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Working Memory for Serial Order and Numerical Cognition:

What Kind of Association?

SHORT TITLE: SERIAL ORDER IN WM AND NUMERICAL COGNITION

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Abstract

The retention of serial order information is a critical element of working memory (WM), as it allows for the structured encoding and maintenance of the sequential order of events and stimuli. The retention of serial order information is critical for success in many different cognitive tasks, including numerical tasks. A number of studies have shown a close association between serial order WM and numerical cognition. We examine here the nature of this association, by highlighting its bidirectional character. On the one hand, serial order WM capacities appear to determine mental arithmetic abilities. On the other hand, the link between serial order WM and numerical cognition involves access to shared ordinal representations, whose spatial, temporal or abstract nature still needs to be determined. The findings reviewed here support the existence of domain-general serial order codes for WM and numerical cognition, but without excluding the possibility of additional, domain-specific codes.

148 words

Keywords: working memory, serial order, numerical cognition, mental calculation, SNARC, spatial, temporal

Numerical cognition: The importance of working memory for serial order

Many studies have explored the associations between working memory (WM) and numerical cognition, by considering that WM capacity may be an important determinant of performance in numerical tasks, such as mental calculation. Indeed, in these tasks, the target numerical information (the numbers and the operators of the arithmetic problem) has to be temporarily maintained in WM as well as the operations that are carried out on the numbers and any intermediate operations and results. At the same time, the studies that have explored the associations between WM capacity and mental calculation show an inconsistent picture, especially as regards the involvement of WM storage abilities studies (e.g., De Smedt et al., 2009; Gathercole & Pickering, 2000a; Holmes, Adams, & Hamilton, 2008; Jarvis & Gathercole, 2003; Noël, 2009; Swanson & Kim, 2007; see Raghobar, Barnes, & Hecht, 2010, for a review). Many studies suggest an association between executive processes of WM tasks, which involve processing of temporarily stored information, and numerical cognition (e.g., Bull & Johnson, 1997; De Smedt et al., 2009; Gathercole & Pickering, 2000b; Imbo, Vandierendonck, & Vergauwe 2007; Noël, 2009). But studies exploring the association between WM *storage* and numerical abilities have led to contradictory results, especially as regards the involvement of *verbal* temporary storage capacities (De Smedt et al., 2009; Holmes & Adams, 2006; Noël, Seron, & Trovarelli, 2004).

Those studies typically did not distinguish between item and serial order storage capacities, two aspects which have been shown to be critical when exploring the associations between WM storage capacity and performance in other cognitive domains (Majerus, Poncelet, Greffe & Van der Linden, 2006; Martinez Perez, Majerus, & Poncelet, 2012). Item information involves the maintenance of the identity of the memoranda and their temporary activation in long-term memory bases (such as language knowledge for verbal stimuli), while serial order information involves the order in which the memoranda have been presented (e.g.,

Nairne & Kelley, 2004). Several studies have shown that the serial order component of WM may be particularly predictive of performance in cognitive tasks that require the processing of sequentially organized information, such as numerical information. Attout, Noël and Majerus (2014) conducted a longitudinal study in typical developing children first tested when they were in third year kindergarten. The authors measured WM for item information by presenting a delayed nonword repetition task; on each trial, a single nonword with a consonant-vowel-consonant structure was presented in order to minimize serial order retention requirements while maximizing sublexical phonological retention requirements. Serial order WM was assessed via a serial order reconstruction task; the children heard sequences of familiar animal names in different orders, and for each sequence, they had to reconstruct the order of the animals using cards on which the animals that had occurred (and only those) were depicted. This procedure ensured that item processing requirements were minimized. Attout et al. (2014) showed that performance on the serial order WM but not on the item WM task predicted performance on mental calculation tasks (additions and subtractions), after control of verbal and non-verbal intelligence estimates. Furthermore, Attout and Majerus (2015) showed that children with dyscalculia present impaired performance for verbal WM tasks that maximize serial order retention requirements, while showing no deficits for verbal WM tasks that maximize item retention requirements (see also De Visscher, Szmalec, Van der Linden, & Noël, 2015). Attout, Salmon and Majerus (2015) observed the same pattern of results in a subsequent study with adult participants presenting a history of developmental dyscalculia.

These results suggest a specific association between serial order WM abilities and numerical abilities. They also allow us to clarify the inconsistent findings about verbal WM impairment in children with dyscalculia observed in previous studies, given that most of these studies used standard verbal WM tasks that confound serial order and item retention abilities.

The studies by Attout et al. indeed show that depending on the type of information that is assessed, verbal WM performance is either preserved or impaired.

