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Beyond magnitude: Judging ordinality of symbolic number is unrelated to magnitude comparison and independently relates to individual differences in arithmetic

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ABSTRACT

In the field of numerical cognition, ordinality, or the sequence of numerals, has received much less attention than cardinality, or the number of items in a set. Therefore it is unclear whether the numerical effects generated from ordinality and cardinality tasks are associated, and whether they relate to math achievement and more domain-general variables in similar ways. To address these questions, sixty adults completed ordinality, cardinality, visual–spatial working memory, inhibitory control and math achievement tasks. The numerical distance effect from the cardinality task and the reverse distance effect from the ordinality task were both relatively reliable but not statistically significantly associated with one another. Additionally, both distance effects predicted independent unique variance in math scores, even when visual–spatial working memory and inhibitory control were included in the regression model. These findings provide support for dissociation in the mechanisms underlying cardinal and ordinal processing of number symbols and thereby highlight the critical role played by ordinality in symbolic numerical cognition.

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1. Introduction

Number symbols have been studied extensively as representations of specific quantities (e.g., Nieder & Dehaene, 2009). For example, much research has investigated how children learn that the Arabic symbol "5" refers to five items (for a review see Ansari, 2008). This referent of symbolic numbers is called the symbol's cardinality, or the number of items in a set that a symbol represents (e.g., Lyons & Beilock, 2013).

An important and often overlooked attribute of symbolic numbers is that they not only have symbol–magnitude associations, as in cardinality, but also symbol–symbol relationships, or ordinality (e.g., Nieder, 2005; Vogel, Remark, & Ansari, 2015). Ordinality refers to the sequencing of number symbols, for example five is the fifth number – it comes after four and before six (Lyons & Beilock, 2013). In order to fully characterize the cognitive nature of symbolic number processing, it is critical to learn more about the differences and similarities between ordinal and cardinal processing of symbolic number. This has important implications for models of symbolic number processing and how children learn to process numerical symbols.

1.1. Measuring cardinality and ordinality

Cardinality – or numerical magnitude – is commonly measured using a number comparison task. In this task, participants are presented with two numbers and asked to choose the larger or smaller of the two. This task generates a behavioural signature called the numerical distance effect (NDE), in which participants are faster and more accurate at choosing the correct number as the numerical distance between the target numbers increases (Moyer & Landauer, 1967). The NDE has been replicated in numerous studies since its first account (e.g., Holloway & Ansari, 2008; Lonnemann, Linkersdörfer, Hasselhorn, & Lindberg, 2011; Maloney, Risko, Preston, Ansari, & Fugelsang, 2010; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Defever, Van den Bussche, & Reynvoet, 2011; Swanson, 2011).

To measure ordinality, participants are typically presented with three number symbols and asked to indicate whether the numbers are in the correct ascending order (e.g., 1 3 5), or not in order (e.g., 1 5 3; Lyons & Beilock, 2011). Alternatively, two symbols may be presented and participants asked whether the digits are in ascending

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(e.g., 1 3), or descending (e.g., 3 1) order (Turconi, Campbell, & Seron, 2006). The reaction time and accuracy data from such ordinality tasks has been found to generate a so-called reverse distance effect (RDE). It is called the reverse distance effect because it exhibits a relationship that is opposite to that of the NDE revealed during number comparison: decreased accuracy and increased reaction time as the numerical distance between the target numbers increases (Franklin & Jonides, 2009). The RDE has been replicated with adult data using the three digit task (Lyons & Beilock, 2013) and has also been demonstrated in the two digit task by Turconi et al. (2006).

1.2. Shared mechanisms for ordinality and cardinality?

It is unclear whether ordinality and cardinality tap into different cognitive mechanisms and neuronal circuits. There has been some research to indicate that magnitude comparison and numerical ordering may be underpinned by different brain processes. Turconi, Jemel, Rossion, and Seron (2004) used event-related potentials (ERPs) and demonstrated a dissociation between cardinality and ordinality processes in the time course of the P2 component from electrodes close to the left parietal cortex. Complementary to the Turconi et al. (2004) results, Lyons and Beilock (2013), in a functional MRI (fMRI) study using a symbolic magnitude comparison task and an ordering task, found no overlapping regions of activation. However, in contrast to Turconi et al. (2004) and Lyons and Beilock (2013), Franklin and Jonides (2009) found common activation of the intraparietal sulcus (IPS) for both the magnitude comparison and ordering tasks. More specifically, the IPS demonstrated both a neural distance effect for the comparison task and a reverse of this distance effect for the ordering task. IPS activation was greater for smaller distances than larger distances for the comparison task, but greater for larger distances than smaller distances for the ordinality task. Thus the neural data concerning the mechanisms underlying cardinality and ordinality are presently inconclusive.

