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Ordinal Processing Differences Between Children With Persistent Dyscalculia and Typically Performing Children

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Ordinal number processing skills are important for adults and children. Recent work demonstrates that children have difficulty with judging the ordinality of sequences that are in-order but do not match the typical count-list (i.e., in-order non-adjacent sequences, such as 2-4-6). Limited evidence in the literature suggests that dyscalculic children show a similar pattern of behavior. In the present study, we sought to explicitly test the hypothesis that children with developmental dyscalculia struggle primarily with extending notions of ordinality to sequences outside of the count-list. We test this hypothesis using a sample of children with persistent developmental dyscalculia, and a comparison group of typically performing children. Both groups completed an ordinality judgment task, in which triplet sequences were judged as being in-order (e.g., 3-4-5; 2-4-6) or in mixed-order (e.g., 3-5-4; 2-6-4). In line with our prediction, results demonstrate that children with persistent developmental dyscalculia make more errors, compared to typically performing children, but only on the in-order non-adjacent trials (e.g., 2-4-6). Broadly, this finding suggests that ordinality processing abilities are impaired in children with developmental dyscalculia, and that this characteristic appears primarily in extending notions of ordinality beyond adjacent sequences.

Public Significance Statement

The ability to understand numerical order (e.g., the sequences 1-2-3 and 2-4-6 are in-order) is fundamental to more complex mathematical thinking. In this work, we show that children with persistent mathematical difficulties (i.e., children with developmental dyscalculia) struggle primarily to recognize/identify order outside of the typical count-list (e.g., 2-4-6) compared to typically performing children. Overall, this work identifies a key characteristic of developmental dyscalculia and provides a potential target for future interventions.

Keywords: ordinality, number, dyscalculia, numerical cognition

Supplemental materials: https://doi.org/10.1037/cep0000343.supp

Ordinal processing (i.e., the ability to recognize the relative rank or position of a number in a sequence) is a fundamental numerical skill that plays a key role in the representation of symbolic numbers (e.g., Arabic numerals; e.g., Lyons & Beilock, 2009, 2013; Merkley et al., 2016) and in the development of more complex mathematics (e.g., Lyons & Beilock, 2011; Lyons et al., 2014; Sasanguie & Vos, 2018; for a review see, Lyons et al., 2016). For example, a growing body of research has documented robust and consistent associations between ordinal processing and arithmetic, in which a better sense of ordinality is associated with better arithmetic performance in both adults (Goffin & Ansari, 2016; Lyons & Beilock, 2011; Morsanyi et al., 2017; Vogel et al., 2017; Vos et al., 2017) and children (Attout & Majerus, 2018; Lyons & Ansari, 2015; Lyons et al., 2014; Sasanguie & Vos, 2018). Further, findings from both behavioral and neuroimaging research have converged to suggest that impairments in ordinal processing are associated with specific math learning disabilities (i.e., dyscalculia; Attout et al., 2015; Attout & Majerus, 2015; De Visscher et al., 2015; Kaufmann et al., 2009; Morsanyi et al., 2018; Rubinsten & Sury; 2011). In fact, while those with developmental dyscalculia (DD) might display impairments across a variety of domain-specific (e.g., Mazzocco et al., 2011; Mussolin et al., 2010; Piazza et al., 2010) and domain-general skills (e.g., Morsanyi et al., 2018; Szucs et al., 2013), recent research suggests that order processing skills is an important predictor of a DD diagnosis in childhood (Morsanyi et al., 2018).

Specifically, Morsanyi et al. (2018) compared the performance of children with persistent DD (i.e., those who scored at least 1 *SD* below the mean on a standardized test of math achievement across at least 2 school years) to the performance of children without

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persistent mathematical difficulties across a range of mathematical and cognitive tasks including executive functioning, magnitude comparison and estimation, and numerical and nonnumerical ordering. Overall, the authors observed that performance on the ordering tasks identified those with persistent DD (vs. those without) with the greatest degree of accuracy (82.5%).

Given the importance of this finding, it is worthwhile to consider whether children with DD struggle with specific subcomponents of ordinal processing, or with ordinal processing as a whole. One possibility is that ordinal impairments observed in children with DD may be primarily driven by difficulties in recognizing ordered sequences that do not match the count-list. Children and adults readily identify sequences like 2-3-4 (which match the standard integer count-list) as "in-order"; however, both children and adults are less efficient at identifying sequences that are in-order, but do not conform to the standard count-list, such as 1-3-5 (e.g., Goffin & Ansari, 2016; Lyons & Ansari, 2015; Vogel et al., 2017). Here, we test the hypothesis that children with DD show particularly pronounced difficulty recognizing noncount-list sequences as in-order.

This hypothesis stems from studies that have found that adults and young children struggle to extend one's sense of numerical order beyond the adjacent count-list sequence. Therefore, this difficulty may be particularly pronounced, and appear as a delay, in children with DD relative to their typically performing peers. To that end, recent findings in the literature suggest that familiarity with the count-list may bias both typically performing children and adults to intuitively perceive adjacent ordered sequences that match the count-list (e.g., "2-3-4") as the *only* ordered sequences (Gattas et al., 2021; Hutchison et al., 2022). This bias is thought to stem from a fundamental misrepresentation of what constitutes numerical order in early childhood. Specifically, Hutchison et al., observed that, while typically performing kindergarten children can easily recognize adjacent ordered sequences that match the count-list (e.g., "2-3-4") as being in the correct order, they incorrectly classify non-adjacent ordered sequences that do not match this list (e.g., "1-3-5") as "not in-order". Indeed, a substantial number of children (59% of the sample) continued to reject the idea that non-adjacent ordered sequences are in the correct order even at the end of first grade. A similar pattern was reported in Gilmore and Batchelor (2021): 30% of their sample (62 children ages 6−8) incorrectly classified ordered sequences that are non-adjacent (i.e., those that do not match the count-list) as being "not in-order". The question we address here is whether the struggle to integrate a broader understanding of numerical order into one's understanding of numbers persists beyond early grade school (into Grades 4−8) in children with DD, thus constituting a significant and highly specific developmental delay.