However, while the studies described here indicate a close association between serial order WM and numerical cognition, they do not directly inform us about the reasons for these associations. The most straightforward explanation would be to consider that numerical tasks, such as mental calculation tasks, require temporary sequential storage abilities for maintaining the numbers and operators of a calculation problem in correct order in WM, and also for relating the successive results of the different operations and sub-operations to each other. This functional link between WM and numerical tasks is supported by the results from the longitudinal study by Attout et al. (2014) showing that early serial order WM abilities predict later calculation abilities, while the reverse prediction is not observed. However, as we will see, the association between serial order WM and numerical cognition may also reflect deeper, representational links, due to the possible sharing of codes used for representing order information in the numerical and WM domains. We consider here that numbers are not only associated with codes informing about their numerical magnitude, but also with codes informing about their ordinal position in the numerical chain, in line with recent studies suggesting that magnitude and ordinal processing can dissociate at behavioral and neural levels (Lyons & Beilock, 2013; Turconi, Jemel, Rossion, & Seron, 2004). Before examining further this representational account of the links between serial order WM and numerical cognition, we need to examine how current models of WM explain the representation and maintenance of serial order information.

WM: The nature of serial order codes

The WM literature is particularly rich as regards theoretical accounts for the representation of serial order. While differing in the precise manner serial order representations are implemented, the vast majority of WM models currently consider distinct representational levels for item and order information. This is in line with an increasing number of empirical studies suggesting a separation of cognitive and neural processes involved in the maintenance of item versus serial order information, such as the studies by Attout and colleagues discussed in the previous section (see also Hachmann et al., 2014; Henson, Hartley, Burgess, Hitch, & Flude, 2003; Martinez-Perez et al., 2012; Majerus et al., 2006a, 2010; Majerus, Attout, Artielle, & Van der Kaa, 2015; Nairne & Kelley, 2004, and later sections of this chapter).

Models considering a separation between item and serial order representational levels assume the existence of specific context signals for encoding serial position information. These context signals can take different forms. Some models consider that the context signal is a uni-dimensional primacy marker which is most active for items occurring at the beginning of a list (e.g., Page & Norris, 1998). Other models assume more specific codes for the representation of serial order. One of these models is the Start-End model proposed by Henson (1998). This model assumes that items are associated to nodes representing the start and the end of the list, respectively. Early items of a WM list will be strongly associated with the start node, and weakly with the end node, while the reverse will be true for end-of-list items; items of the middle of a WM list will show intermediate levels of association with both the start and the end nodes. This model was one of the first positional models of serial order WM by explicitly assuming that items of a WM list are associated with distinct codes as a function of their serial position within a list. At the same time, these positional codes are still rudimentary, as they code for only two positional dimensions: start-of-list and end-of-list.

The idea of position-specific codes for serial order has been further developed by proposing context signals that contain specific codes for each serial position. One instance of

this type of model is the architecture proposed by Burgess and Hitch (1999, 2006). Burgess and Hitch proposed a mechanism by which item representations are associated with a context signal dynamically changing for each successively presented item during WM list encoding. At recall, a replay of the context signal and its successive states allows to retrieve the items associated with each state, and to output the items in correct serial position. This model assumes that each serial position is represented by a specific code although the nature of this code is not further specified. Brown, Preece and Hulme (2000) proposed an even more explicit architecture, by assuming that the contextual signals are time-based signals such as oscillators. In this type of architecture, each item is associated with the successive peaks of the oscillator which can be compared to the advancement of the hands of a clock. The authors further assume that multiple oscillators can be in operation, oscillating at different speeds, allowing to encode serial position information simultaneously at different time scales, as needs to be the case when items are temporally grouped; in that case, the order of the items can be defined relative to their order in the whole memory list, but also relative to their order within the temporal subgroups. In sum, Brown et al. assume that serial position information is encoded via time-based codes which have an intrinsically ordinal organization, just like numerical codes. This type of account has been recently refined by Hartley, Hurlstone and Hitch (2016). The authors proposed an architecture containing a population of oscillators for encoding serial position information at different levels of the list, with the oscillators fitting best the temporal regularities of a stimulus sequence being chosen in a bottom-up manner, based on the amplitude modulations of the speech envelope.

A final model comes even closer to the notion of ordinal codes for the representation of serial order information, by proposing numerical rank-based ordinal codes. In their neurocomputational model, Botvinick and Watanabe (2007) proposed that numerical rank order information is associated with each item representation, as a function of the order of

presentation of each item. A similar assumption characterizes the context-serial-order-in-a-box model (Lewandowsky & Farrell, 2008) as well as the first model proposed by Burgess and Hitch (1992); these models also considered that serial order is encoded via a context signal that reflects absolute position from the start of the sequence, like numerical rank order information.

