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Verbal count sequence knowledge underpins numeral order processing in children☆

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ABSTRACT

Recent research has suggested that numeral order processing – the speed and accuracy with which individuals can determine whether a set of digits is in numerical order or not – is related to arithmetic and mathematics outcomes. It has therefore been proposed that ordinal relations are a fundamental property of symbolic numeral representations. However, order information is also inherent in the verbal count sequence, and thus verbal count sequence knowledge may instead explain the relationship between performance on numeral order tasks and arithmetic. We explored this question with 62 children aged 6- to 8-years-old. We found that performance on a verbal count sequence knowledge task explained the relationship between numeral order processing and arithmetic. Moreover many children appeared to explicitly base their judgments of numerical order on count sequence information. This suggests that insufficient attention may have been paid to verbal number knowledge in understanding the sources of information that give meaning to numbers.

From the earliest stages of formal mathematics education wide individual differences are observed in children's numeracy skills (Ginsburg, Lee, & Boyd, 2008;Jordan, Kaplan, Locuniak, & Ramineni, 2007). These individual differences are remarkably persistent throughout education and into adulthood (Duncan et al., 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009) with the consequence that a quarter of adults have insufficient numeracy skills for everyday activities (Department for Business Innovation & Skills, 2011). As a result, there has been increased interest over the past two decades in understanding the basic skills associated with individual differences in mathematics performance. This work is driven, in part, by a belief that understanding the basic skills involved could lead to developments in mathematics education practices and the earlier identification of children at risk for mathematics difficulties.

According to the Triple Code Model (Dehaene, 1992), numerical information can be internally represented in three codes: number words, Arabic digits and analogue magnitudes. Number words and digits are both forms of symbolic representations and can represent numerical information precisely. Analogue magnitudes are non-symbolic representations and can only represent numerical information approximately. The Triple Code Model proposes that these three representations are associated with one another, but certain numerical actions can be processed within a specific code.

For many years, attention has been paid to the role of analogue magnitude information in explaining individual differences in mathematics outcomes, in particular arithmetic (see Chen & Li, 2014; Fazio, Bailey, Thompson, & Siegler, 2014; Schneider et al., 2017 for reviews). This work has explored whether individual differences in the precision of magnitude representations or mappings between numerical symbols and magnitude representations (e.g. the connection between 7 and the analogue magnitude representation for ●●●●●●●) can account for differences in mathematics performance (De Smedt, Noël, Gilmore, & Ansari, 2013; Mundy & Gilmore, 2009; Sasanguie, Smedt, Defever, & Reynvoet, 2012; Schneider et al., 2018). The evidence to date is mixed and the role of symbol-magnitude mappings in mathematics remains a question of debate.

More recently attention has turned to symbol knowledge and the role of symbol to symbol mappings (i.e. the connections between a symbol, e.g. 5, and adjacent or more distant symbols, e.g. 4, 6, 7) in explaining differences in mathematics performance (e.g. Lyons, Ansari, & Beilock, 2012; Reynvoet & Sasanguie, 2016). In particular, an increasing number of studies have explored performance on numeral order processing

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tasks. These tasks typically involve showing participants triplets of Arabic digits and asking participants to decide whether the triplets are in numerical order (e.g. 4 5 6) or not (e.g. 4 6 5). Studies have demonstrated that performance on numeral order tasks is associated with mathematics performance, typically measured with an arithmetic task, in both adults (Goffin & Ansari, 2016; Lyons & Beilock, 2009, 2011; Morsanyi, O'Mahony, & McCormack, 2017; Sasanguie, Lyons, De Smedt, & Reynvoet, 2017; Vogel et al., 2017; Vos, Sasanguie, Gevers, & Reynvoet, 2017) and children (Attout & Majerus, 2018; Lyons & Ansari, 2015; Lyons, Price, Vaessen, Blomert, & Ansari, 2014). It has also been proposed that deficits in numeral order processing may be one factor that contributes to mathematical learning difficulties and dyscalculia (Morsanyi, van Bers, O'Connor, & McCormack, 2018; Rubinsten & Sury, 2011).

The accumulating evidence that performance on numeral order tasks is an important predictor of individual differences in mathematics outcomes has been interpreted in light of the debate about the relative importance of symbol-symbol relationships vs. symbol-magnitude relationships for mathematics learning and performance (Lyons et al., 2012; Reynvoet & Sasanguie, 2016). It has been suggested that, rather than number symbols gaining meaning from links to magnitude representations, symbols gain meaning from ordinal links to other symbols. This has implications not only for our understanding of how young children initially learn the meaning of numbers, but also the mechanisms which underlie symbol processing in older children and adults, and why some individuals have particular difficulties in performing operations with numerical symbols, e.g. arithmetic.

However, in order to shed light on these debates we need to identify the underlying mechanisms or processes that drive performance on numeral order tasks and account for the relationship between performance on numeral order tasks and mathematics. Why are individual differences in numeral order processing associated with individual differences in mathematics? There are several possible explanations. First, much of the previous literature suggests that order is a fundamental property of symbolic numeral representations and plays a crucial role in how we process and understand number symbols (Goffin & Ansari, 2016; Lyons & Ansari, 2015; Lyons & Beilock, 2011; Sasanguie et al., 2017). According to this proposal, long-term ordinal associations exist between symbols such that each symbol is associated with, and acts as a trigger for, adjacent symbols (Sasanguie et al., 2017). This order information is inherent in the numeral (digit) representation itself and doesn't arise from other numerical processes, such as count sequence knowledge i.e. number word representations, (Lyons & Ansari, 2015) or associations to magnitude (Goffin & Ansari, 2016). More advanced numerical skills, such as arithmetic, build on this order information and hence individual differences in ordinal processing are associated with individual differences in arithmetic performance.

Alternatively, the relationship between numeral order tasks and mathematics could arise because both numeral order tasks and symbolic mathematics involve fluently accessing semantic information from symbols. Rapid Automatized Naming (RAN) is the ability to name familiar stimuli (e.g. digits, letters, colours) quickly and accurately. Previous studies have demonstrated that RAN measures are related to mathematics outcomes (Cui et al., 2017; Geary, 2011; Hornung, Martin, & Fayol, 2017; Koponen, Salmi, Eklund, & Aro, 2013). In a meta-analysis of 38 studies, Koponen, Georgiou, Salmi, Leskinen, and Aro (2017) identified that RAN was significantly related to mathematics outcomes, with a stronger relationship for arithmetic and fluency measures rather than overall mathematics achievement. RAN is therefore a candidate skill that could explain the relationship between numeral order processing and arithmetic. Identifying whether the digits presented in a numeral order task are in order first requires the digits themselves to be identified. We would therefore expect RAN, and particularly RAN of digits to be associated with performance on a numeral order task.