The Present Study

Overall, familiarity with adjacent count-list sequences appears to influence ordinal processing via a tendency to perceive non-adjacent ordered sequences that do not match the count-list as "not in-order" (Gattas et al., 2021). This tendency may be a vestige of a nontrivial struggle in the early stages of formal schooling (kindergarten–Grade 1) to extend ordinal principles beyond the count-list, with some children experiencing more difficulty in doing so than others (Hutchison et al., 2022). What remains to be understood is whether difficulties or a delay in extending ordinal principles beyond the count-list is observed in older children, and in particular, whether such a delay may be a particularly salient marker of persistent dyscalculia. The present study aims to address this gap in the literature by comparing the ordering performance of elementary school children with persistent DD to those without consistent mathematical difficulties, separately for trials that do and do not match the count-list.

By *persistent* DD, we mean individuals who score at least 1 *SD* below the mean on two standardized assessments of mathematics across five testing sessions over a 4-year span. The fact that we include persistency in our criteria for identifying those with DD is notable, as many prior studies in this area tend to rely on information from only one time point when classifying children with DD (see Bugden et al., 2021, for a recent discussion). Relying on information from only one time point is problematic as it does not allow one to distinguish between those with short-term math difficulties and those with true dyscalculia. Identifying those with short-term math difficulties as having DD may lead to inaccurate conclusions regarding the core deficits that contribute to a DD diagnosis (Bugden et al., 2021; Mazzocco & Räsänen, 2013). By ensuring that we are capturing those with true dyscalculia, we can be more confident in our conclusions regarding potential difficulties with specific aspects of ordinality.

In sum, building on insights from prior literature (Gattas et al., 2021; Gilmore & Batchelor, 2021; Hutchison et al., 2022; Morsanyi et al., 2018), we hypothesize that difficulties in ordinal processing among children with persistent DD will be particularly pronounced for ordered sequences that do not match the count-list compared to those that do. If this is in fact the case, then it would suggest that difficulties or delays in extending ordinal principles beyond the count-list to include non-adjacent sequences of numbers is at minimum a clear marker for dyscalculia and may have other repercussions for understanding delays in children's math processing more broadly.

Method

Participants

The sample was made up of 33 children (ages 9–13) who participated in a larger longitudinal study described in detail elsewhere (Archibald et al., 2013; Bugden & Ansari, 2016; Bugden et al., 2021). The experimental design for the larger study is summarized in Figure 1. Children were initially screened for inclusion into the larger study in the fall of 2009 and were tested on a series of mathematical and cognitive tasks each year thereafter until the fall of 2013. In the present study, the primary measure of interest was the ordinality task administered at the final time point. Performance on the other mathematical and cognitive tasks at prior time points was used to identify children with and without persistent DD. Children were included in the present study if they met the inclusion criteria for persistent dyscalculia and completed the ordinality task at the final time point (n = 14) or if they were typically performing and completed the ordering task at the final time point (n = 19). Inclusion criteria for persistent dyscalculia was based on persistent performance across a series of standardized measures of mathematical ability, as well as a series of cognitive tasks (intelligence, reading, working memory), across the testing sessions.

Figure 1
The Data Collection Timeline for the Entire Study

Testing Session	Cognitive Standardized Tests and Numerical Tasks
Fall 2009	Math Fluency
Spring 2010	Math Calculation Reading Fluency Spatial Recall Listening Recall Vocabulary Matrix Reasoning
Spring 2011 & Spring 2012	Math Fluency Math Calculation Reading Fluency Spatial Recall Vocabulary Matrix Reasoning
Fall 2013	Math Fluency Math Calculation Reading Fluency Panamath **Ordinality Task**

Note. The ordinality task in the final testing session is analyzed in the present study.

Identifying Children With Persistent DD

Children were initially recruited for the persistent DD group if they obtained standard scores at least 1 *SD* below the mean (≤85) on both the Math Fluency and Math Calculation subtests from the Woodcock Johnson Tests of Achievement–III (Woodcock et al., 2001—see Materials section) in the first three testing sessions (Fall 2009 and Spring 2010, 2011). In these, and the following sessions, we allowed exceptions for scores that deviated slightly from this strict cutoff, provided scores were consistently low (see full list of exceptions below).[1] Children identified as having persistent DD had an average standard math composite score of 73.06 across all testing sessions, ranging from 64.83 to 81.75. Consistent with *Diagnostic and Statistical Manual of Mental Disorders, fifth edition* criteria for learning disorders (American Psychiatric Association, 2013), children had to obtain standard intelligence scores above 70 across all testing sessions. Fifteen children met the criteria for persistent DD and completed the ordinality task. One participant with persistent DD was removed for a high number of outlier trials (23.33%; see task description for more details on what constituted an outlier trial). We did not exclude participants who had chance performance overall for the task ($n = 2$; average error rates of 51.67% and 48.33%) because closer inspection of their performance did not reveal a pattern related to purely guessing on the task (e.g., both participants showed high accuracy in the adjacent in-order trials: 100% and 71.43%, respectively).[2] Overall, 14 children with persistent DD were included in the final sample (four females; $M_{\text{age}} = 12.35$ years, $SD_{\text{age}} = 1.25$).