It should be noted that a few models do not consider a separation between item and serial order codes but consider that serial order is encoded via item-by-item chaining mechanisms, by intrinsic encoding energy levels which decrease with each new incoming item or by cues inherent to phonological item information (e.g., Botvinick & Plaut, 2006; Farrell & Lewandowsky, 2002; Jones, Madden, & Miles, 2007; Lewandowsky & Murdock, 1989). These models typically have difficulties in accounting for several critical phenomena of serial order processing such as temporal grouping or in dealing with item repetitions (Farrell & Lewandowsky, 2002; Hurlstone, Hitch, & Baddeley, 2014; Hartley et al., 2016). Furthermore, as already mentioned, an increasing number of studies suggests that capacities for maintaining item and serial order information can dissociate at both behavioral and neural levels (Henson et al., 2003; Majerus et al., 2006a, 2010, 2015; Majerus, Attout, Artielle, & Van der Kaa, 2015; Marshuetz, Smith, Jonides, DeGutis, & Chenevert, 2000). Importantly, distinct variables influence item and serial order recall, with linguistic factors such as word frequency and semantic knowledge affecting mainly item recall (Nairne & Kelley, 2004; Poirier & Saint-Aubin, 1995); conversely, articulatory suppression, temporal grouping and rhythmic grouping exert stronger effects on serial order than item memory performance (Henson et al., 2003). Hence, there is currently no strong evidence in favour of serial order WM models that consider that item and serial order information are represented via a single, common mechanism.

This short review of the most representative serial order WM models allows us to consider the associations observed between serial order WM and numerical cognition in a new light. One common feature of most of the models reviewed here is the use of domain-general positional codes, which in addition, for some models, have an inherent ordinal organization, such as temporal or numerical signals. By comparing these theoretical proposals with the empirical data presented in the first section of this chapter, we can raise the hypothesis that serial order WM and numerical cognition are not only associated due to the involvement of WM resources in numerical tasks, but that their association may be due to a common activation of ordinal, and possibly numerical codes. In other words, the codes used to represent the ordinality of number information may also be those used to represent the serial positions in WM. In the next section, we will first examine the evidence in favour of domain-general codes used for representing serial order information across different WM domains, as implicitly or explicitly assumed by current theoretical models of serial order WM. After this more general focus on the existence of domain-general serial order codes across WM domains, we will examine more specific empirical evidence for shared ordinal codes in the numerical and the WM domains.

Evidence for domain-general codes for the representation of serial order in WM

An increasing number of empirical studies are supporting the assumption of domain-general mechanisms for the representation and maintenance of serial order information in WM. A first part of evidence stems from studies that have compared serial order processing across verbal and visuo-spatial WM domains. These studies show that several hallmark effects of serial order WM in the verbal domain can also be observed in the visuo-spatial domain (see Hurlstone et al., 2014, for a recent review). A first hallmark effect concerns the overall shape of the serial response curve which is marked by a strong primacy and smaller recency effect,

reflecting better recall of initial and late items as compared to middle of list items. These primacy and recency effects are very robust in verbal immediate serial recall (e.g., Less & Estes, 1981) and have also been observed for various visuo-spatial material such as spatial locations (Guérard & Tremblay, 2008), visual configurations (Avons, 1998) and unknown faces (Smyth, Dennis, & Hitch, 2005; Ward, Avons, & Melling, 2005).

The type of serial order errors observed during serial recall provide further, and also more direct evidence for the similarity of the serial order maintenance processes involved in verbal and visuo-spatial domains. Of special importance here are the transposition gradients which reflect a locality constraint: serial position exchanges are more likely to occur for adjacent than for more distant items, with the likelihood of serial position exchange errors decreasing linearly with the increase of the distance between the two serial positions. This gradient is very typical for verbal immediate serial recall tasks (e.g., Burgess & Hitch, 1999; Henson, 1998), and is also observed for the reproduction of visuo-spatial sequences (Hurlstone & Hitch, 2015; Parmentier, Andres, Elford, & Jones, 2006; Smyth et al., 2005).

A further important characteristic of serial order is the way it can influence recall performance by the nature of its temporal organization: Items whose serial positions are temporally grouped (by using shorter inter-item temporal intervals for within-group items relative to items at the boundaries of two groups), lead to higher recall performance than items presented at a monotonous presentation rate. Temporal grouping effects have been studied quite extensively at the level of verbal WM (e.g., Frankish, 1985; Henson, 1998; Hitch, Burgess, Towse, & Culpin, 1996). In addition to leading to higher WM recall performance, they also induce within-group micro-primacy and micro-recency effects. As a corollary, temporal grouping leads to an increase of interposition errors, with serial position exchanges involving more frequently the same intra-group serial positions (e.g., the likelihood of serial position exchanges between the first item of a group and the first item of another

group is higher than the likelihood of serial position exchanges between the first item of a group and the second item of another group). The temporal grouping effect and several of its consequences listed here have also been observed for the reproduction of auditory-spatial and visuo-spatial sequences (Parmentier, Mayberry, & Jones, 2004; Parmentier et al., 2006). Further evidence for cross-modal serial order coding mechanisms stems from studies that have shown that retention of serial order information in the verbal modality is impacted by a concurrent task involving the retention of serial order information in the visuo-spatial domain, and vice-versa (Depoorter & Vandierendonck, 2009; Vandierendonck, 2016). Importantly, these cross-domain interference effects were diminished when the concurrent task involved item rather than serial order recall.

