chance (~25% chance position matches, *p*s <.0001). To demonstrate contributions of both beginning- and end-based position, a residual analysis was carried out that looked only at the approximately 1,000 perseveration errors that did not match on end based position and showed that they matched on beginning based position (36% of the time) more than would be expected by chance (20%, $p < .0001$). Similarly, a residual analysis was carried out that looked only at the approximately 1,200 perseveration errors that did not match on beginning based position and showed that they matched on end based position (44% of the time) more than would be expected by chance (22%, $p < .0001$). Because of these findings, I could conclude that there are contributions of both beginning- and end-based representations of position, or the both-edges scheme. I then considered a graded position representation scheme, and showed that once exact both-edges position matches were removed, perseveration errors matched nearby positions more than would expected by chance, supporting a graded both-edges representation of position. These results are indicated by checkmarks on the top line of Table 3 under begin, end, and graded.

This graded both-edges representation of position was then compared to a variety of other content-independent position representations schemes, to context-dependent position representation schemes and to syllabic position representation schemes. In all cases, there was no additional contribution of these alternative schemes above and beyond the graded both-edges scheme. For example, when graded both-edges position matches were removed from the analysis, the remaining perseveration errors did not match syllabic position more than would be expected by chance. In contrast, when the syllabic position matches were removed from the analysis, the remaining perseverations matched graded both-edges position significantly more often than would be expected by chances. This pattern, showing a significant contribution of the graded both-edges position above and beyond other position representation schemes, but no contribution of the other scheme above and beyond both-edges position is indicated in Table 3 by the xs under the columns for “other content-independent”, “content-dependent” and “syllabic.”

Each row of Table 3 reflects a unique contribution to the literature, helping to settle domain-specific questions about position representation. As an example, consider the analysis of speech errors in VS (Fischer-Baum, 2011; Chapter 6), which yielded perhaps the most unexpected result. Most theories of speech production assume a syllabic representation of phoneme position, at least at some level of representation, with some of the strongest evidence for this claim coming from the syllabic position constraint – the observation that phoneme swaps in speech errors tend to appear in the same syllabic role (e.g., Boomer & Laver, 1968; Fromkin, 1971; MacKay, 1970; Nootebloom, 1969; Stemberger, 1990). When considered alone, there was evidence for a syllabic position constraint in VS's errors. Her perseveration errors matched syllabic position more than would be expected by chance. However, once the graded both-edges scheme was taken in to account, the result was that errors maintained graded both-edges position and not syllabic position. This observation of non-syllabic representations of phoneme positions is in line with some theories of speech production. The Levelt, Roelofs and Meyers (1999) model proposes that during the first stage of phonological encoding, phoneme position is represented by a beginning-based representation of position, with syllabification occurring at a later stage. In a recent paper, Olson, Halloran and Romani (2015) argue that VS's speech errors occur because of an impairment in the selection of phonemes during phonological encoding. Therefore, this analysis provides evidence for the non-syllabic encoding of phoneme position at this level, in line with what was proposed by Levelt and colleagues, and further argues for the graded both-edges representational scheme at this level.

Focusing only on the domain-specific questions can obscure the larger pattern that has become clear from this body of research. As can be seen in Table 3, for nearly all of the data sets that have been analyzed, an identical result is obtained – evidence for a graded, both-edges representation of position, without any contribution of any other position representation schemes. This pattern was seen in all three spelling patients, in the reading patient and in the patient who produced phoneme perseveration errors when speaking. Graded both-edges position representations were observed in the verbal immediate serial recall experiments, though extremely small (about 10 errors out of about 1500 total) contributions of a preceding-item representation of position above and beyond the graded both-edges scheme were also found in three of the verbal immediate serial recall experiments. For the task in which participants had to recall a sequence of orientations for the same objects, there was also support for a both-edges scheme, though the sequences used in the experiment (length 2-4) were too short to test the graded version of that scheme. Looking at all of these experiments together, there appears to be common scheme for representing the position of an item in a sequence, namely one in which the position of an item is defined by its distance from both edges of the sequence, and where the representation of position is graded rather than discrete, such that nearby positions are represented more similarly to each other than more distant positions.