Finally, the relationship between numeral order processing and mathematics could be driven by verbal count sequence knowledge. According to this explanation participants solve numeral order tasks by drawing on knowledge of the structure of the number system that is based on number word representations, rather than numeral (digit) representations. If verbal count sequence knowledge does underlie performance on numeral order processing tasks, then it is highly likely that this could explain the relationship between numeral order processing and arithmetic. Children's knowledge of the count sequence (often assessed as part of a general number system knowledge battery) is related to concurrent and later arithmetic and mathematics skills (Chard et al., 2005; Cowan, Donlan, Newton, & Llyod, 2005; Cowan & Powell, 2014; Geary, Hoard, & Hamson, 1999; Jordan et al., 2007; Stock, Desoete, & Roeyers, 2009). For example, Koponen et al. (2013) demonstrated that a measure of count sequence knowledge predicted arithmetic skills five years later. It is unsurprising that count sequence knowledge should be associated with arithmetic skills given that children (Geary, Hoard, Byrd-Craven, & DeSoto, 2004) and even adults (LeFevre, Sadesky, & Bisanz, 1996) make use of overt or covert counting strategies to solve arithmetic problems. Fluent access to count sequence knowledge would make these strategies more accurate and efficient. For frequently encountered problems, this in turn could increase number fact knowledge because more efficiently executed counting strategies would increase the likelihood that number facts could be later recalled.

There is some existing evidence to support the proposal that count sequence knowledge explains the relationship between numeral order processing and arithmetic skill. Lyons and Ansari (2015) explored which trials of a numeral order task were most closely associated with arithmetic in children. They found that performance on trials with ascending sequences of consecutive numbers (e.g. 4 5 6) were more closely associated with arithmetic performance than performance on trials in which the triplets were either not in order, or were in order but with larger distances (e.g. 4 6 8). Trials of ascending consecutive numbers are most closely associated with verbal count sequence knowledge.

Lyons and Ansari (2015) discounted count sequence knowledge as an explanation of the relationship between numeral order processing and arithmetic because the relationship between children's numeral order processing and arithmetic remained significant after controlling for performance on a counting task. However, the counting task used in this study only assessed the speed of object counting with between 1 and 9 objects. This is likely to have been only an imprecise measure of verbal count sequence knowledge and performance may have been influenced by subitizing. A purer count sequence knowledge task was used by Morsanyi et al. (2017) in which children were asked to count forwards and backwards from different numbers. They found that counting performance was correlated with performance on the numeral order task. Furthermore, counting performance, and not performance on a numeral order task, was a significant independent predictor of concurrent mathematics performance (alongside non-numerical order tasks). However, they made use of a somewhat different numeral order task in which children were asked to place the digits 1–9 in order, and therefore it's unclear the extent to which this result may also apply to studies using standard numeral order processing tasks.

Here we explored the relationship between numeral order processing and arithmetic and tested different potential mechanisms underlying this association. We sought to test the specific question of whether numeral order processing is related to concurrent arithmetic skills over and above verbal count sequence knowledge and RAN.

1. Method

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. The data is available at: doi:10.17028/rd.lboro.7731524

1.1. Participants

Sixty-two children took part in the study (34 = male) aged from 6;0 to 8;11 (mean 7;7). The children were in Years 1, 2 and 3 of primary school and would therefore all have received at least two years of formal arithmetic instruction (Year 1 is the second year of compulsory school in the UK). The children were recruited through the University of Nottingham's 'Summer Scientist Week' (www.summerscientist.org), an event where children and parents visit the university to take part in a range of research studies. We tested all the children in our age range who were available during Summer Scientist Week. This sample size gives 95% power to detect an R^2 change of 0.18 in a multiple regression with 5 predictors (90% power to detect a change of 0.15; GPower 3.1, Faul, Erdfelder, Buchner, & Lang, 2009). All studies were approved by the University of Nottingham School of Psychology Ethics Committee and all parents provided written consent for their child to participate. Children received a goody bag to thank them for taking part in the event. One participant did not complete the RAN colours task and one participant did not provide their exact date of birth.

1.2. Tasks

Children took part in a 20-min session during which they completed four tasks in a set order: a verbal count sequence knowledge task; the colours and numbers subtests of the RAN test; a computerized numeral order task; and the numerical operations subtest from the WIAT II-UK. These tasks are described below.

1.2.1. Verbal count sequence task

The verbal count sequence knowledge task was adapted from Cowan et al. (2011) and Gilmore et al. (2018). Children were asked to complete a series of 4 ascending and 4 descending count sequences. On the four ascending trials they were asked "Can you count up from…" and the experimenter stopped the children once they had reached a target number by saying "Great, let's try another one". The ascending trials were 28 to 35, 45 to 52, 194 to 210 and 2995 to 3004. On the four descending trials children were asked "Can you count down from…" and again the experimenter stopped children once they had reached a target number. The descending trials were 12 to 5, 33 to 26, 325 to 317 and 1006 to 997. Children were given a point for each sequence completed correctly so a total score out of 8. For the easiest descending trial performance was 100% correct and for the easiest ascending trial performance was 98.3% (one single error). Cronbach's alpha (not including these two trials) was 0.71.

1.2.2. Numeral order task

This task was based on Lyons et al. (2014). In each of 28 experimental trials children were shown triplets of single digits (e.g. 6 7 8) presented on a laptop screen and were asked "You need to decide, as quickly as possible, whether or not the numbers are in the correct order (from smallest to biggest)". On half of the trials the digits were in ascending numerical order with varying numerical distances. On five trials the numerical distance was one (e.g. 4 5 6), on five trials the numerical distance was two (e.g. 1 3 5), and on the remaining four trials the numerical distance was three (e.g. 2 5 8). All of the ordered trials were symmetrical i.e. the numerical distance between the first and second digit was the same as the numerical distance between the second and third digit. The remaining 14 trials comprised triplets that were not in order (e.g. 4 2 3). The trials used were identical to the single digit trials used by Lyons and Ansari (2015). The full set of trials is provided in the appendix.

On each trial children were presented with a fixation cross for 500 ms, followed by a triplet of digits. The digits remained on the screen until the child responded by pressing either "1" with their left hand (for in order trials) or "0" with their right hand (for not in order trials) on the computer keyboard. There were no practice trials.

Three dependent variables were used: 1) accuracy scores for the proportion of trials answered correctly; 2) mean RT for correctly answered trials; 3) a combined accuracy and RT measure (Lyons et al., 2014; Lyons & Ansari, 2015). This was calculated by performance = RT (1 + 2ER) where ER = error rate and RT was mean response time for correct trials (hereafter "combined score"). According to this measure if a participant made no errors then their combined score would be equal to their mean RT. If they were at chance (i.e. 50% error) then their combined score would be twice their mean RT. Cronbach's alpha for the task was 0.83 (accuracy).

1.2.3. Rapid Automatized Naming task

The RAN task (Wolf & Denckla, 2005) assesses the accuracy and speed of naming familiar stimuli. We used the colours and numbers subtests. Each subtest includes five different stimuli (colours: red, blue, green, black and yellow; numbers: 2, 4, 6, 7, 9). During the practice phase the participant names the five stimuli to confirm these are known. Then, during the test phase, the participant is asked to name each of 50 stimuli per test as quickly and accurately as possible. The time for participants to name each set of 50 stimuli was measured with a stopwatch. The number of errors or self-corrections was low (mean errors 1.6% colours 0.6% numbers; mean self-corrections 2.6% colours 1.2% numbers) and therefore we used the total naming time for each subtest as the measure of performance.