Identifying Typically Performing Children

In line with the recruitment of children with persistent DD, children were initially identified as “typically performing” if they did not fall below 1 *SD* of the mean (>85) on the standardized tests of math achievement across in the first three sessions (Fall 2009 and Spring 2010, 2011). We allowed for some exceptions from this threshold, provided math performance was relatively consistent and that average standard scores across sessions were above 85 (see exceptions described below[3]). One child was initially identified as typically performing (standard of 96 and 105 for Math Fluency and Math Calculation in Sessions 1 and 2, respectively), but excluded for generally low math scores in the following sessions (average standard score of 79.67 across these sessions, standard scores ranging from 73 to 88). This child was not included in the DD group because their math scores were not consistently low across sessions. Overall, typically performing children had an average standard math composite score of 95.13, ranging from 86.38 to 105.17. There were a total of 19 typically performing children who also completed the ordinality task (11 females; M_{age} 11.46 years, $SD_{\text{age}} = .97$). We found that children with persistent DD were significantly older than typically performing children, $t(31) = -2.33$, $p = .027$, $BF_{10} = 2.45$. All typically performing children obtained persistent standard scores above 85 on the Reading Fluency subtest for each session. Nearly, all TP children (exception noted below[4]) also obtained persistent standard scores above 85 on working memory composite scores[5] for

[1] There was one child in the DD group who initially obtained a standard score of 97 on the Math Fluency subtest during the first testing session but obtained a standard score below 80 on both subtests for all remaining testing sessions. In addition, three other children with DD obtained standard scores greater than 85 during the first testing session (but not the second or third sessions). Each of these subjects also obtained standard scores greater than 85 on math fluency in one ($n = 2$) or two ($n = 1$) of the fourth and fifth sessions. These three participants obtained scores below 85 in all other instances. In Session 4, there was one child who obtained a standard score of 94 and 86 on the Math Calculation and Math Fluency subtests, respectively, but obtained a standard score below 84 in all other testing sessions. Last, there were two children who obtained standard scores of 86 and 95 on the Math Fluency subtest in Session 5, but both children obtained scores below 85 in all other testing session (including a score of 52 and 76, respectively, on the Math Calculation subtest in Session 5). Within the final sample of children with persistent DD, there were three children who did not participate in the fourth testing session.

[2] As a robustness test, analyses were also run without these participants with near chance overall accuracy (~50%). Broadly, findings are consistent with those reported here.

[3] One typically performing (TP) child received a standard score of 74 and 83 on Math Fluency in the first and fourth sessions, respectively, and a standard score of 85 on Math Calculation in the third session. This child obtained standard scores above 88 on the math measures in all other sessions. Two TP children obtained a standard score of 85 in the third session (one on the Math Fluency subtest and one on the Math Calculation subtest). These two children also had standard scores below 85 in both the Math Fluency and Math Calculation subtests in the fifth session but obtained standard scores above 85 in all other instances. After the three initial sessions, six children obtained a standard score between 79 to 85 on either or both the Math Fluency or Math Calculation subtests in only one of the last two sessions (Spring 2012 and Fall 2013) but obtained standard scores between 86 and 122 in all other instances. Three other TP children received a standard score between 79 and 84 on either or both the Math Fluency or Math Calculation subtests in both the fourth and fifth sessions but obtained standard scores between 87 and 110 in all other instances. In the final sample of TP children, five missed one or both math measures in Session 4.

[4] One TP child had a working memory composite score of 84.5 in the second session but had a working memory composite score of 106 in the third session (the only other session with working memory data for this participant).

[5] Working memory scores calculated as mean standard score for verbal and visuospatial working memory subtests.

each session. As a result of our selection criteria, we also found that our groups differed on measures of reading, intelligence, and verbal working memory (see Supplemental Methods and Results section for a full description of those measures and analyses).

Materials

Symbolic Ordinality Task

Children's ability to recognize both adjacent (count-list) and non-adjacent (noncount-list) ordered sequences as being in the correct order was assessed using a computerized Symbolic Ordinality Task that was administered at the final time point. In this task, participants were presented with three single digit Arabic numerals horizontally (e.g., 1–9) on the screen and were asked to indicate whether the sequences were in the correct ascending order or not. For half the trials, numbers were presented in correct ascending order (from left to right, e.g., 2-3-4). In the remaining trials, numbers were presented in mixed-order (e.g., 2-4-3). None of the trials were presented in correct descending order. Responses were made by a button press on the keyboard using letters "c" or "m". The buttons indicating whether a trial was in the correct order or not was counterbalanced across participants. Numbers within a given sequence for both in-order and mixed-order conditions were either adjacent (also known as close distance; e.g., 1-2-3, 1-3-2) or non-adjacent (also referred to as far distance; e.g., 2-4-6; 2-6-4). Distance was defined as the absolute difference between the largest, middle, and smallest numbers within the sequence (e.g., max–min/2). In the adjacent condition, all three numbers were separated by a distance of one (e.g., 2-3-4, or 5-7-6 for ordered and mixed conditions respectively). In the non-adjacent distance condition, all three numbers were separated by a distance of two (e.g., 2-4-6 or 6-2-4) or a distance of three (e.g., 1-4-7, or 4-1-7). There were seven, five, and three combinations of triplets for distance one, two, and three, respectively, for both in-order and mixed-order trials (see Appendix B for a list of trials). Therefore, distance two and three trials were collapsed into the non-adjacent distance condition to achieve adequate power in each condition bin. There were three blocks of 20 trials separated by a short break. In each block, there were 10 ordered and 10 mixed-ordered trials that were selected randomly from the trial list. Each of the 15 in-order sequences were administered twice, and there were thirty mixed-order sequences each administered once. There was a total of 60 trials.