The one place where the results diverge from this overarching pattern of both-edges based position were in the two experiments in which participants had to recall sequences of locations presented on the screen. In one experiment, these locations were scattered across the screen in a Corsi block-like presentation and in the other experiment, these locations were presented on a 4-by-4 grid. In these experiments, perseveration errors maintained position, but only position defined by a graded beginning-based scheme, with no contribution of any other position representation schemes, including the end-based position representation scheme. This surprising result was probed further, and I found that there was no contribution of end-based position even when the analysis was restricted to perseverations in the final position of the sequence. While it is possible that these two studies deviate from the overall pattern for uninteresting reasons, like false negatives that are inherent to null hypothesis testing, this seems unlikely since (1) the two datasets out of twelve that do not show both-edges position representation are very similar to each other – both are sequences of spatial locations and (2) both of these data sets converge on the same position representation scheme – one in which position is defined only by its distance from the beginning of the sequence. Therefore, I generalize the results in the following way: a graded both-edges representation is a general scheme for representing the order of items in a sequence that applies broadly to many of the different types of sequences I have investigated, including linguistic sequences of letters and phonemes that make up words and some sequences in short-term memory, though it does not apply to all types of sequences in short-term memory, with sequences of spatial locations relying on a beginning-based representation of position. The next section provides a framework for making sense of this pattern of results.

Discussion

Many cognitive systems require the ability to process sequences of items or events, requiring the system to be able to represent both the items in a sequence and their positions. The fact that the graded both-edges scheme is so widely observed as the mechanism for representing the position of items in a sequence make it a strong candidate for being a cognitive primitive, a part of a general cognitive toolbox that our minds use to make sense of the world around us. The diversity of possible position representation schemes outlined in Table 1 make it clear that there are many ways to solve the problem of representing the order of items in a sequence. The consistency of position representation schemes across disparate domains, shown in Table 3, suggests that our brain relies on a limited number of these possible schemes.

The proposal that both-edges representations of position are a cognitive primitive falls nicely in line with several existing proposals in the literature. Endress, Nespor and Mehler (2009) argue that assuming edge-based representation of position as a cognitive primitive can help explain patterns of language learning observed both in laboratory and natural settings. This precise scheme has been proposed by computational modelers of both language (Houghton, 1990; Houghton, Glasspool & Shallice, 1994; Houghton, 2018; Glasspool & Houghton, 2005) and working memory (Henson, 1998, 1999) as a common solution to the problem of serial order. The fact that similar conclusions have been reached from these other empirical approaches strengthens the claims made here. The current body of work uses carefully controlled cross-domain experimentation with a common analysis framework and a common set of hypotheses to identify cognitive primitives for position representation. In an effort to make the approach as similar as possible across domains, the kind of data used to draw conclusions about position representation was limited to perseveration errors. Perhaps there is something unique about these errors that leads to conclusions about both-edges position encoding and the same conclusions would not be reached if other methods were used to probe position representations. This concern is partially alleviated by the fact that other researchers have independently reached the same conclusion through other approaches. Still, one area for future research is to develop other cross-domain experimental approaches that can provide converging evidence for the claims made here. Furthermore, while the current work presents evidence for this cognitive primitive from a number of different experiments, there are still many different types of sequences to examine. In the language domain, the analysis could be applied to the representation of the position of words in a sentence. Here, I would be surprised to find evidence of both-edges representation of position, since there is clear evidence that favors tree structure over linear data structures in syntax (see Perfors, Tenenbaum and Regier, 2011 for a computational argument favoring this point). There are also other non-linguistics domains that depend on serial order processing – like the planning of actions or the comprehension of complex events that unfold over time – that could be investigated.

The fact that this graded both-edges scheme is used to code position for both linguistic and non-linguistic sequences can help situate language processing in the larger cognitive system. Processing language requires the ability to process a set of items and their serial order. The items themselves are certainly domain specific, as the reading system is specialized to recognize letters, speech production is specialized to produce phonemes. But these results suggest that the ordering mechanisms might not be specialized for a specific domain, instead relying on more general principles of representation that apply broadly across the cognitive system. In this way, our ability to represent and process language can be conceived of as the combination of domain-specific knowledge and domain-general mechanisms for organizing that knowledge. When posed this way, the graded both-edges representation of position might just be one of a series of cognitive primitives that our brains use to organize the input so that we can learn about the world. Endress, Nespor and Mehler (2009) argue that another cognitive primitive might be a system for recognizing the immediately repeated items or events. Part of the connectionist research program has been to argue that delta-rule learning and back-propagation is another cognitive primitive that we use to learn about regularities in the world, that could explain how human behavior in a wide assortment of domains (Rumelhart et al., 1986). Another area for future research would be to more fully investigate the contents of the toolbox of cognitive primitives, identifying the various general systems our minds use to organize both linguistic and non-linguistic information.