Some of these hallmark effects of serial order coding can also be observed in other modalities than in the verbal and visuo-spatial domains, although these domains have been investigated less extensively. In the auditory non-verbal domain such as the musical WM domain, several studies have shown similar serial order effects as for the verbal and visuo-spatial domains. A recent study by Gorin, Kowialiewski and Majerus (2016) showed that tone sequence WM tasks probing retention of serial order but not item information lead to detrimental performance when a temporally organized, rhythmic sequence has to be reproduced during the retention interval. These findings parallel earlier findings observed for the verbal WM domain by Henson et al. (2003), where the same type of rhythmic interference task had a negative impact on serial order but not item recognition of verbal memoranda. Similarly, the impact of temporal grouping, observed in the verbal and visuo-spatial domains, has also been observed for musical WM tasks: Deutsch (1980) observed higher memory performance for grouped than ungrouped tone sequences in expert musicians, and Gorin, Mengal and Majerus (submitted) observed similar findings in non-musician participants using a serial order recognition task for tone sequences. Finally, the same type of transposition

gradients for serial order exchange errors observed in the verbal and visuo-spatial WM domains also characterize the serial order errors observed during musical sequence recall tasks (Mathias, Pfordresher, & Palmer, 2014; Pfordresher, Palmer, & Jungers, 2007). A recent study also showed that reproduction of tactile stimulus sequences leads to the same type of serial position curve, with marked primacy and recency effects, as in the verbal WM tasks (Johnson, Shaw & Miles, 2016).

Neuroimaging studies further support the similarity of mechanisms involved in the retention of serial order information in verbal and visuospatial domains, as well as the specificity of serial order coding mechanisms relative to item maintenance. Several studies showed that the encoding and recognition of serial order information recruits a fronto-parietal network centered on the right intraparietal sulcus for sequences of verbal information such as letters, words and nonwords, as well as for sequences of visual information such as sequences of unfamiliar faces (Majerus et al., 2006b, 2007, 2010; Marshuetz et al., 2000; Martinez Perez, Poncelet, Salmon, & Majerus, 2015). These shared neural activity foci cannot be simply attributed to domain-general attentional control processes involved in WM (Cowan, 1995; Barrouillet, Bernardin, & Camos, 2004) given that the activations in the right fronto-parietal network were specific to the serial order conditions; cross-domain and cross-condition shared activity foci were also observed but these involved a fronto-parietal network centered on the left intraparietal sulcus which, in other studies, has indeed been associated with domain-general attentional control processes (Cowan et al., 2011; Majerus et al., 2010, 2012, 2016). It should also be noted that domain-specific activations were observed for the verbal and visuo-spatial WM tasks, and mainly involved sensory cortices, with fronto-temporal cortices for the verbal WM tasks, and fusiform cortices for visual WM tasks.

Evidence for domain-general codes for the representation of ordinal information in WM and numerical cognition

The cognitive and neural similarities observed for coding of serial order information across several WM domains presented in the preceding section and synthesized in Table 1 are in line with the assumption of specific but domain-general mechanisms for serial order, as proposed by most of current theoretical models of serial order WM. Importantly, some of the effects described in the preceding section extend the WM domain and also characterize the numerical domain.

< INSERT TABLE 1 ABOUT HERE >

A first of these effects is the distance effect in recognition WM tasks, which is the corollary of the transposition gradients that characterize the serial ordering errors in WM recall tasks. In recognition WM tasks, participants make more errors and show slowed response times when judging items from adjacent serial positions than when judging items from more distant serial positions (Henson et al., 2003; Holyoak, 1977; Marshuetz et al., 2000). This distance effect is one of the hallmark effects also observed in the numerical literature. An important number of studies has shown that during number comparison tasks, such as magnitude judgment or ordinal judgment, number pairs that are close (such as 64-65) take more time to be judged than more distant numbers (such as 32-65) (Buckley & Gillman, 1974; Foltz, Poltrock, & Potts, 1984; Moyer & Landauer, 1967; Turconi, Campbell, & Seron, 2006). Very interestingly, these distance effects in the numerical domain seem to depend upon the same neural substrates as those supporting serial order coding in the WM domain. In several neuroimaging studies, the intraparietal sulcus has been shown to be sensitive to the distance between different numbers, with greater activation for close versus distant numbers (Pinel, Dehaene, Rivière, & LeBihan, 2001; Chochon, Cohen, van de Moortele, & Dehaene, 1999). Marshuetz et al. (2006) showed that the same intraparietal sulcus area is also sensitive

to distance effects in serial order WM tasks: the intraparietal sulcus is more strongly activated when participants have to compare close serial positions than when they have to compare more distant serial positions.