All participants received the same instructions to complete the task (see Appendix A for exact wording). Children first completed 10 practice trials, five ordered and five nonordered trials were randomly selected from the list of trials that were in-order (15 possible trials) and mixed-order (30 possible trials) where both adjacent and non-adjacent sequences were administered. Participants received corrective feedback for the practice trials only. Cronbach's α was calculated on reaction time data for the entire sample revealing high internal consistency of the ordinality task, $\alpha = .93$. We also evaluated the split-half reliability of reaction time and error rates. Pearson correlations revealed strong stability across matched halves for reaction time, $r(31) = .91$, $p < .001$, $BF_{10} = 6.05 \times 10^{+10}$ and error rates, $r(31) = .84$, $p < .001$, $BF_{10} = 1.59 \times 10^{+7}$. Trials less than 125 ms and greater than 10,000 ms were removed to ensure results reflect actual processing of the stimuli. For the typically performing participants, this meant no trials were removed. For the participants with persistent DD, this resulted in 0.71% of trials being removed.

Mathematics Achievement

Children completed the Math Calculation and Math Fluency subtests from the Woodcock Johnson Tests of Achievement–III (Woodcock et al., 2001). The Math Calculation task is a nonspeeded assessment of general mathematical competence. Items begin with simple single digit addition and subtraction problems and progressively increase in difficulty. The Math Fluency task is a speeded assessment of simple arithmetic fluency. Children had 3 min to answer as many single digit addition, subtraction, and multiplication problems as they could without making any errors.

Procedure

The ordinality task was administered among a subset of other computerized numerical tasks during the fifth testing session (Bugden & Ansari, 2016), as well as the standardized math and reading tests. Participants were tested individually in a quiet laboratory testing room. Ethical approval was obtained by the University of Western Ontario's Health Sciences Research Ethics Board. Consent and assent were obtained by the parents and participants, respectively.

Analysis Plan

To assess if difficulties in ordinal processing among children with persistent DD are particularly pronounced for ordered sequences that do not match the count-list compared to those that do, we take a stepwise approach. We assess error rate data (i.e., how many items are incorrectly answered) because we predict that differences in ordinal processing are primarily about extending the notion of what is in-order beyond the count-list. In other words, we predict group differences will appear in their response choices rather than their response latency (see Supplemental Materials for reaction time results). First, we run a 2 × 2 × 2 mixed model analysis of variance (ANOVA), with group (persistent dyscalculia or typically performing) as a between-subjects factor, while trial type (in-order or mixed-order) and distance (adjacent or non-adjacent) as within-subjects factors. Here, a three-way interaction may support our hypothesis that performance differences between groups are primarily on the ordered non-adjacent trials. To specifically isolate if our hypothesis that differences in ordinal processing are localized to in-order non-adjacent trials, we run a 2 × 2 ANOVA with group and distance, but only include the in-order trials. In this case, a significant interaction between group and distance on in-order trials would be expected if children with persistent DD specifically differ from typically performing children on one type of trials. To rule out that the three-way interaction is not also driven by difference in processing the mixed-order trials, a similar 2 × 2 ANOVA is run with group and distance, using only the mixed-order trials. Here, we predict no interaction between group and distance, since mixed-ordered trials are generally considered to be processed by magnitude comparison processes, and not ordinal specific processes. We follow 2 × 2 ANOVA results with frequentist and Bayesian post hoc *t* tests to assess specific groupwise differences. Bayesian analyses were conducted in the statistical program, JASP (JASP Team, 2023), with default priors. Bayes factors are interpreted using the typical guidelines (Faulkenberry et al., 2020; Jeffreys, 1961), such that values between 1 and 3 (as well as between 0.33 and 1) constitute anecdotal evidence. Values between 3 and 10, 10 and 30, 30 and 100, and greater than 100 are moderate, strong, very strong, and extreme evidence, respectively.

Results

Combined across trial types and the two groups, the entire sample (n = 33) made an average of 14.97% errors (SD = 12.82%) in the ordering task. A mixed analysis of variance was conducted to examine how performance rates varied as a function of whether sequences were in correct and or incorrect order, as well as whether the sequence matched or did not match the count-list between children with DD and typically performing children. To ensure similar number of trials were within each distance condition (adjacent and non-adjacent), non-adjacent trials with a distance of two (e.g., 2-4-6) and three (e.g., 1-4-7) were collapsed to form the non-adjacent condition. Consistent with our prediction, the 2 × 2 × 2 mixed factorial ANOVA revealed a significant three-way interaction, $F(1, 31) = 8.16$, $p = .008$, $\eta_p^2 = .21$ (see Figure 2). All three main effects and two-way interactions were also significant: distance, $F(1, 31) = 23.76$, $p < .001$, $\eta_p^2 = .43$; group, $F(1, 31) = 10.14$, $p = .003$, $\eta_p^2 = .25$; order, $F(1, 31) = 4.61$, $p = .040$, $\eta_p^2 = .13$; Order × Group interaction, $F(1, 31) = 4.87$, $p = .035$, $\eta_p^2 = .14$; Distance × Group interaction, $F(1, 31) = 13.72$, $p < .001$, $\eta_p^2 = .31$; and Order × Distance interaction, $F(1, 31) = 28.48$, $p < .001$, $\eta_p^2 = .48$.