If the graded both-edges scheme is a cognitive primitive for representing position for different types of sequences, the natural question is why this scheme as opposed to other possibilities. Both Endress and colleagues (2009) and Henson (1998) argue that since start and the end of a sequence are its most salient aspects, these edges provide the strongest anchoring points relative to which the items in the sequence can be ordered. This argument makes the most sense for letter sequences in reading, where all of the letters are presented simultaneously and processed in parallel, making it easy to track how far each letter is from both edge-based anchoring points. The argument falters somewhat for a task like immediate serial recall, in which words are presented one at a time. When the sequences presented are of variable length participants do not know when the end of the sequence is going to come, making it more difficult to code position of each item relative to the end of the sequence (Farrell & Lelièvre, 2009).

A recent proposal in short-term memory – the “mental whiteboard“ hypothesis (Abrahamse et al., 2014, 2017) – might help us make sense of why ends are salient even for temporally presented sequences. According to this hypothesis, when confronted with a temporal sequence of items or events, the brain generates an internal spatial template and binds each item to specific coordinates in that spatial template in a left to right fashion, the mental equivalent of writing down the sequence on a piece of paper. I will refer to this process as spatialization. With this type of spatial representation of the position of items in a sequence, once the entire sequence has been encoded, both edges of the sequences are salient anchoring points, with the first item being the leftmost and the final item being the rightmost. A variety of sources of evidence support this link between temporal order and space. Van Dijck and Fias (2011) reported an interaction between serial position in verbal working memory and hand of response, with judgements about items presented in the first half of the list being faster with the left hand than the right hand, and judgements about items presented in the second half of the list being faster with the right hand than the left hand. Fischer-Baum and Benjamin (2014) report better immediate serial recall of temporal order when the items are presented left to right than when they are presented right to left. Bonato, Saj and Vuilleumier (2016) report that patients who neglect the left half of space also have more difficulty recalling events that occurred before a central event, relative to controls, than recalling events that occurred afterward.

Assuming spatialization of temporal order information can help to explain why both edges are salience for temporally presented sequences. It can also explain why some, but not all, of the sequence types described in Table 3 show graded both-edges position representation. In the twelve data sets analyzed, only two showed no contribution of end-based representation of position. Both of these data sets involved recalling sequences of locations and both showed clear evidence of beginning-based representation of position. In the framework described above, for these sequences, the beginning of the sequence is a salient edge, but the end of the sequence is not, perhaps because these sequences are not spatialized.

Of all of the sequences tested, sequences in which the items are locations in space are likely the most difficult to spatialize. This point is illustrated in Figure 1, which contrasts sequences of digits with sequences of locations. For the digits in the digit span task (Figure 1, top), spatialization provides a straightforward means to recovering serial order information. The identity of each digit is not changed by where it lies in the spatial template and the leftmost digit was the first item presented and the rightmost digit is last. Since maintaining the identity of the items in this task does not rely on a spatial template, space can be repurposed to support memory for serial order. In contrast, the locations in the matrix span task are distinguished from each other solely on the basis of where they are located in space. In Figure 1, middle, what distinguishes the first and the second item in the sequence is that the first item is in the bottom, right corner and the second item is in the top, left corner. Because space is being used to distinguish the identity of the items, it cannot also be used to maintain their serial order, as illustrated in Figure 1, middle. If these grids of locations were placed on a mental white board, it would be hard to distinguish which spatial information was being used to represent the items in the sequence from which spatial information is being used to represent the order of the items.