In a recent neuroimaging study, Attout et al. (2014) directly compared ordinal number comparison and serial order WM recognition tasks, while varying the distance effect in both tasks. In the number ordinal comparison tasks, the participants had to decide whether a number appearing on the screen occurs before or after a target number; the numerical distance between the probe number and the target number was varied. In the WM tasks, the participants had to maintain a sequence of four letters, followed by a probe display presenting two letters from the sequence, and the participants had to decide whether the two letters were presented in the same order as in the memory list; the serial position distance between the two target letters was varied. The authors observed a parametric modulation of activity in the intraparietal sulcus for the distance effects in both the numerical and serial order WM tasks, suggesting that processing of ordinal information in WM and numerical domains is supported by similar neural substrates. It should be noted that these distance-sensitive activity foci in the intraparietal sulcus were bilateral, while previous studies associated serial order processing in WM more specifically with the right intraparietal sulcus (Majerus et al., 2010). This bilateral activation of the intraparietal sulci could have been due to the additional involvement of attentional control processes: when judging close and distant serial positions/numbers, there is not only a difference at the level of ordinal representations, but closer positions/numbers are also harder to judge, which may recruit attentional control processes to a larger extent. As we have already noted, the left intraparietal sulcus has been associated more specifically with attentional control processes as compared to the right intraparietal sulcus in the context of WM tasks (see also, Majerus et al., 2016). Studies comparing directly magnitude and ordinal judgment in the numerical domain, thereby controlling for attentional processes equally

associated with both types of judgments, have indeed observed a stronger recruitment of right hemisphere activity for the ordinal judgment tasks as compared to the magnitude judgment tasks (Turconi et al., 2004).

Further evidence for a close association between the representations involved in coding order information in the WM and numerical domains comes from a series of studies initiated by Van Dijck and Fias. A hallmark effect in the numerical literature is the SNARC effect for Spatial Numerical Association of Response Codes. The SNARC effect, in the numerical domain, is characterized by faster responses with the left hand for judging small numbers (and hence positioned to the left of the number sequence) and faster responses with the right hand for judging larger numbers (positioned to the right in the number sequence) (Dehaene, Bossini, & Giraux, 1993). This effect has been explained as representing an association between numerical and spatial representations. Importantly, a very similar effect has been recently documented in the WM domain. In their seminal study, Van Dijck and Fias (2011) had participants memorize sequences of words which, during the maintenance interval, were represented for semantic judgment together with words that had not been present in the memory list; participants had only to judge those words that had been present in the list (go-trial). No explicit numerical or positional judgment had to be performed, but participants had to activate each word in WM before deciding to make a response. The authors observed similar positional effects and position-space associations as observed during the SNARC effect: Participants were faster in judging the semantic category of the words with their left hand when the words came from the beginning of the memory list, and they were faster in responding with their right hand when the words were situated towards the end of the memory list. These results suggest that the serial position of stimuli in a WM list activates similar representations as those involved when processing numbers in number comparison tasks, and further suggest that these representations are not only organized in an ordinal numerical

manner, but also in a spatial manner. This positional SNARC effect has been shown to be independent of the visual or auditory presentation of the memory list, and hence cannot be explained by spatial encoding strategies only (Ginsburg, van Dijck, Previtali, Fias, & Gevers, 2014; Guida, Leroux, Lavielle-Guida, & Noël, 2016).

The importance of the spatial dimension associated with serial position codes has been further demonstrated by a follow-up study. Van Dijck, Abrahamse, Majerus and Fias (2013) had participants conduct a dot location task rather than a word or number judgment task during the retention interval of a list of numbers. The dots appeared on the left or the right side of the screen, and were preceded by the presentation of numbers, some being part of the memory list, some being new; participants had to respond to the dots only if the number that preceded was from the memory list. The authors observed that participants were faster in detecting dots located on the left of the screen when the memory list item they had just seen was from an early serial position in the memory list. Conversely, they were faster in detecting dots located on the right of the screen when they just seen a memory item stemming from late serial positions. A similar result was observed in a study by Antoine, Ranzini, Gebuis, Van Dijck and Gevers (2016). These authors used the paradigm developed by Van Dijck et al. (2013) but replaced the dot location task by a line bisection task. Antoine et al. observed that the line bisection midpoint was shifted to the right when participants were retrieving items from the end of the memory and it was shifted to the left when participants were retrieving items from the start of the memory list. These results suggest that codes involved in the representation of serial position information in WM have a spatial, ordinal organization, just like numbers, and are able to bias the focus of spatial attention (Abrahamse, van Dijck, Majerus, & Fias, 2014).