1.2.4. Numerical Operations task

To assess arithmetic skill children solved items from the WIAT II-UK Numerical Operations subtest (Wechsler, 2005). This is a written test of arithmetic and includes items involving addition, subtraction, multiplication and division all presented in abstract form with Arabic digits (e.g. 8 + 5 =). The items get progressively more difficult through the test. Children all began at the same item (Item 8) and had a total of five minutes working on the task. However, they were not informed that this task had a time limit because we did not wish children to prioritize speed over accuracy. Scores were the total number of items correctly answered in five minutes.

2. Results

Below we first present descriptive statistics for each of the tasks and discuss correlations between the tasks. We then explore the extent to which numeral order processing performance, verbal count sequence knowledge and RAN scores are associated with Numerical Operations score via a series of hierarchical regressions. These are presented for each of the three dependent variables for the numeral order task. Bayesian statistics are presented to quantify the evidence in support of count sequence knowledge vs. numeral order as predictors of concurrent Numerical Operations score. Analyses were conducted in JASP 0.9.0.1.

2.1. Descriptive statistics

Descriptive statistics for each of the tasks are presented in Table 1. Pearson correlations were conducted to explore the relationships

Table 1
Descriptive statistics for all tasks (n = 62 except for RAN colours n = 61).

Task	Mean	SD	Minimum	Maximum
Count sequence	5.95	1.59	3	8
Numeral order (accuracy)	0.764	0.17	0.43	1
Numeral order (mean RT, *msec*)	3093	1117	816	6402
Numeral order (combined score)	4581	2085	1340	10,975
RAN (colours, sec)	52.78	12.54	33.50	99.00
RAN (numbers, sec)	36.54	9.56	23.80	66.50
Numerical Operations	8.15	4.63	1	23

between the tasks. A full correlation matrix can be found in Table 2. Of most relevance, we found that verbal count sequence knowledge was moderately correlated with RT and the combined score on the numeral order task (RT $r = -0.327$; combined score $r = -0.302$). Performance on the Numerical Operations task was strongly correlated with verbal count sequence knowledge ($r = 0.698$) and moderately correlated with other measures (numeral order accuracy $r = 0.291$, numeral order RT $r = -0.395$, numeral order combined score $r = -0.432$, RAN numbers $r = -0.399$).

2.2. Performance on the numeral order task

We explored children's performance on the numeral order task to identify how children interpreted this task. We examined accuracies for the different types of numeral order trials (in-order and not-in-order with distances of 1, 2 and 3). We found that, as a group, children did not perform significantly above chance on the in-order trials with distances of 2 and 3 (Table 3). Examination of histograms for performance on these trials (Fig. 1) reveals a bi-modal distribution with some children performing above chance and others below chance (chance = 0.5). This was confirmed with Hartigan's dip statistic, (Freeman & Dale, 2013), a test of unimodality/multimodality, assessed using the diptest package in R (in-order distance 2 trials: D = 0.124, $p < .001$; in-order distance 3 trials: D = 0.137, $p < .001$). This indicates that a subset of children systematically reported that trials such as 2 4 6 were not in order. It is difficult to determine whether such children have misunderstood the task or, for them, order means count sequence order, i.e. only with distances of 1. Consequently, we performed our regression analyses twice, once for the full sample of children ($n = 62$) and once after excluding children who performed below 50% on both the distance 2 and distance 3 in-order trials (remaining $n = 41$).

2.3. Regression analyses for full sample

To explore the extent to which numeral order processing and verbal count sequence knowledge were associated with Numerical Operations score we ran a series of hierarchical regression models (Table 4). In the first set of models (Models 1a, 1b, 1c) we tested whether numeral order processing was associated with Numerical Operations score over and above age, verbal count sequence knowledge and RAN. Separate models were conducted with numeral order processing performance indexed by accuracy (Model 1a), RT (Model 1b) or the combined score used in previous literature (Model 1c). This revealed that adding numeral order accuracy or RT to the model did not improve the fit. When performance on the numeral order task was indexed by the combined score then numeral order processing performance did improve the model fit, although the improvement in fit was modest ($\Delta R^2 = 0.03$, $p = .042$). RAN scores were not a significant predictor in any model.

In the second set of models we tested whether verbal count sequence knowledge was associated with Numerical Operations score over and above age, numeral order processing performance and RAN. Again, separate models were conducted with numeral order performance indexed by accuracy (Model 2a), RT (Model 2b) or combined score (Model 2c). In all of these models verbal count sequence knowledge substantially and significantly improved the fit of the model (Model 2a:

Table 3
Accuracy on different trials of the numeral order task.

Trials	Full sample (n = 62)			Subset (n = 41)		
	Mean	SD	t-test[a]	Mean	SD	t-test[a]
In-order distance 1	0.84	0.22	p < .001	0.86	0.20	p < .001
In-order distance 2	0.56	0.42	p = .256	0.81	0.28	p < .001
In-order distance 3	0.58	0.42	p = .139	0.85	0.21	p < .001
Not-in-order distance 1	0.82	0.25	p < .001	0.85	0.25	p < .001
Not-in-order distance 2	0.90	0.17	p < .001	0.88	0.19	p < .001
Not-in-order distance 3	0.87	0.18	p < .001	0.84	0.20	p < .001

[a] One sample t-test compared to chance (0.5).

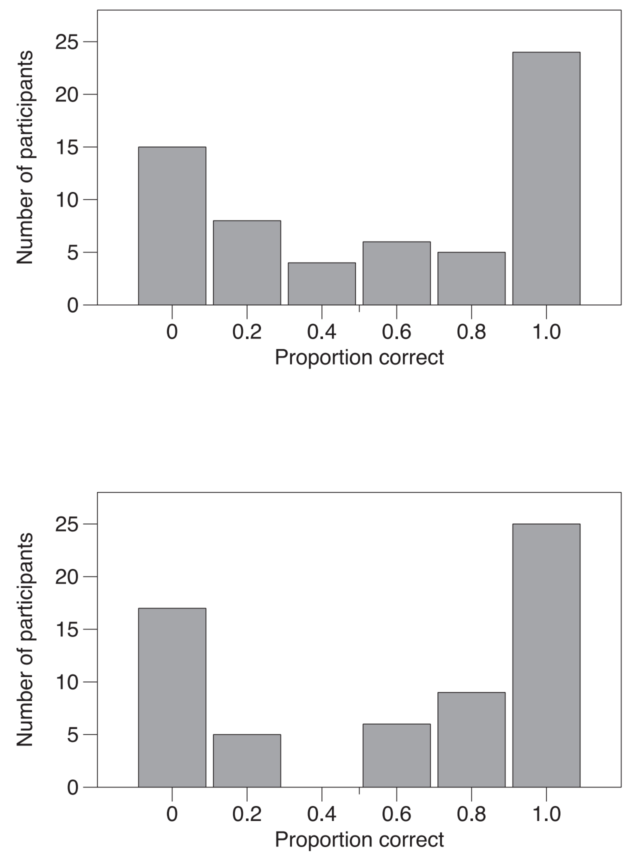

Fig. 1. Histogram of children's accuracy on in-order distance 2 (top panel), and in-order distance 3 (bottom panel) trials of the numeral order processing task.

Table 2
Pearson correlations between all variables.