Note that this account predicts that spatialization should only fail when the sequences are of locations defined in two-dimensional space. When different types of spatial information are used to distinguish the items in the sequence, the prediction is that spatialization should still occur. Some of the data reported above already supports this conclusion. When items in a sequence are distinguished by a different type of spatial information – the orientation of the object – the temporal order information can be encoded as spatial coordinates, and the end becomes a salient edge. Thus, it is unsurprising that both-edges representation of position were identified when analyzing perseveration errors produced when participants recalled sequences of orientations. More strikingly, this account predicts that spatialization should only fail for sequences of locations that are defined in two-dimensional space. For sequences of locations defined in one-dimension, for example along a horizontal line (as shown in Figure 1, bottom), the mental white board could construct a spatial representation such that the horizontal dimension contains information about the identities of the items in the sequence, while the vertical dimension contains information about their order, with the top-most item being first and the bottom-most item being last. Because spatial information can be used to support serial order information for these types of sequences, the prediction is that both-edges based representations of positions should be observed. Indeed, in an unpublished experiment, I collected perseveration errors while participants recalled a sequence of locations in which the locations were presented along a single dimension – a horizontal line of 16 possible locations. In line with the prediction, the perseveration errors produced in this experiment matched both beginning- and end-based position, unlike the experiments in which the same number of locations were organized in a 4 by 4 grid. Therefore, one interpretation of the full pattern of results presented in this chapter is that spatialization of temporal order is a cognitive primitive. Graded both-edges representation of position emerge from that spatialization, because with spatializization, both edges of the sequence are salient. For all types of sequences for which this spatialization is possible, graded both-edges position is observed. For those sequences in which spatialization is not possible, the only salient edge is the beginning of the sequence, and only beginning-based representations of position are observed.

Note that this proposal goes beyond the mental whiteboard hypothesis which proposes spatialization for temporal order sequences only in the context of working memory. Here, I am arguing that we mentally spatialize sequences of all types, at least including phonemes in speech and letters in writing. There is some evidence for this spatialization in writing. Caramazza and Hillis (1990) report a patient with right-side neglect following a left-hemisphere stroke who neglects the second half of words in both reading and spelling, linking temporal order with spatial position in writing. To my knowledge, there is no evidence of spatialization in speech, though it could easily be tested, for example seeing whether participants are faster at making judgements with their left hands about phonemes that appear earlier in a word and faster with the right hands about phonemes that appear later in a word. However, spatialization is a prime candidate for being a cognitive primitive as there are many other examples of the brain spatially organizing non-spatial information. For example, the spatial-numerical association of response codes effect has been used to argue that numerical information is organized in a mental number line that is oriented spatially from left-to-right, at least in populations with a left-to-right writing system (Dehaene, Bossini & Giraux, 1993).

Overall, the claim here is that serial position representation is yet another example of how language processing relies on domain-general mechanisms. But what exactly does it mean to say that serial position representation is domain-general? Nozari and Novick (2017) make a distinction between two notions of domain-generality, the idea that different cognitive systems rely on similar computational principles and that different cognitive systems rely on a common neural resource. The work presented here supports the former notion of domain-generality – that there is a common principle of representation that applies across different sequence types – and says nothing about whether there is a shared neural resource for serial order processing.

As Nozari and Novick (2017) note, common computational principles do not entail a common a neural resource. It is possible, for example, that basic information about neuronal computation place constraints on how neural networks can represent position. This point is beautifully illustrated by Grossberg (1986) who derives a theory of order representation from a few basic assumptions about neuronal computation – self-inhibitory feedback, lateral inhibition and adaptive resonance – and demonstrates how well this theory could explain seemingly disparate findings from different cognitive domains. While Grossberg's theory is not a graded both-edges representation of position, his work illustrates how different sequence types could rely on the same representation scheme not because they rely on a shared neural substrate, but because limitations on the types of computations neurons can carry out means that whenever a neural network is given the responsibility of processing order, the same representational scheme is used.

At the same time, it is also possible that the similarities in the representation of serial position across cognitive domain arise because each of these different cognitive systems rely on a common neural structure for representing and processing order information. It remains an open question, therefore, whether there is a common neural resource that is used for serial order processing across different types of sequences. Cognitive science is filled with methodological tools that could be used to address this question. If there is a common neural substrate for order processing across language and working memory, individuals with deficits in order processing in one domain should also have order processing deficits in the other (e.g., Majerus & Cowan, 2016). Structural equational modelling could be used to ask whether individual differences in serial order processing across different types of sequences can be explained by a common latent variable. Dual-task paradigms could be used to show that demands on order processing in one domain influence order processing performance on a concurrent task in another domain. Neuroimaging studies could identify a common neural locus of order processing across sequence types. Investigations of whether there is a common neural resource for serial order processing could provide additional insights into what it means to have identified graded both-edges as a common representational principle.