To uncover the locus of the three-way interaction and to directly test our hypothesis that group differences are driven primarily by performance on the in-order non-adjacent sequences, we conducted a 2 distance (adjacent vs. non-adjacent) × 2 group (DD, TP) mixed ANOVA using only in-order trials. There was a significant main effect of distance, $F(1, 31) = 37.70$, $p < .001$, $\eta_p^2 = .55$, whereby error rates were greater for non-adjacent trials compared to adjacent trials. There was also a main effect of group, such that children with DD made more errors than TP children, $F(1, 31) = 13.85$, $p < .001$, $\eta_p^2 = .31$. Importantly, there was also a significant two-way interaction between group and distance, $F(1, 31) = 14.21$, $p < .001$, $\eta_p^2 = .31$ Children with DD made significantly more errors than typically performing children when ordered sequences did not match the count-list (i.e., they were not adjacent) compared to when they did, $t(16.61) = -3.50$, $p = .003$, Levene's test of equality of variance was violated, $F(1, 31) = 8.96$, $p = .005$, so equal variances were not assumed, $d = -1.37$, $BF_{10} = 55.89$. However, there were no significant differences in performance between groups when determining if an adjacent ordered sequence was indeed in the correct ascending order, $t(31) = -1.09$, $p = .286$, $d = -.38$, $BF_{10} = 0.53$. The Bayes factors constitute anecdotal evidence of an absence of group differences on the in-order adjacent sequences. Conversely, there is very strong Bayesian evidence that children with DD make more errors on the in-order non-adjacent sequences compared to TP children. Overall, error rates only differed between children with persistent DD and typically performing children when the target stimuli were in the correct ascending order but did not match the count-list. Given that error rates are not normally distributed, average task error rates: Shapiro–Wilk, $W(33) = .86$, $p < .001$; error rates for in-order adjacent trials: Shapiro–Wilk, $W(33) = .70$, $p < .001$; error rates for in-order non-adjacent trials: Shapiro–Wilk, $W(33) = .82$, $p < .001$; error rates for mixed-order adjacent trials: Shapiro–Wilk, $W(33) = .69$, $p < .001$; error rates for mixed-order non-adjacent trials: Shapiro–Wilk, $W(31) = .60$, $p < .001$, nonparametric statistics were conducted and are consistent with the parametric analyses.[6]

To assess if differences between the DD and TP group were localized to in-order trials, we ran a follow-up 2 (adjacent, non-adjacent) × 2 (DD, TP) Mixed ANOVA using only the mixed-order trials. Within the mixed-order trials, there was a significant main effect of distance, whereby error rates were greater for close distance trials compared to far distance trials across both groups, $F(1, 31) = 6.63$, $p = .015$, $\eta_p^2 = .18$, but there was no significant interaction between group and distance, $F(1, 31) = 0.49$, $p = .491$, $\eta_p^2 = .02$; and critically there was no main effect of group, $F(1, 31) = 1.24$, $p = .273$, $\eta_p^2 = .04$. For completeness, we also ran independent samples t tests for adjacent and non-adjacent mixed-order sequences. Consistent with the ANOVA results, children with DD did not differ from TP children on adjacent trials, $t(31) = -1.13$, $p = .269$, $d = -.40$, $BF_{10} = 0.54$, or on non-adjacent mixed-order trials, $t(31) = -0.71$, $p = .485$, $d = -.0.25$, $BF_{10} = 0.41$. The Bayes factors provide anecdotal evidence that the DD group does not differ from the TP group on the mixed-order adjacent or mixed-order non-adjacent sequences. Consistent with our hypothesis, we found that children with DD did not differ in error rates during the mixed-ordered trials compared to typically performing controls.

Discussion

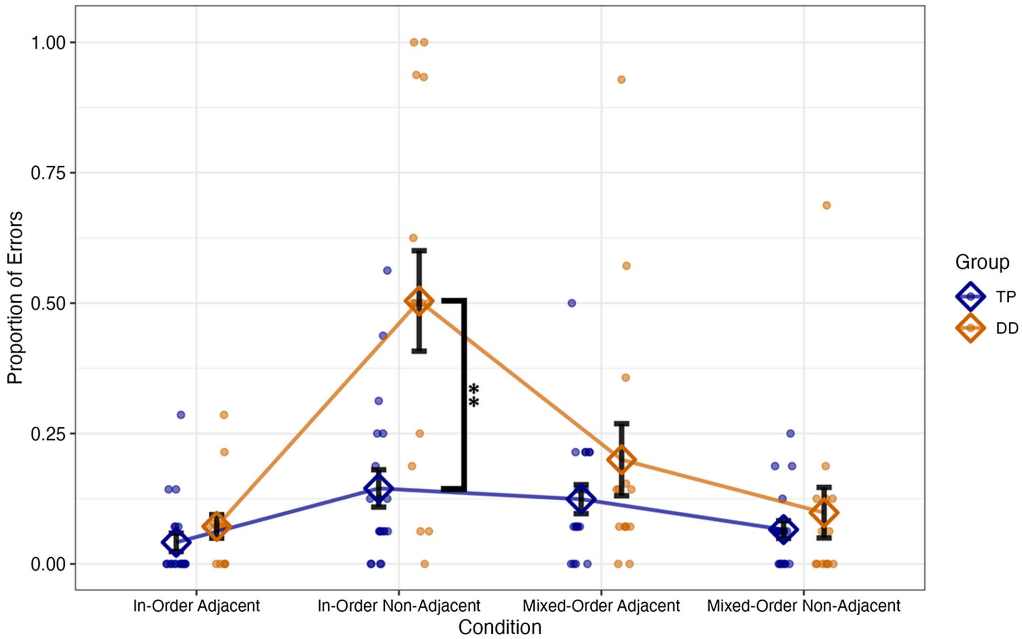
Recent work demonstrates that typically performing children in kindergarten and early elementary school have difficulty with judging the ordinality of sequences that are in-order but do not match the typical count-list, such as 2-4-6 (Gilmore & Batchelor, 2021; Hutchison et al., 2022). Prior work also demonstrates that children with DD may struggle with ordinal processing of numbers in general (Attout et al., 2015; Attout & Majerus, 2015; De Visscher et al., 2015; Kaufmann et al., 2009; Morsanyi et al., 2018; Rubinsten & Sury; 2011), and there is preliminary evidence that this may be especially pronounced in assessing ordinality of noncount-list sequences (Morsanyi et al., 2018). In the present study, we sought to explicitly test the hypothesis that children with DD struggle primarily with extending notions of ordinality to sequences outside of the count-list.