At the behavioural level, Turconi et al. (2006) asked participants either to judge the relative magnitude or order of pairs of single digits. They found different behavioural signatures depending on how the participants were asked to process the symbolic numerical stimuli: an NDE for the comparison task and an RDE for ascending pairs (e.g. 1 2) in the ordering task. This finding of a divergence in the behavioural signatures generated from the two tasks provides support for different underlying processes. However, it is important to note the demonstration of different task effects does not preclude the existence of shared mechanisms. In other words, it is still possible that the different effects for ordinality and comparison are significantly correlated with one another, which would suggest a common mechanism that gives rise to different effects depending on the task context.

The only study that has directly correlated judgements of symbolic ordinality and cardinality with one another focussed on grade one students. Specifically, using a paradigm similar to that employed by Turconi et al. (2006), Vogel et al. (2015) demonstrated an absence of a correlation between symbolic comparison and ordering performance in grade one children. Given that these data were obtained from young children, they leave unanswered the question of whether such an association emerges over developmental time or not.

1.3. Associations with math achievement

Although it is currently unknown whether there are common mechanisms underlying symbolic cardinality and ordinality, both are thought to be important for the development of more complex mathematical skills, such as arithmetic. Numerous studies have shown that the NDE from the symbolic number comparison task is related to math achievement in both adults and children (for a review see: De Smedt, Noël, Gilmore, & Ansari, 2013). A significantly smaller body of emerging evidence also demonstrates that ordering abilities are related to calculation skills in adults (Lyons & Beilock, 2011). This then raises the question of whether ordinality and cardinality play equally important roles in more complex mathematical skills.

In children it has been demonstrated that magnitude comparison and ordering skills relate differently to math achievement. Vogel et al. (2015) found that performance on a comparison task correlated significantly with math achievement in grade one children, while ordering abilities did not. Furthermore, Lyons, Price, Vaessen, Blomert, and Ansari (2014) captured a switch in the relative contributions to math achievement of cardinality and ordinality between grades one through six. Specifically, symbolic magnitude comparison predicted math achievement better than ordinality in the earlier grades, whereas ordinality was the stronger unique predictor in later grades. Thus, from the developmental literature it appears that ordinality and cardinality may relate differently to more complex mathematics, which may indicate that different mechanisms underpin them.

In adults there is a lack of research addressing the relationship between ordinality, cardinality and math achievement. Lyons and Beilock (2011) found that a performance measure (a combination of error rate and reaction time) derived from an ordinality task fully mediated the relationship between a non-symbolic (dot) magnitude comparison task and arithmetic. In support for the importance of ordinal skills, as opposed to symbolic number skills more generally, this mediation effect remained after controlling for performance on a symbolic number comparison task. This finding provides evidence of an important role for ordering abilities in adult mathematical skills. In support of this behavioural finding, Knops and Willmes (2014) demonstrated that clusters of activation in regions of the right IPS were correlated with both ordering and arithmetic tasks; however, a magnitude comparison task was not included. To date, there is no adult study that has looked at both symbolic comparison and ordering, and their relationships with math achievement.

Additionally, there has been no study relating the RDE to math performance. The RDE is a behavioural signature that differentiates ordering from magnitude comparison, a task which conversely shows a canonical distance effect (Turconi et al., 2006). The NDE is considered a measure of magnitude processing, and has been associated with math achievement in the literature (De Smedt et al., 2013). The NDE is often considered a measure of the precision of the number representation system (De Smedt, Verschaffel, & Ghesquière, 2009; Holloway & Ansari, 2009). Accordingly, the NDE has been shown to decrease across development (Holloway & Ansari, 2008; Sekuler & Mierkiewicz, 1977). Moreover evidence from both children and adults has consistently demonstrated that a smaller NDE is associated with increased math achievement scores (e.g. Castronovo & Göbel, 2012; De Smedt et al., 2009; Holloway & Ansari, 2009). As is the case for the NDE, the RDE could be considered a task-specific measure of ordering abilities, and therefore it is important to probe whether there exists an association between this effect and math achievement. In addition, in the context of investigating the similarities and differences between cardinal and ordinal processing of number symbols, it is critical to investigate whether the NDE and RDE explain shared or independent variance in individual differences in math achievement.

1.4. The current study

From the available neural and behavioural literature on ordinality and cardinality, it is unclear whether different mechanisms underlie these constructs in adults. Furthermore, it is unclear

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