As a final note, I want to highlight how this work illustrates the importance of studying language in the context of broader questions about cognitive science. The ability to comprehend and produce language is a remarkable capacity that is arguably unique to humans. Psycholinguistic research has largely focused on developing theories of the representations and processes that enable that capacity. While these theories frequently depend on insights from other aspects of cognitive psychology – perception, memory, cognitive control, statistical learning – the relationship can be characterized as being largely unidirectional. The line of thinking is that language research is specialized. It can draw on more general areas of cognitive psychology, but findings from psycholinguistics research are not relevant for developing theories of how cognitive control works, how statistical learning works, or how memory works.

Serial order processing research provides a nice counterpoint to this way of thinking about language research. In his seminal paper on the problem of serial order in behavior, Karl Lashley (1951) marveled at the human capacity to produce complicated sequences of actions rapidly and largely without error. The paper goes through many examples of these sequential behavior, but many of the aspects of serial order behavior that impress him the most have do with language processing. Framed this way, language processing can be seen as a model system for studying a more general aspect of cognition, as a theory of the human capacity for serial order processing needs to be able to explain the complex nature of serial order processing in language (Hartley & Houghton, 1996). Of course understanding language processing is an important goal in its own right. But the role of language research in psychology is not limited to answering this question. Producing and comprehending language are complex human behaviors that engage many different cognitive operations and a full understanding of these cognitive operations requires understanding how they work in the context of language processing.

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Table 1: Set of possible position representation schemes considered with examples of theories that posit these schemes in written and spoken language and in short-term memory.

		Cognitive Domain		
		Written Language	Spoken Language	Short-term memory
	Beginning-based	Coltheart et al., 2001	Levelt et al., 1999[a]	Burgess & Hitch, 1999
	End-based			Neath & Crowder, 1990
Context-Independent	Midpoint-based	Caramazza & Hillis, 1990		
	Closest-edge	Jacobs et al., 1998		
	Both-edges	Houghton, 2018	Houghton, 1990	Henson, 1998
	Immediately Preceding			
Context-Dependent	Multiple Preceding	Grainger et al., 2006		Lewandowsky & Murdock, 1989
	Trigram	Seidenberg & McClelland, 1989	Wickelgren, 1969	Wickelgren, 1965
Other	Syllabic	Taft, 1979	Dell, 1986	

[a] Levelt, Roelofs and Meyers (1999) propose different representations of phoneme position at different levels of phonological representation, with beginning-based scheme at the immediately post-lexical level.

Table 2: Example of a two trial sequence with patient CM in which the intruded R on Trial 2 is a possible perseveration from the response FRENCE on Trial 1

	Target	Response
Trial 1	FRENCH	FRENCE
Trial 2	EDGE	ERGE

Table 3: Summary of the results of the position representation scheme analysis across data from sequences of different types – letters in spelling and in reading, phonemes in speaking, words and letters in verbal immediate serial recall and locations and orientations in nonverbal immediate serial recall.

		Begin	End	Graded	Other content-independent	Content-dependent	Syllabic
Spelling	Fischer-Baum et al. (2010); LSS	✓	✓	✓	×	×	×
	Fischer-Baum et al. (2010); CM	✓	✓	✓	×	×	×
	Fischer-Baum (2011; Ch. 5): LHT	✓	✓	✓	×	×	×
Reading	McCloskey et al. (2013): LHD	✓	✓	✓	×	×	×
Speaking	Fischer-Baum (2011; Ch. 6): VS	✓	✓	✓	×	×	×
Verbal Immediate Serial Recall	Fischer-Baum & McCloskey (2015); Exp .1	✓	✓	✓	×	(a)	n/a
	Fischer-Baum & McCloskey (2015); Exp .2	✓	✓	✓	×	(a)	n/a
	Fischer-Baum & McCloskey (2015); Exp .3	✓	✓	✓	×	(a)	n/a
	Miozzo et al. (2016); Deaf Signers	✓	✓	✓	×	×	n/a
Nonverbal Immediate Serial Recall	Fischer-Baum (2011; Ch. 9): Locations 1	✓	×	✓	×	×	n/a
	Fischer-Baum (2011; Ch. 9): Locations 2	✓	×	✓	×	×	n/a
	Fischer-Baum (2011; Ch. 9): Orientations	✓	✓	n/a	×	×	n/a

[a] Small but significant contributions of preceding –item position were observed in all three verbal short-term memory experiments, thought the effects were quite small (~10 errors out of about1500 perseverations)

Figure 1: Mental white board hypothesis representations for three sequence types, sequences of digits (top), sequences of locations defined in 2-dimensional space (middle) and sequences of locations defined only along the horizontal dimension (bottom). Note that in the top and the bottom mental white boards, serial order can be easily reconstructed, by reading off items either left to right or top to bottom. In contrast, in the mental white board for the sequences of locations defined in 2-dimensional space, reconstructing serial order is more of a challenge, since both the vertical and horizontal dimensions are used to distinguish the items in the sequence.