Evidence against a direct assimilation of numerical ordinal codes and serial order WM codes

These findings lead us to further speculate on the nature of the codes used to represent serial order information in WM. Some of the studies presented here suggest that their nature could be spatial (van Dijck et al., 2013; Abrahamse et al., 2014; Ginsburg et al., 2014; Van Dijck & Fias, 2011). Other studies indicate a number of striking similarities between the processing of serial position information in WM and ordinal numerical information, as shown by the similar distance effects that appear when participants have to compare different serial positions in WM or different numbers in a number comparison task (Attout et al., 2014). This raises the possibility that numerical codes may also support the coding of serial position information in WM, in line with some of the computational models of serial order WM described earlier in this chapter (Botvinick & Watanabe, 2007). Intuitively, we are very frequently using numbers to label, maintain and retrieve serial position information. Typically, when recalling information in WM tasks, we are using numbers to retrieve the items and their serial positions, by saying: “This item was first, the second and the third items were ..., the fourth and fifth items I don’t remember any more ...”.

We report here the results of two recent studies that have explored more directly the hypothesis of the intervention of numerical ordinal codes for the representation of serial order information in WM. A first study re-explored the associations between serial order WM and numerical abilities, by taking into account both general numerical arithmetic abilities, ordinal numerical judgement abilities and magnitude numerical judgment abilities in 102 children aged 8 to 10 years (Attout & Majerus, submitted). The authors first confirmed the findings of previous studies, by showing a specific association between serial order WM abilities and mental arithmetic abilities, after control of age, non-verbal and verbal intelligence estimates ($r_{\text{partial}}=.30, p<.01$). Critically, when determining to what extent the association between serial

order WM abilities and mental arithmetic abilities was due to activation of numerical representations, the authors observed that ordinal numerical judgment abilities fully mediated the link between serial order WM and mental arithmetic abilities. At the same time, the link between ordinal numerical and mental arithmetic abilities remained significant when testing the mediation of this effect by serial order WM abilities. These results suggest that, at least for children aged 8 to 10 years, the link between serial order WM abilities and mental arithmetic abilities reflects a shared component of ordinal processing abilities. Note however that this link is not necessarily specific to processing of numerical information, given that numerical magnitude judgment did not mediate the link between serial order WM and mental arithmetic abilities. The existence of more general ordinal processing abilities being involved in serial order WM abilities is also supported by findings from an earlier study by Attout et al. (2014), showing that the cognitive and neural distance effects observed in serial order WM and ordinal numerical judgment tasks also characterize alphabetic judgment abilities; furthermore, the correlations between the size of the behavioral distance effects were more robust for serial order WM and alphabetic judgment tasks than for serial order WM and numerical judgment tasks.

Another recent study assessed the hypothesis of numerical codes for serial order coding in WM by pre-installing associations between numbers and stimuli to be maintained in a verbal WM task (Majerus & Oberauer, in preparation). The rationale of this study was that if number codes are directly used to represent serial position information in WM, then word-digit associations may facilitate or interfere with serial position coding in WM, depending on the congruency of the digit associated to each word with the numerical rank of the word's serial position in the WM list. Participants learnt a list of twelve word-digit associations, with each digit (from 1 to 6) being associated to two different words. In a subsequent phase, the words were presented in memory lists, with the words occurring in serial positions whose

numerical rank matched the learnt word-digit association (facilitation condition) or did not match the word-digit association (interference condition). Memory was probed either using a serial order recognition task or an immediate serial recall task. For the serial order recognition task, no effect of either facilitation or interference of word-digit associations on memory performance was observed. In the immediate serial recall task, an effect of interference was observed for both the interference and facilitation conditions. These results indicate that if number codes intervene during serial order WM tasks, then this intervention is limited to the recall stage, given that no effect was observed for the serial order recognition task. But even for the recall stage, the results need to be nuanced, given that interference effects were observed for both the facilitation and the interference conditions, indicating that, if numerical codes accompany retrieval of serial position information, they are easily disturbed by the concomitant presentation of any other numerical information.

The equivalence of numerical and WM ordinal representations has also been questioned in a series of studies following up the SNARC effect observed in WM tasks. In several studies, Ginsburg and collaborators showed that SNARC effects in WM tasks and typical numerical SNARC effects can co-exist, and hence result from different levels of representation. In a first study, Ginsburg et al. (2014) showed that when participants had to categorize both memorized and non-memorized numbers during a WM retention delay, the positional SNARC effect for WM items disappeared, while a typical numerical SNARC effect emerged. They observed faster left-hand responses for small numbers and faster right-hand responses for large numbers, independently of the numbers' WM status and, for the numbers in WM, independently of their serial position in the WM list. Ginsburg et al. (2014) argued that the positional SNARC effect is due to the temporary creation of position–space bindings in WM while the numerical SNARC effect is due to the long-term activation of the mental number line. They directly showed the operation of these two types of SNARC effects in a

subsequent study in which participants were randomly instructed, within the same task, to classify only WM items or to classify all items: both a positional SNARC and a numerical SNARC effect were observed (Ginsburg & Gevers, 2015). These results show that numerical ordinal representations have their own existence, independently of temporary serial position – space associations created in WM.