Prior research studies have used varying criteria to identify children with DD. Often, only a single session is used to identify children with poor math performance, despite the fact that math performance varies over time (Mazzocco & Myers, 2003; Mazzocco & Räsänen, 2013). To address this limitation, we tested our hypothesis in a sample of children who demonstrated persistently low math achievement scores across five different time points over a 4-year span. Results showed that children with persistent DD made more errors, compared to typically develop children, specifically on ordered, noncount-list trials (e.g., 2-4-6). We found no group

[6] Mann–Whitney U test for independent samples revealed that there was a significant group difference for only the in-order non-adjacent trials (p = .003). There were no significant group differences for in-order adjacent trials (p = .163), mixed-order adjacent (p = .627) and mixed-order non-adjacent trials (p = .900).

Figure 2

The Average Proportion of Errors Plotted for Adjacent (e.g., 1-2-3; 1-3-2) and Non-Adjacent (e.g., 1-3-5; 3-5-1) Trials Within the In-Order and Mixed-Order Conditions



Note. The TP group is shown in blue, while the DD group is shown in orange. Average scores are shown with the open diamond point with raw data points in the background. Error bars denote standard error. DD = developmental dyscalculia; TP = typically performing. See the online article for the color version of this figure.
** $p < .01$.

differences on any of the other ordering trial-types. This finding is thus consistent with the hypothesis that ordinal processing deficits in children with DD primarily manifest in their difficulty with extending notions of ordinality beyond count-list sequences.

It is important to clarify that our argument is not that children with DD are the only individuals who struggle to process the numerical order of noncount-list sequences. Indeed, in this same data set, we saw evidence of lower performance on ordered, noncount-list trials (e.g., 2-4-6) in typically performing children as well (compared to ordered, count-list trials; see Figure 2). Prior work has shown that younger, typically performing children struggle to verify that noncount-list sequences like 2-4-6 are in-order (Gilmore & Batchelor, 2021; Hutchison et al., 2022). Highly numerate adults also tend to show less efficient performance on noncount-list trials than count-list trials (Franklin et al., 2009; Lyons & Beilock, 2013), and recent work suggests this is primarily driven by poor efficiency on noncount-list trials as opposed to increased efficiency on count-list trials (Gattas et al., 2021). Hence, our view of this literature is that young children struggle to extend their concept of numerical order beyond the count-list. This early developmental struggle continues to manifest in reduced efficiency in adults when processing the ordinality of sequences like 2-4-6. Our results suggest that school-aged children with dyscalculia have difficulties extending one's notion of ordinality to ordered sequences outside of the count-list. This difficulty is faced by many children and may be simply more acute and appear as a significant delay in children with dyscalculia (for congruent findings, see Morsanyi et al., 2018). The difficulty that children with DD show on order non-adjacent sequences may be considered similar to the difficulty that typically performing children show when they start formal schooling (Hutchison et al., 2022). In this way, our results may be highlighting that children with DD have a developmental delay for extending ideas of ordinality beyond the count-list. An interesting theoretical and practical question is thus why children with DD show delays in noncount-list processing, and what utility may lie in interventions aimed at reversing these delays.

With respect to underlying mechanisms, there are several possibilities. One possibility is that the count-list is a procedure that can be learned primarily via repetition (Wynn, 1992), increasing its automaticity and decreasing its sensitivity to available working memory resources (Ashcraft et al., 1992; Tronsky, 2005). In this view, learning and use of the count-list, unlike many other math skills, may be relatively insulated from challenges to working memory capacity that children with DD may experience (Attout & Majerus, 2015; Menon, 2016). As such, children with DD may be more inclined to fall back on more routinized techniques that are less susceptible to disruption, like counting. This in turn may lead to a stronger emphasis on the count-list, making it more difficult to forgo the count-list as one's primary anchor for processing numerical order.

A second possibility, not mutually exclusive with the first, places the focus on the moment when children with DD must essentially inhibit the inclination to use the integer count-list as their primary means of evaluating numerical order. In this view, a sequence like 2-4-6 does not match the count-list, and to identify it as in-order, one must first inhibit the inclination to say “not in-order” because it does not match the count-list (Gattas et al., 2021). If children with dyscalculia struggle with inhibiting prepotent responses, especially in the numerical domain (Devine et al., 2013; Szucs et al., 2013), this may lead to particular difficulties in inhibiting the immediate response that 2-4-6 is not in-order. In this respect, the mechanism that explains why children with dyscalculia struggle to go beyond the count-list in ordinal processing is much the same as that which explains their difficulty with other counterintuitive numerical ideas (e.g., $\frac{1}{2} > \frac{1}{3}$; Mazzocco & Räsänen, 2013). Notably, we encourage caution about overinterpreting domain-general antecedents as direct mechanisms for differences in children with DD. For instance, Wilkey et al. (2020) showed that number-specific executive functioning was associated with DD and math skills while nonnumerical executive functioning was not. This is in line with the notion that executive function skills, such as working memory and inhibition, interplay with numerical skills and play a more context specific role in math development (Bugden & Ansari, 2016; Coolen et al., 2021; Wilkey et al., 2020). As such, executive-functioning skills may not be a general cause, but perhaps a biproduct as general cognitive and numerical skills support each other across development.