	Num Ops	Age	Counting	RAN (col)	RAN (num)	Order (acc)	Order (RT)
Age	0.627***						
Counting	0.698***	0.562***					
RAN (colours)	−0.228	−0.169	−0.186				
RAN (num)	−0.399**	−0.257*	−0.378**	0.586***			
Order (acc)	0.291*	0.152	0.152	−0.227	−0.297*		
Order (RT)	−0.395**	−0.258*	−0.327*	0.265*	0.168	−0.073	
Order (comb)	−0.432***	−0.276*	−0.302*	0.323*	0.281*	−0.551***	0.857***

N = 62, except one participant did not complete RAN colours and one participant did not provide exact age. Num Ops = WIAT Numerical Operations subtest.
*** $p < .001$.
** $p < .01$.
* $p < .05$.

Table 4
Hierarchical regressions exploring the predictors of Numerical Operations raw scores (n = 62).

		Variables entered	Model a Numeral order accuracy			Model b Numeral order = RT			Model c Numeral order combined[a]		
			β	*p*	Δ R^2	β	*p*	Δ R^2	β	*p*	Δ R^2
Model 1	Step 1	Age	0.63	< 0.001	0.40***	0.63	< 0.001	0.40***	0.63	< 0.001	0.40***
	Step 2	Age	0.33	0.002	0.20***	0.33	0.002	0.20***	0.33	0.002	0.20***
		Counting	0.48	< 0.001		0.48	< 0.001		0.48	< 0.001	
		RAN (Col)	−0.02	0.849		−0.02	0.849		−0.02	0.849	
		RAN (Num)	−0.11	0.345		−0.11	0.345		−0.11	0.345	
	Step 3	Age	0.32	0.003	0.014	0.32	0.003	0.02	0.31	0.004	0.03*
		Counting	0.48	<0.001		0.44	<0.001		0.45	<0.001	
		RAN (Col)	−0.01	0.931		0.02	0.836		0.03	0.796	
		RAN (Num)	−0.08	0.474		−0.12	0.271		−0.10	0.369	
		Ordinality	0.12	0.167		−0.16	0.083		−0.19	0.042	
Model 2	Step 1	Age	0.63	<0.001	0.40***	0.63	<0.001	0.40***	0.63	<0.001	0.40***
	Step 2	Age	0.56	<0.001	0.07	0.52	<0.001	0.11*	0.52	<0.001	0.11*
		Ordinality	0.13	0.201		−0.24	0.019		−0.25	0.020	
		RAN (Col)	0.03	0.818		0.08	0.530		0.08	0.533	
		RAN (Num)	−0.23	0.077		−0.26	0.034		−0.23	0.059	
	Step 3	Age	0.32	0.003	0.14***	0.32	0.003	0.11***	0.31	0.004	0.12***
		Ordinality	0.12	0.167		−0.16	0.083		−0.19	0.042	
		RAN (Col)	−0.01	0.931		0.02	0.836		0.03	0.796	
		Ran (Num)	−0.08	0.474		−0.12	0.271		−0.10	0.369	
		Counting	0.48	<0.001		0.44	<0.001		0.45	<0.001	

DV = Numerical Operations raw scores.
[a] Combined measure = RT(1 + 2ER) where ER = error rate and RT = mean response time.
*** $p < .001$.
* $p < .05$.

$\Delta R^2 = 0.14$, $p < .001$; Model 2b: $\Delta R^2 = 0.11$, $p < .001$; Model 2c: $\Delta R^2 = 0.12$, $p < .001$). In all models RAN scores were not a significant predictor of Numerical Operations score once count sequence knowledge was included.

Finally, to quantify the evidence for including verbal count sequence knowledge and numeral order processing performance in the model we ran Bayesian Linear Regression models. These analyses allowed us to estimate the likelihood of model parameters on the basis of the data collected. The models used a Jeffreys-Zellner-Siow (JZS) prior which assumes a normal distribution for each predictor. The scale width selected was 0.354 (JASP default). Further analyses confirmed that our results were robust to changes in the prior width.

RAN scores were not included in these analyses. We first tested the evidence supporting the inclusion of verbal count sequence knowledge over a null model that included age and numeral order processing. There was extreme evidence (Wagenmakers et al., 2018) for the inclusion of verbal count sequence knowledge regardless of how numeral order processing performance was indexed (BF_{10} = 2088, 618, 827 when numeral order performance was indexed by accuracy, RT or combined score respectively). In contrast when we tested the evidence in support of numeral order processing as a predictor over a null model that included age and verbal count sequence knowledge there was no

Table 5
Hierarchical regressions exploring the predictors of Numerical Operations raw scores after exclusions (n = 41).

		Variables entered	Model a Numeral order accuracy			Model b Numeral order = RT			Model c Numeral order combined[a]		
			β	*p*	Δ R^2	β	*p*	Δ R^2	β	*p*	Δ R^2
Model 3	Step 1	Age	0.61	< 0.001	0.38***	0.61	< 0.001	0.38***	0.61	< 0.001	0.38***
	Step 2	Age	0.38	0.005	0.18**	0.38	0.005	0.18**	0.38	0.005	0.18**
		Counting	0.49	< 0.001		0.49	< 0.001		0.49	< 0.001	
		RAN (Col)	0.03	0.836		0.03	0.836		0.03	0.836	
		RAN (Num)	0.00	0.977		0.00	0.977		0.00	0.977	
	Step 3	Age	0.38	0.006	0.001	0.39	0.004	0.02	0.39	0.005	0.01
		Counting	0.49	<0.001		0.44	0.003		0.46	0.002	
		RAN (Col)	0.03	0.842		0.08	0.573		0.06	0.670	
		RAN (Num)	0.01	0.954		−0.02	0.869		−0.01	0.965	
		Ordinality	0.03	0.818		−0.16	0.190		−0.12	0.336	
Model 4	Step 1	Age	0.61	<0.001	0.38***	0.61	<0.001	0.38***	0.61	<0.001	0.38***
	Step 2	Age	0.59	<0.001	0.01	0.57	<0.001	0.08	0.58	<0.001	0.05
		Ordinality	0.04	0.744		−0.27	0.040		−0.20	0.138	
		RAN (Col)	0.06	0.733		0.14	0.380		0.11	0.499	
		RAN (Num)	−0.13	0.438		−0.16	0.311		−0.14	0.376	
	Step 3	Age	0.38	0.006	0.17***	0.39	0.004	0.13**	0.39	0.005	0.14**
		Ordinality	0.03	0.818		−0.16	0.190		−0.12	0.336	
		RAN (Col)	0.03	0.842		0.08	0.573		0.06	0.670	
		RAN (Num)	0.01	0.954		−0.02	0.869		−0.01	0.965	
		Counting	0.49	<0.001		0.44	0.003		0.46	0.002	

DV = Numerical Operations raw scores.
[a] Combined measure = RT(1 + 2ER) where ER = error rate and RT = mean response time.
*** $p < .001$.
** $p < .01$.

evidence in support of including numeral order processing (but also no evidence against including it) when it was indexed by accuracy or RT ($BF_{10} = 0.93$, 0.63 respectively) and anecdotal evidence to support including it when it was indexed by combined score ($BF_{10} = 1.69$).

2.4. Regression analyses after exclusions

We repeated the regression analyses after excluding children who performed below 50% on both the distance 2 and distance 3 in-order trials (Table 5). The results of these analyses were in line with the analyses for the full sample and indeed there was less evidence for the importance of numeral order processing. Therefore, our original results cannot be explained by the inclusion of children who treated all in-order trials of the numeral order task with a distance greater than 1 as incorrect.