Conclusions

Two main conclusions can be drawn from this theoretical review. First, there is an increasingly large body of research indicating that domain-general representations and processes support the representation of serial order information in verbal, non-verbal auditory and visuo-spatial WM. This is in line with the majority of current theoretical accounts of serial order WM which consider that serial order is processed by specific positional context signals distinct from the modality-specific mechanisms used to represent item information in WM (see also Hurlstone et al., 2014). At the same time, there remain many open questions as regards the nature of the codes used to represent serial position information in WM. Serial position effects across domains can look similar and yet stem from distinct processes. This is nicely illustrated by the multiplicity of computational models of serial order WM models reviewed in this chapter: all the models we discussed are able to simulate most of the hallmark effects that characterize serial order WM while substantially differing in the precise implementation of the mechanisms used for representing serial order information. Also, overlapping neural activity has been observed in the right intraparietal sulcus for processing serial order information in the verbal and visuo-spatial domains, but multivariate voxel pattern analysis (MVPA) studies still need to be conducted in order to determine whether the same type of neural information characterizes right intraparietal sulcus activity when processing serial order information in the verbal and visuo-spatial domains (see Fias, Lammertyn,

Caessens, & Orban, 2007, and Zorzi, Di Bono, & Fias, 2011, for studies illustrating how univariate and MVPA analyses of intraparietal sulcus activity can lead to very different conclusions about the similarity of neural processes involved in several order processing tasks). Also, we should not exclude the possibility that both domain-general and domain-specific processes could support serial order WM. Kalm and Norris (2014), using MVPA, showed that neural patterns in linguistic sensory cortices, dedicated to verbal item processing, can also represent serial order information, at least as regards sublexical phonological sequence information. At the same time, Kalm and Norris showed that, within the language cortices, distinct codes were involved for representing item and serial order information, and the neural representations identified by MVPA supported positional context signal rather than chaining models of serial order coding.

The second important conclusion we can draw from this theoretical review is that there is a growing body of research indicating close associations between serial order WM and numerical cognition. A number of studies have shown that there is a functional association between the two domains, by highlighting the specific links that exist between verbal WM capacity for serial order information and arithmetic abilities, and by showing specific serial order WM deficits in participants with dyscalculia or a history of dyscalculia. As we have argued at the beginning of this chapter, this association could reflect the fact that temporary sequential storage processes are necessary for actively maintaining the numbers and operators of a mental calculation problem as well as the sequence of operations carried out and their associated results. There are also some indications for a representational link between serial order WM and number domains, as shown by the existence of similar ordinal effects in both domains such as the distance effect or the SNARC effect. Furthermore, the same neural substrates in the intraparietal sulci support distance effects in the serial order WM and the numerical domains, although, again, these conclusions are drawn from studies using

univariate study analysis designs; the neural representational similarity of distance effects observed in WM and numerical tasks still needs to be determined using MVPA experimental designs. Further evidence for representational overlap comes from the recent study by Attout and Majerus (submitted) showing that the link between serial order WM and mental calculation is fully mediated by ordinal numerical judgment abilities, suggesting that there are shared ordinal representations or processes in the WM and numerical domains.

At the same time, these results do not indicate that the shared ordinal representations are necessarily or exclusively numerical. There is even some evidence against a purely numerical nature of these shared representations. As we have noted, ordinal distance effects can be observed across many different domains, and Attout et al. (2014) observed that the correlation between alphabetical and serial order WM distance effects is stronger than the correlation between numerical and serial order WM distance effects. Furthermore, the studies by Ginsburg and colleagues have shown a clear independence between numerical SNARC effects and positional SNARC effects in WM. The fact that numerical representations cannot drive the positional SNARC effect in WM is most clearly demonstrated by the fact that a numerical SNARC effect can occur on the stimuli held in WM (Ginsburg & Gevers, 2015, Experiment 2). If the positional SNARC effect in WM was due to the activation of number codes associated with the serial positions of number stimuli held in WM, then it should be difficult to obtain a typical numerical SNARC on the same numbers: The numerical value of the numbers and that of their serial position in the WM list should interfere with each other. In the study by Ginsburg and Gevers (2015), there was no hint that the numerical SNARC would have been attenuated for items activated in WM relative to non-WM items. Similarly, the study by Majerus and Oberauer provided very limited evidence for a direct involvement of number codes in the representation of serial order information in WM.