A third possibility is that children with DD primarily struggle with more abstract numerical concepts in general (Butterworth, 2005, 2011). Numerical order is an especially powerful numerical concept precisely because it allows one to reason about relations between numbers without only oblique reference to their underlying magnitudes (Lyons et al., 2016). For instance, the rank order of $\sqrt{5}, e, \pi$ is 1-2-3, and the rank order of 2, 4, 6 is also 1-2-3, meaning the values e and 4 both occupy the same ordinal position, 2, even though the actual cardinal value of 2 is both contained in the second set and numerically less than all three of the values in the first set. Indeed, it is this insight that makes working with more exotic numbers that are difficult to ground in concrete experience (very large numbers, irrational numbers, negative numbers, etc.) far more tractable (Coles & Sinclair, 2018; Peano, 1889). While mathematically powerful, this sort of abstraction can also be conceptually challenging even for typically performing individuals. If children with DD find even simple versions of this sort of abstraction especially difficult (Butterworth, 2005, 2011), then the idea that number sequences that do not match the count-list can still be in-order may be one manifestation of a broader struggle with numerical abstraction.

On a practical level, it is worth asking why deficits in ordinal processing matter. Ordinal verification performance is highly predictive of other types of math skills, such as arithmetic (Lyons et al., 2016), although it is important to note evidence for causality is mixed (Devlin et al., 2022). Perhaps more to the point, ordinal ranking is a ubiquitous aspect of many situations, from academic achievement to sports to online product rankings. A flexible and accurate understanding of how numerical ranking works is thus of basic practical value in its own right. Further, as noted above, ordinality is a foundational aspect of several types of more abstract mathematical thinking, which many students will encounter as they advance through the mathematics curriculum. Hence, there are several reasons why the specific sort of ordinal processing deficit shown here for children with dyscalculia is worthy of researchers' and educators' attention.

To that end, while specific interventions are beyond the scope of the current article, based on the discussion of possible mechanisms described above, we can make two predictions regarding intervention efficacy. In the first case, if the primary issue children with DD face is in inhibiting a highly routinized procedure (reciting the count-list), then the most effective interventions would likely involve substantial, repeated practice with counterexamples. Over time, repeated exposure to counterexamples can weaken over-learned associative links (Izquierdo et al., 2017; Yaple & Yu, 2019), a technique that could be used to increase flexibility in the link between the count-list and ordinality. Similarly, if children with DD struggle with inhibitory control (Devine et al., 2013; Szucs et al., 2013), then one may need to rely more on procedural mechanisms that build up positive associations with alternative ordinal examples (e.g., 2-4-6), which in turn will obviate the need for inhibitory mechanisms over time (Ashcraft, 1992; Izquierdo et al., 2017). In a second, alternative scenario, if the primary issue children with DD face is in understanding abstract concepts (Butterworth, 2005, 2011), then additional conceptual scaffolding may be the most effective form of intervention. For instance, combining manipulatives and use of a visual–spatial number-line has been effective in other contexts (Siegler & Ramani, 2009; Xu & LeFevre, 2016). A similar approach that also involves explicit instruction about the difference between magnitude and order could be useful in grounding this idea in more concrete experience.

Limitations

One key limitation of this study is its relatively small sample-size. This is balanced by our ability to make a strong claim that the children with DD in our sample are consistently so, showing persistent math deficits over multiple measurements and an extended developmental period. That said, it is important to note, that our estimates of the relevant effect-sizes are likely to carry a high degree of error and in particular may be over-estimated. As such, we encourage caution against overinterpreting the reported effect-sizes and their exact value should be treated only as a rough guide for what to expect in future studies. A second limitation is that we used noncontinuous groups, essentially comparing a group on the extreme end of the distribution with a group roughly in the middle of the distribution. We did so because our focus was on characterizing ordinal performance in a group of children with unambiguously persistent math deficits. However, our approach should be understood as only limited snapshot of the overall distribution, which, as others have argued, is perhaps best thought of as continuous.

Conclusion

Ordinal number processing skills are important for children and adults (e.g., Goffin & Ansari, 2016; Lyons & Ansari, 2015). Recent research demonstrates that children have difficulty with judging the ordinality of sequences that are in-order but do not match the typical count-list (i.e., in-order non-adjacent sequences, such as 2-4-6; Hutchison et al., 2022). Notably, children with dyscalculia may show a similar pattern of behavior. In the present study, we sought to explicitly test the hypothesis that children with DD struggle mainly with extending notions of ordinality to sequences outside of the count-list. Results demonstrate that children with persistent DD make more errors, compared to typically develop children, but only when verifying the order of in-order non-adjacent trials (2-4-6). Overall, our results suggest that ordinal processing skills are lower in children with DD, and that this characteristic appears primarily in extending notions of ordinality beyond adjacent sequences.