Specifically, we first explored whether numeral order processing (accuracy: Model 3a, RT: Model 3b or combined score: Model 3c) was associated with Numerical Operations score over and above age, verbal count sequence knowledge and RAN. Adding numeral order performance to the model did not improve the fit regardless of how performance on the numeral order task was assessed.

Secondly, we tested whether verbal count sequence knowledge was associated with Numerical Operations score over and above age, numeral order processing performance (accuracy: Model 4a, RT: Model 4b or combined score: Model 4c) and RAN. In all of these models verbal count sequence knowledge substantially and significantly improved the fit of the model (Model 4a: $\Delta R^2 = 0.17$, $p < .001$; Model 4b: $\Delta R^2 = 0.12$, $p = .003$; Model 4c: $\Delta R^2 = 0.14$, $p = .002$). RAN was not a significant predictor in any model.

Finally, we repeated the Bayesian Linear Regression models. There was very strong evidence for the inclusion of verbal count sequence knowledge compared to a null model including age and numeral order processing score, regardless of how this was measured ($BF_{10} = 73.39$, 26.51, 42.65 when numeral order performance was indexed by accuracy, RT or combined score respectively). In contrast there was no evidence for the inclusion of numeral order processing compared to a null model including age and verbal count sequence knowledge, regardless of how numeral order processing was measured ($BF_{10} = 0.24$, 0.46, 0.33 when numeral order performance was indexed by accuracy, RT or combined score respectively). In the case of numeral order accuracy or combined score these Bayes Factors can be interpreted as evidence in support of the null model.

3. Discussion

In this study we explored the relationships among verbal count sequence knowledge, RAN, numeral order processing and arithmetic performance. Our findings demonstrated for the first time that performance on a typical numeral order processing task was not associated with concurrent arithmetic performance once children's verbal count sequence knowledge had been taken into account. On the other hand, verbal count sequence knowledge was a strong and significant predictor of concurrent arithmetic performance over and above numeral order processing performance. In other words, performance on an arithmetic test involving written Arabic symbols was more closely associated with performance on a purely verbal counting task than with performance on a task which involved processing written Arabic symbols. Moreover, approximately one third of our sample appeared to base their judgments of numerical order explicitly on the count sequence, considering in-order trials with a distance more than one (e.g. 2 4 6) as not being in numerical order.

In contrast to the important role of verbal count sequence knowledge we found that fluent access to semantic information, as indexed by the RAN task, did not account for the relationship between ordinal number processing and arithmetic. The speed with which children could name digits was correlated with count sequence knowledge, ordinal number processing and arithmetic performance. However, fluency of digit naming was no longer significantly related to arithmetic when either of the other number skills were taken into account. The association with RAN was specific to numerical stimuli: speed of naming colours was unrelated to any of the numerical measures.

Below we discuss the theoretical and methodological implications of our findings regarding the nature of numeral order processing and the role of count sequence knowledge. We also consider the extent to which differences in number range involved in each task may drive differences in the association with arithmetic. To our knowledge this was the first exploration of these issues and therefore our findings should be considered preliminary until replicated in future studies with different samples.

3.1. What do numeral order tasks measure?

Our findings help shed light on what is measured by numeral order tasks. We found no evidence that numeral order tasks measure a fundamental aspect of number representation or processing that is distinct from knowledge of the verbal count sequence. This contrasts with the findings of Lyons and Ansari (2015) who found that the relationship between performance on a numeral order task and arithmetic remained significant after controlling for counting skill. However, the counting task they employed simply involved counting up to 9 objects, and therefore was only a limited measure of verbal count sequence knowledge. Using a task which involved forwards and backwards multidigit counting sequences and the ability to begin counting from various points in the count sequence, we found that the relationship between numeral order processing and arithmetic is fully explained by count sequence knowledge.

The crucial role of count sequence information in numeral order processing fits with previous findings in the literature. One of the key characteristics of performance on numeral order tasks is a reverse distance effect whereby performance is faster and more accurate for trials with a smaller numerical distance between the numbers than trials with a larger numerical distance (Goffin & Ansari, 2016; Lyons & Ansari, 2015; Lyons & Beilock, 2013; Vogel et al., 2017). This pattern, and in particular the findings that reverse distance effects are only observed for ordered trials (I.M. Lyons & Ansari, 2015) and that larger reverse distance effects are observed for ascending than descending sequences (Vos et al., 2017), are consistent with the role of verbal count sequence information. Count sequence knowledge would be more beneficial for solving trials with a smaller, rather than a larger, distance between the numbers (e.g. 2 3 4 vs. 2 4 6) and more beneficial for ascending than descending number sequences, because children typically learn to count forwards first and are more proficient at this than counting backwards.

Small distance ascending trials are also most predictive of arithmetic performance. In a study with children in Grades 1 to 6, Lyons and Ansari (2015) found that performance on trials with ascending sequences of consecutive numbers (e.g. 4 5 6) were more closely associated with arithmetic performance than trials in which the triplets were either not in order, or were in order but with larger distances (e.g. 4 6 8). This indicates that the trials which are most predictive of arithmetic are those taken directly from the count list. However, Vos et al. (2017) did not replicate this finding with adults, instead finding that the association between numeral order task performance and arithmetic was similar for different trial types. It is possible therefore that performance on the numeral order task might be driven by different processes in children and adults. Consequently, it would be valuable to explore the relationship between numeral order processing, count sequence knowledge and arithmetic in adults.

Finally, the role of verbal count sequence knowledge in numeral order processing is also consistent with evidence from imaging. Performance on an ordinal, but not cardinal, processing task was associated with activation of regions known to be involved in complex visuo-motor processing (left pre-motor cortex, Lyons & Beilock, 2013). This pattern was interpreted by the authors as reflecting the role of count list knowledge.

It is notable that we found a substantial subset of children who performed below chance level on in-order trials with a numerical distance of 2 or 3 (e.g. 2 4 6). These children only considered consecutive ascending trials to be in numerical order. This may have been due to a misunderstanding of the task instructions (we used the same instructions as previous studies) or this may imply that these children interpret “order” to have a more specific meaning. Children who held this restricted interpretation of order had lower arithmetic scores (M = 6.43 vs 9.02; $t(60) = -2.15, p = .036$) but were no younger (M = 89.9 vs 90.0; $t(59) = -0.90, p = .371$) than the rest of the group. This may suggest that this wasn’t a simple task misunderstanding (which we might expect to happen more frequently for younger children), but rather that a full understanding of the meaning of “order” is associated with mathematical learning. Exploring this would be a valuable avenue for future research, as previous studies have not reported the distributions of children’s scores and therefore it is unclear if the existence of these subgroups is common.

Nevertheless, our findings cannot be explained simply by these different interpretations of the task. Our pattern of findings held up when children who interpreted “in order” to mean “in consecutive order” were excluded from the analysis. Therefore the role of count sequence knowledge in explaining the link between numeral order processing and arithmetic does not simply reflect children’s interpretation of the numeral order task.