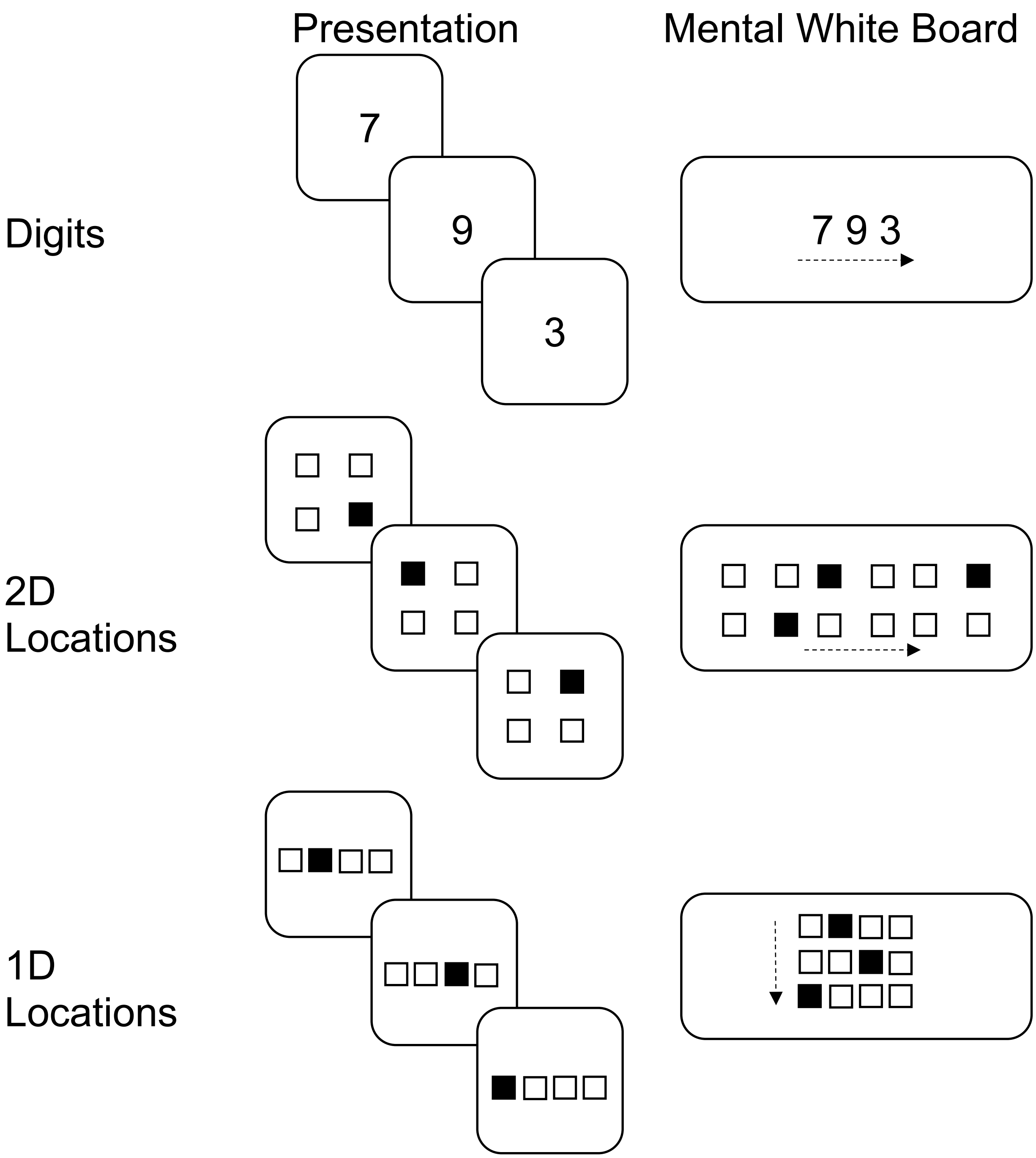
Presentation
Mental White Board
Digits
7
9
3
7 9 3
2D
Locations
1D
Locations

Figure 1