What could the codes used to represent serial order then be like? On the basis of the empirical and theoretical studies discussed here, the codes used to represent serial order information appear to be positional, ordinal and in close connection to spatial and/or temporal dimensions (see also Fias, 2017, this volume). The results of the positional SNARC effect and its ability to orient spatial attention support the notion of spatial markers for serial position, in a left-to-right dimension. These results are also in line with some of the theoretical models of serial order WM discussed here, such as the Start-End model (Henson, 1998) which represents serial position information via a dimension that can be easily translated in spatial terms (the start of a verbal sequence is typically represented to the left, and the end of a verbal sequence list is typically represented to the right, at least for individuals used to a left-to-right writing system). Other studies suggest the role of temporal processes, such as the studies demonstrating the impact of temporal regularities on serial position coding, with temporal grouping of memoranda facilitating serial order coding, and the presentation of non-memory rhythmic sequences interfering with serial order recall, in verbal, visuo-spatial and musical modalities. We also have seen that a significant number of computational models implementing temporal codes provide robust accounts for the representation of serial order information, and are the only models able to explain temporal grouping effects (Brown et al., 2000; Hartley et al., 2016). Currently, given the available data, it is difficult to tease apart the spatial and temporal hypotheses, both types of codes could intervene simultaneously, or could reflect an even more abstract type of ordinal reference frame which would allow to represent the spatial and temporal relations between successive elements (Fias, et al., 2007, Ragni, Franzmeier, Maier, & Knauff, 2016). Neuroimaging studies highlighting right intraparietal involvement for serial order processing in WM are compatible with both spatial and temporal hypotheses, as the right parietal cortex is typically involved in both spatial and temporal tasks, (Arend, Rafal, & Ward, 2011; Cabeza et al., 1997; Cazzoli, Müri, Kennard, & Rosenthal,

2014; Chechlacz, Rotshtein, & Humphreys, 2014; Corbetta & Shulman, 2011; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Konoike et al., 2015; Hubbard, Piazza; Pinel & Dehaene, 2005; Rao, Mayer, & Harrington, 2001).

Future studies need to determine the exact nature of the context signals used for representing serial order information in WM, by manipulating simultaneously temporal and spatial dimensions and their impact on serial order WM, in order to determine whether only one of the two dimensions is important for serial order WM, whether both dimensions support independently serial order WM, or whether both dimensions reflect a more general, abstract ordinal reference frame. Future studies also will need to determine how these dimensions interact with numerical ordinal representations and mediate the link observed between serial order WM and numerical cognition.

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Table 1. Synthesis of studies examining the domain-generality of serial order processing

Main findings	Studies
Serial order effects across WM domains	
<ul style="list-style-type: none"> • Primacy and recency effects in verbal, visual, visuo-spatial and tactile WM 	Avons, 1998; Guérard & Tremblay, 2008; Johnson et al., 2016 ; Lee & Estes, 1981; Smyth et al., 2005 ; Ward et al., 2005
<ul style="list-style-type: none"> • Transposition gradients in verbal, visuo-spatial and musical WM 	Burgess & Hitch, 1999 ; Henson, 1996 ; Hurlstone & Hitch, 2015; Mathias et al., 2015 ; Palmer & Pfordresher, 2003 ; Parmentier et al., 2006; Pfordresher et al., 2007 ; Smyth et al., 2005
<ul style="list-style-type: none"> • Temporal grouping effects in verbal, auditory-spatial, visuo-spatial and musical WM 	Deutsch, 1980 ; Frankish, 1985; Henson, 1996; Hitch et al., 1996; Parmentier et al., 2004, 2006
<ul style="list-style-type: none"> • Cross-domain (verbal, visuo-spatial, motor, musical) interference by maintenance/reproduction of serial order 	Depoorter & Vandierendonck, 2009 ; Gorin et al., 2016; Henson et al., 2003 ; Vandierendonck, 2016
Ordinal effects in WM and numerical cognition	
<ul style="list-style-type: none"> • Distance effects in WM and number comparison tasks 	Attout et al., 2014 ; Henson et al., 2003 ; Holyoak, 1977 ; Marshuetz et al., 2000 ; Moyer & Landauer, 1967; Turconi et al., 2006
<ul style="list-style-type: none"> • Position-space associations in WM and numerical cognition 	Antoine et al., 2016 ; Dehaene et al., 1993 ; Ginsburg et al., 2014 ; Guida et al., 2016 ; Van Dijck & Fias, 2011 ; Van Dijck et al., 2013
<ul style="list-style-type: none"> • Independence of position-space associations in WM and numerical cognition 	Ginsburg et al., 2014; Ginsburg & Gevers (2015)
Overlapping neural substrates	
<ul style="list-style-type: none"> • Bilateral or right intraparietal sulcus involvement for serial order WM in verbal and visuo-spatial domains and for ordinal numerical processing 	Attout et al., 2015 ; Majerus et al., 2006, 2007, 2010; Marshuetz et al., 2000, 2006 ; Martinez Perez et al., 2015 ; Pinel et al., 2001