The role of count sequence knowledge in numeral order processing tasks is consistent with three alternative possible interpretations. First, verbal count sequence knowledge may be involved because when participants complete the numeral order task they silently vocalize the digits and compare these with the stored verbal count sequence. Consequently, count sequence knowledge is directly involved while solving the task. Second, verbal count sequence information may be associated with performance on numeral order tasks because children draw on their knowledge of the count sequence when first acquiring Arabic numeral representations of number. Children with good count sequence knowledge at the age of testing (6 to 8 years) may also have had good count sequence knowledge at earlier ages, allowing them to form stronger ordinal links between representations of Arabic digits when these were acquired. Finally, our findings may reflect the nature of exact symbolic numerical representations. It is possible that, rather than consisting of separate verbal and Arabic codes (Dehaene, 1992), symbolic representations of number may integrate sequence information derived from both the verbal code and ordinal associations between Arabic digits. In this case, verbal information associated with the count list may be incorporated into purely symbolic digit representations.

Our findings are unable to distinguish between these possible interpretations. However, recent evidence from a different paradigm may be relevant. Previous studies have shown that characteristics of verbal number names (e.g. the transparency of the number naming system), influences performance on a symbolic comparison task involving Arabic numerals (Dowker & Roberts, 2015; Nuerk, Weger, & Willmes, 2005). However, this influence disappears when participants complete the task under conditions of articulatory suppression (Bahnmueller, Maier, Göbel, & Moeller, 2019). This suggests that the influence of verbal number names arises because participants silently vocalize the digits while completing the task, and not because the information about the verbal label is incorporated into the representation of the Arabic digit. It remains to be tested whether preventing participants from silently vocalizing digits would influence the patterns of performance on numeral order tasks and the nature of the relationship with arithmetic performance.

Some recent studies have proposed that the relationship between performance on a numeral order task and arithmetic could reflect the role of general serial order learning mechanisms. De Visscher, Szmalec, Van Der Linden, and Noël (2015) suggested that some adults with dyscalculia have a deficit in serial order learning of non-numerical information. Similarly, order working memory is associated with arithmetic performance in children (Attout & Majerus, 2018), and children with dyscalculia have been found to have impaired memory for order, but not item information (Attout & Majerus, 2015). This proposal is not incompatible with the current findings. It is possible that better serial order learning could help children to learn the counting sequence more quickly and effectively. Consequently, the role of verbal count sequence information in explaining the relationship between numeral order processing and arithmetic could itself reflect underlying serial order learning mechanisms. However, Attout and Majerus (2018) found that numeral order processing is associated with arithmetic skills independently from order working memory, suggesting that verbal count sequence information might capture more than simply serial order learning.

Previous studies exploring the role of counting skills in mathematics development have often focused on the importance of understanding counting principles (Geary, 2004; Gelman & Gallistel, 1978). Our counting task did not assess conceptual understanding of counting, but simply the ability to recite the count list. Nevertheless, we found that performance on our counting task was strongly associated with arithmetic performance. The importance of counting skill lies not only in understanding of counting principles, but also in simple recall of the count list. Our task included trials with large numbers up to 3004. The ability to recall the count list with these large numbers may also have reflected children’s place value knowledge, which is known to be an important predictor of arithmetic performance (Jordan, Hanich, & Kaplan, 2003; Moeller, Pixner, Zuber, Kaufmann, & Nuerk, 2011). However, we do not believe that the counting task was a better predictor of arithmetic than the numeral order task simply because it included larger numbers. The relationship between performance on numeral order trials and arithmetic performance is stronger for single digit than double digit trials of the numeral order task (Lyons & Ansari, 2015), indicating that simply including larger numbers does not lead to a stronger relationship with arithmetic. Nevertheless, it remains to be determined the extent to which differences in number range drives the associations we observed here.

3.2. Implications for theories of number and arithmetic development

The involvement of verbal count sequence knowledge in explaining the relationship between numeral order processing and arithmetic performance has implications for theories of number and arithmetic development more generally. It is possible that insufficient attention may have been paid to verbal number knowledge, as opposed to numeral number knowledge. These two aspects of exact symbolic representations are often conflated in theoretical accounts of number processing and development. However, children learn verbal numbers first and typically some time before learning Arabic digits. To better understand how children develop understanding of the meaning of numbers we need a clearer picture of the separate roles of verbal number words and number symbols, and whether they form two separate numerical codes or combine to a single representation.

When testing theoretical accounts of number representation and processing, Arabic numerals are often preferred to verbal numbers for methodological ease. In particular, when studies rely on reaction time measures, as is often required with adult participants, it is far easier to present Arabic numerals on a screen than to use audio recordings of verbal number words. For example, while numerous studies have used Arabic numerals to investigate symbolic magnitude comparison (89 separate effect sizes for Arabic numeral magnitude comparison were included in a recent meta-analysis by Schneider et al., 2017), only a handful of studies have investigated symbolic magnitude comparison with written number words (Damian, 2004; Lukas, Krinzinger, Koch, & Willmes, 2017; Macizo & Herrera, 2010, 2011; Nuerk et al., 2005; Pinel, Dehaene, Riviere, & LeBihan, 2001; Skagenholt, Träff, Västfjäll, &

Skagerlund, 2018) and we could not identify any published studies of verbal number word magnitude comparison. Given existing evidence for the influence of the characteristics of number names on the processing of Arabic digits (Dowker & Nuerk, 2016), it seems important that more attention be paid to verbal number representations in both the acquisition and processing of symbolic numbers.

The study presented here provides evidence for the importance of verbal count sequence knowledge. Recent studies have proposed that ordinal information plays a more important role in symbolic number processing than magnitude information (Lyons et al., 2012; Reynvoet & Sasanguie, 2016). We didn't study the role of magnitude representations and processing and therefore our findings do not speak directly to that question. Despite evidence for the important role of verbal count sequence knowledge, it is possible that magnitude information is also important for arithmetic, either in acquiring or processing verbal and Arabic symbolic representations of number. The children involved in our study were 6–8 years old and so they had already had several years of experience in using both verbal and Arabic symbolic numbers, whereas magnitude information may play a more important role at earlier ages.

There are multiple potential sources of information about the meaning of numbers including magnitude information, ordinal relations between digits and the verbal count sequence. It is only by considering the combination of these multiple sources of information that we will understand how children initially learn the meaning of numbers, how numerical representations change over development and with education, and the influences (magnitude, ordinal, verbal) on adult number processing. A narrow focus on one source of information is unlikely to be sufficient to build appropriate models of number acquisition and processing or allow recommendations to be made regarding education. Our findings highlight one example of the complexities in identifying the sources of information that individuals use to solve numerical tasks. Further research, including longitudinal studies, and theoretical development is needed to identify how magnitude, ordinal and verbal count sequence information together combine to give meaning to numbers.