Résumé

Les compétences de traitement des nombres ordinaux sont importantes tant chez l'enfant que chez l'adulte. Des travaux récents démontrent que les enfants éprouvent des difficultés à juger l'ordinalité des séquences ordonnées, mais qui sortent du cadre de décompte habituel (p. ex., des séquences de nombres dans l'ordre, mais non adjacents, comme 2-4-6, etc.) Les données probantes restreintes dans la documentation donnent à penser que les enfants qui éprouvent une dyscalculie présentent des comportements analogues. Dans la présente étude, nous voulions examiner explicitement l'hypothèse selon laquelle les enfants présentant une dyscalculie développementale éprouvent avant tout des difficultés à appliquer les notions de l'ordinalité à des séquences qui sortent du cadre de décompte habituel. Nous mettons donc cette hypothèse à l'épreuve sur un échantillon d'enfants présentant une dyscalculie développementale persistante et un groupe de référence composé d'enfants possédant des capacités de calcul « habituelles ». Les deux groupes devaient effectuer une tâche de jugement de l'ordinalité, où ils devaient déterminer si des séquences de triplets étaient ordonnées (3-4-5) ou pas (3-5-4, 2-6-4, etc.) Les résultats de l'étude cadrent avec nos prévisions et démontrent que les enfants qui présentent une dyscalculie développementale persistante font plus d'erreurs comparativement aux enfants possédant des capacités de calcul habituelles, mais seulement dans les essais ordinaux non adjacents (p. ex., 2-4-6). Dans l'ensemble, ces constatations donnent à penser qu'il y a une défaillance des capacités de traitement de l'ordinalité chez les enfants qui présentent une dyscalculie développementale, et que ce trait se manifeste principalement lorsque vient le temps d'appliquer les notions de l'ordinalité au-delà des séquences adjacentes.

Mots-clés : ordinalité, nombre, dyscalculie, cognition numérique

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(*Appendices follow*)

Appendix A

Ordering Task Instructions

"Welcome to the Order Task!
Your job is to decide whether three numbers are all in the right order.
For example:
1 2 3
are in order.
For example:
1 3 2
and
2 1 3
are NOT in order.
Press space to continue."
"When the three numbers are in order, you should press the [correct order button*] key.
The examples below are all in order.
1 2 3
2 4 6
3 6 9
6 7 8
In every case, you should press the [correct order button*] key.
Press [correct order button] now to continue."
"When the three numbers are NOT in order, you should press the [incorrect order button*] key.
The examples below are all in the wrong order.
2 1 3
2 6 4
6 3 9
6 8 7
In every case, you should press the [incorrect order button*] key.
Press [incorrect order button*] now to continue."
"If you have any questions, please ask the experimenter now.
In a moment, you will have a chance to practice the task.
Press the button that means NOT IN ORDER to continue."
"The next block of trials is about to begin.
A block cannot be paused, so make sure that you are completely ready.
Reminder:
[correct order button*] means IN ORDER.
[incorrect order button*] means NOT in order.
Place your fingers over the [correct order button*] and [incorrect order button*] keys now.
Press either key to begin."**
"The practice session is over.
The main part of the task will begin in a moment.
You will no longer be told whether your response was correct or not.
Please ask the experimenter now if you have any questions.
Press space to continue."
*Note. The correct/incorrect order button were randomly assigned as "M" or "V" for each subject.
**Note. The next block instructions were presented before the practice and then again before each of the three main blocks.

(*Appendices continue*)

Appendix B

Ordering Task Trials

Condition	Left	Middle	Right	Distance
In-order adjacent	1	2	3	1
In-order adjacent	2	3	4	1
In-order adjacent	3	4	5	1
In-order adjacent	4	5	6	1
In-order adjacent	5	6	7	1
In-order adjacent	6	7	8	1
In-order adjacent	7	8	9	1
In-order adjacent	1	2	3	1
In-order adjacent	2	3	4	1
In-order adjacent	3	4	5	1
In-order adjacent	4	5	6	1
In-order adjacent	5	6	7	1
In-order adjacent	6	7	8	1
In-order adjacent	7	8	9	1
In-order non-adjacent	1	3	5	2
In-order non-adjacent	2	4	6	2
In-order non-adjacent	3	5	7	2
In-order non-adjacent	4	6	8	2
In-order non-adjacent	5	7	9	2
In-order non-adjacent	1	3	5	2
In-order non-adjacent	2	4	6	2
In-order non-adjacent	3	5	7	2
In-order non-adjacent	4	6	8	2
In-order non-adjacent	5	7	9	2
In-order non-adjacent	1	4	7	3
In-order non-adjacent	2	5	8	3
In-order non-adjacent	3	6	9	3
In-order non-adjacent	1	4	7	3
In-order non-adjacent	2	5	8	3
In-order non-adjacent	3	6	9	3
Mixed-order adjacent	2	1	3	1
Mixed-order adjacent	3	2	4	1
Mixed-order adjacent	4	3	5	1
Mixed-order adjacent	5	4	6	1
Mixed-order adjacent	6	5	7	1
Mixed-order adjacent	7	6	8	1
Mixed-order adjacent	8	7	9	1
Mixed-order adjacent	1	3	2	1
Mixed-order adjacent	2	4	3	1
Mixed-order adjacent	3	5	4	1
Mixed-order adjacent	4	6	5	1
Mixed-order adjacent	5	7	6	1
Mixed-order adjacent	6	8	7	1
Mixed-order adjacent	7	9	8	1
Mixed-order non-adjacent	3	1	5	2
Mixed-order non-adjacent	4	2	6	2
Mixed-order non-adjacent	5	3	7	2
Mixed-order non-adjacent	6	4	8	2
Mixed-order non-adjacent	7	5	9	2
Mixed-order non-adjacent	1	5	3	2
Mixed-order non-adjacent	2	6	4	2
Mixed-order non-adjacent	3	7	5	2
Mixed-order non-adjacent	4	8	6	2
Mixed-order non-adjacent	5	9	7	2
Mixed-order non-adjacent	4	1	7	3
Mixed-order non-adjacent	5	2	8	3
Mixed-order non-adjacent	6	3	9	3
Mixed-order non-adjacent	1	7	5	3
Mixed-order non-adjacent	2	8	6	3
Mixed-order non-adjacent	3	9	9	3

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