Appendix A. Trials in the numeral order processing task

First Digit	Second Digit	Third Digit	Order Type	Distance
2	3	4	In order	1
4	5	6	In order	1
4	5	6	In order	1
6	7	8	In order	1
6	7	8	In order	1
1	3	5	In order	2
1	3	5	In order	2
3	5	7	In order	2
3	5	7	In order	2
5	7	9	In order	2
2	5	8	In order	3
2	5	8	In order	3
3	6	9	In order	3
3	6	9	In order	3
4	3	2	Not in order	1
4	2	3	Not in order	1
6	4	5	Not in order	1
6	5	4	Not in order	1
8	7	6	Not in order	1
5	3	1	Not in order	2
5	3	7	Not in order	2
7	5	9	Not in order	2
9	7	5	Not in order	2
5	8	2	Not in order	3
6	3	9	Not in order	3
7	1	4	Not in order	3
7	4	1	Not in order	3
8	5	2	Not in order	3

References

Attout, L., & Majerus, S. (2015). Working memory deficits in developmental dyscalculia: The importance of serial order. *Child Neuropsychology, 21*, 432–450. https://doi.org/10.1080/09297049.2014.922170

Attout, L., & Majerus, S. (2018). Serial order working memory and numerical ordinal processing share common processes and predict arithmetic abilities. *British Journal of Developmental Psychology, 36*, 285–298. https://doi.org/10.1111/bjdp.12211

Bahnmueller, J., Maier, C. A., Göbel, S. M., & Moeller, K. (2019). Direct evidence for linguistic influences in two-digit number processing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 45*(6), 1142–1150.

Chard, D. J., Clarke, B., Baker, S., Otterstedt, J., Braun, D., & Katz, R. (2005). Using measures of number sense to screen for difficulties in mathematics: Preliminary findings. *Assessment for Effective Intervention, 30*, 3–14. https://doi.org/10.1177/073724770503000202

Chen, Q., & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica, 148*, 163–172. https://doi.org/10.1016/j.actpsy.2014.01.016

Cowan, R., Donlan, C., Newton, E. J., & Llyod, D. (2005). Number skills and knowledge in children with specific language impairment. *Journal of Educational Psychology, 97*, 732–744. https://doi.org/10.1037/0022-0663.97.4.732

Cowan, R., Donlan, C., Shepherd, D. L., Cole-Fletcher, R., Saxton, M., & Hurry, J. (2011). Basic calculation proficiency and mathematics achievement in elementary school children. *Journal of Educational Psychology, 103*(4), 786. https://doi.org/10.1037/a0024556.

Cowan, R., & Powell, D. (2014). The contributions of domain-general and numerical factors to third-grade arithmetic skills and mathematical learning disability. *Journal of Educational Psychology, 106*, 214–229. https://doi.org/10.1037/a0034097

Cui, J., Georgiou, G. K., Zhang, Y., Li, Y., Shu, H., & Zhou, X. (2017). Examining the relationship between rapid automatized naming and arithmetic fluency in Chinese kindergarten children. *Journal of Experimental Child Psychology, 154*, 146–163. https://doi.org/10.1016/j.jecp.2016.10.008

Damian, M. F. (2004). Asymmetries in the processing of Arabic digits and number words. *Memory & Cognition, 32*(1), 164–171. https://doi.org/10.3758/BF03195829

De Smedt, B., Noël, M.-P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior.

Trends in Neuroscience and Education, 2, 48–55. https://doi.org/10.1016/j.tine.2013.06.001

De Visscher, A., Szmalec, A., Van Der Linden, L., & Noël, M.-P. (2015). Serial-order learning impairment and hypersensitivity-to-interference in dyscalculia. *Cognition, 144*, 38–48. https://doi.org/10.1016/j.cognition.2015.07.007

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*, 1–42. https://doi.org/10.1016/0010-0277(92)90049-N

Department for Business Innovation & Skills. (2011). 2011 Skills for Life Survey: Headline findings. BIS Research Paper Number 57.

Dowker, A., & Nuerk, H.-C. (2016). Editorial: Linguistic influences on mathematics. *Frontiers in Psychology, 7*, 1035. https://doi.org/10.3389/fpsyg.2016.01035

Dowker, A., & Roberts, M. (2015). Does the transparency of the counting system affect children's numerical abilities? *Frontiers in Psychology, 6*, 945. https://doi.org/10.3389/fpsyg.2015.00945

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., … Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*, 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*, 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Fazio, L. K., Bailey, D. H., Thompson, C. A., & Siegler, R. S. (2014). Relations of different types of numerical magnitude representations to each other and to mathematics achievement. *Journal of Experimental Child Psychology, 123*, 53–72. https://doi.org/10.1016/j.jecp.2014.01.013

Freeman, J. B., & Dale, R. (2013). Assessing bimodality to detect the presence of a dual cognitive process. *Behavior Research Methods, 45*, 83–97. https://doi.org/10.3758/s13428-012-0225-x

Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities, 37*, 4–15. https://doi.org/10.1177/00222194040370010201

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: A 5-year longitudinal study. *Developmental Psychology, 47*, 1539–1552. https://doi.org/10.1037/a0025510

Geary, D. C., Hoard, M. K., Byrd-Craven, J., & DeSoto, M. C. (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability. *Journal of Experimental Child Psychology, 88*, 121–151. https://doi.org/10.1016/j.jecp.2004.03.002

Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology, 74*, 213–239. https://doi.org/10.1006/jecp.1999.2515 1

Gelman, R., & Gallistel, C. R. (1978). *The child's understanding of number*. Cambridge, MA: Harvard University Press.

Gilmore, C., Clayton, S., Cragg, L., McKeaveney, C., Simms, V., & Johnson, S. (2018). Understanding arithmetic concepts: The role of domain-specific and domain-general skills. *PLoS One, 13*(9), Article e0201724. https://doi.org/10.1371/journal.pone.0201724

Ginsburg, H. P., Lee, J. S., & Boyd, J. S. (2008). *Mathematics Education for Young Children: What It Is and How to Promote It.* Social Policy Report. Volume 22, Number 1. Society for Research in Child Development.

Goffin, C., & Ansari, D. (2016). Beyond magnitude: Judging ordinality of symbolic number is unrelated to magnitude comparison and independently relates to individual differences in arithmetic. *Cognition, 150*, 68–76. https://doi.org/10.1016/j.cognition.2016.01.018

Hornung, C., Martin, R., & Fayol, M. (2017). General and specific contributions of RAN to reading and arithmetic fluency in first graders: A longitudinal latent variable approach. *Frontiers in Psychology, 8*, 1746. https://doi.org/10.3389/fpsyg.2017.01746

Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). A longitudinal study of mathematical competencies in children with specific mathematics difficulties versus children with comorbid mathematics and reading difficulties. *Child Development, 74*, 834–850. https://doi.org/10.1111/1467-8624.00571

Jordan, N. C., Kaplan, D., Locuniak, M. N., & Ramineni, C. (2007). Predicting first-grade math achievement from developmental number sense trajectories. *Learning Disabilities Research & Practice, 22*, 36–46. https://doi.org/10.1111/j.1540-5826.2007.00229.x

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45*, 850–867. https://doi.org/10.1037/a0014939

Koponen, T., Georgiou, G., Salmi, P., Leskinen, M., & Aro, M. (2017). A meta-analysis of the relation between RAN and mathematics. *Journal of Educational Psychology, 109*, 977–992. https://doi.org/10.1037/edu0000182

Koponen, T., Salmi, P., Eklund, K., & Aro, T. (2013). Counting and RAN: Predictors of arithmetic calculation and reading fluency. *Journal of Educational Psychology, 105*, 162–175. https://doi.org/10.1037/a0029285

LeFevre, J. A., Sadesky, G. S., & Bisanz, J. (1996). Selection of procedures in mental addition: Reassessing the problem size effect in adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(1), 216.

Lukas, S., Krinzinger, H., Koch, I., & Willmes, K. (2017). Number representation: A question of look? The distance effect in comparison of English and Turkish number words. *The Quarterly Journal of Experimental Psychology, 67*, 260–270. https://doi.org/10.1080/17470218.2013.802002

Lyons, I. M., & Ansari, D. (2015). Numerical order processing in children: From reversing the distance-effect to predicting arithmetic. *Mind, Brain, and Education, 9*, 207–221. https://doi.org/10.1111/mbe.12094

Lyons, I. M., Ansari, D., & Beilock, S. L. (2012). Symbolic estrangement: Evidence against a strong association between numerical symbols and the quantities they represent. *Journal of Experimental Psychology: General, 141*, 635–641. https://doi.org/10.1037/a0027248

Lyons, I. M., & Beilock, S. L. (2009). Beyond quantity: Individual differences in working memory and the ordinal understanding of numerical symbols. *Cognition, 113*, 189–204. https://doi.org/10.1016/j.cognition.2009.08.003

Lyons, I. M., & Beilock, S. L. (2011). Numerical ordering ability mediates the relation between number-sense and arithmetic competence. *Cognition, 121*(2), 256–261. https://doi.org/10.1016/j.cognition.2011.07.009

Lyons, I. M., & Beilock, S. L. (2013). Ordinality and the nature of symbolic numbers. *Journal of Neuroscience, 33*, 17052–17061. https://doi.org/10.1523/JNEUROSCI.1775-13.2013

Lyons, I. M., Price, G. R., Vaessen, A., Blomert, L., & Ansari, D. (2014). Numerical predictors of arithmetic success in grades 1–6. *Developmental Science, 17*, 714–726. https://doi.org/10.1111/desc.12152

Macizo, P., & Herrera, A. (2010). Two-digit number comparison: Decade-unit and unit-decade produce the same compatibility effect with number words. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale, 64*(1), 17. https://doi.org/10.1037/a0015803.

Macizo, P., & Herrera, A. (2011). Cognitive control in number processing: Evidence from the unit–decade compatibility effect. *Acta Psychologica, 136*(1), 112–118. https://doi.org/10.1016/j.actpsy.2010.10.008

Moeller, K., Pixner, S., Zuber, J., Kaufmann, L., & Nuerk, H.-C. (2011). Early place-value understanding as a precursor for later arithmetic performance—A longitudinal study on numerical development. *Research in Developmental Disabilities, 32*, 1837–1851. https://doi.org/10.1016/j.ridd.2011.03.012

Morsanyi, K., O'Mahony, E., & McCormack, T. (2017). Number comparison and number ordering as predictors of arithmetic performance in adults: Exploring the link between the two skills, and investigating the question of domain-specificity. *The Quarterly Journal of Experimental Psychology, 70*, 2497–2517. https://doi.org/10.1080/17470218.2016.1246577

Morsanyi, K., van Bers, B. M. C. W., O'Connor, P. A., & McCormack, T. (2018). Developmental dyscalculia is characterized by order processing deficits: Evidence from numerical and non-numerical ordering tasks. *Developmental Neuropsychology, 43*, 595–621. https://doi.org/10.1080/87565641.2018.1502294

Mundy, E., & Gilmore, C. (2009). Children's mapping between symbolic and nonsymbolic representations of number. *Journal of Experimental Child Psychology, 103*, 490–502. https://doi.org/10.1016/j.jecp.2009.02.003

Nuerk, H.-C., Weger, U., & Willmes, K. (2005). Language effects in magnitude comparison: Small, but not irrelevant. *Brain and Language, 92*, 262–277. https://doi.org/10.1016/j.bandl.2004.06.107

Pinel, P., Dehaene, S., Riviere, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage, 14*(5), 1013–1026. https://doi.org/10.1006/nimg.2001.0913

Reynvoet, B., & Sasanguie, D. (2016). The symbol grounding problem revisited: A thorough evaluation of the ANS mapping account and the proposal of an alternative account based on symbol–symbol associations. *Frontiers in Psychology, 7*, 1581. https://doi.org/10.3389/fpsyg.2016.01581

Rubinsten, O., & Sury, D. (2011). Processing ordinality and auantity: The case of developmental dyscalculia. *PLoS One, 6*(9), Article e24079. https://doi.org/10.1371/journal.pone.0024079

Sasanguie, D., Lyons, I. M., De Smedt, B., & Reynvoet, B. (2017). Unpacking symbolic number comparison and its relation with arithmetic in adults. *Cognition, 165*, 26–38. https://doi.org/10.1016/j.cognition.2017.04.007

Sasanguie, D., Smedt, B. D., Defever, E., & Reynvoet, B. (2012). Association between basic numerical abilities and mathematics achievement. *British Journal of Developmental Psychology, 30*, 344–357. https://doi.org/10.1111/j.2044-835X.2011.02048.x

Schneider, M., Beeres, K., Coban, L., Merz, S., Schmidt, S. S., Stricker, J., & Smedt, B. D. (2017). Associations of non-symbolic and symbolic numerical magnitude processing with mathematical competence: A meta-analysis. *Developmental Science, 20*, Article e12372. https://doi.org/10.1111/desc.12372

Schneider, M., Merz, S., Stricker, J., Smedt, B. D., Torbeyns, J., Verschaffel, L., & Luwel, K. (2018). Associations of number line estimation with mathematical competence: A meta-analysis. *Child Development, 89*, 1467–1484. https://doi.org/10.1111/cdev.13068

Skagenholt, M., Träff, U., Västfjäll, D., & Skagerlund, K. (2018). Examining the Triple Code Model in numerical cognition: An fMRI study. *PLoS One, 13*(6), Article e0199247. https://doi.org/10.1371/journal.pone.0199247

Stock, P., Desoete, A., & Roeyers, H. (2009). Mastery of the counting principles in toddlers: A crucial step in the development of budding arithmetic abilities? *Learning and Individual Differences, 19*, 419–422. https://doi.org/10.1016/j.lindif.2009.03.002

Vogel, S. E., Haigh, T., Sommerauer, G., Spindler, M., Brunner, C., Lyons, I. M., & Grabner, R. H. (2017). Processing the order of symbolic numbers: A reliable and unique predictor of arithmetic fluency. *Journal of Numerical Cognition, 3*, 288–308. https://doi.org/10.5964/jnc.v3i2.55

Vos, H., Sasanguie, D., Gevers, W., & Reynvoet, B. (2017). The role of general and number-specific order processing in adults' arithmetic performance. *Journal of Cognitive Psychology, 29*, 469–482. https://doi.org/10.1080/20445911.2017.1282490

Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., … Morey, R. D. (2018). Bayesian inference for psychology. *Part II: Example applications*

with JASP. Psychonomic Bulletin & Review, 25, 58–76. https://doi.org/10.3758/s13423-017-1323-7
Wechsler, D. (2005). *Wechsler individual achievement test 2nd edition (WIAT II)*. London: The Psychological Corporation.
Wolf, M., & Denckla, M. (2005). *The rapid automatized naming and rapid alternating stimulus tests* (Pro-ed).