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Predictors of Middle School Students’ Growth in Symbolic Number Comparison Performance

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Abstract

The ability to efficiently compare number symbols, such as digits, is associated with mathematics competence across the lifespan. Performance on symbolic number comparison tasks differ across age groups; young students who are developing fluency with digits improve on symbolic number comparison, and performance is better in adults than children. However, whether this improvement continues for older students who are fluent with number symbols, and what cognitive factors relate to this improvement, is unknown. This study used a longitudinal sample of U.S. middle school students (n = 394) to examine whether symbolic number comparison performance changes over middle school (i.e., students aged 11-14), whether there are individual differences in students’ rate of change, and potential predictors of that change. Students completed measures of single-digit symbolic number comparison, nonsymbolic number comparison, executive function (EF), and mathematics competence in Grade 5 (M = 11.02 years; SD = 0.32), and double-digit symbolic number comparison in Grades 6-8. Results showed that, on average, students’ symbolic number comparison performance improved from Grades 6-8. Grade 5 Symbolic number comparison performance predicted Grade 8 symbolic number comparison and rate of change over Grades 6-8. Grade 5 nonsymbolic number comparison, EF, and mathematics competence predicted Grade 8 symbolic number comparison performance. Results suggest that numerical magnitude processing, executive functions, and mathematics competence are related to symbolic number processing well into middle school, and that students continue to refine their ability to process number symbols into adolescence.

Keywords

number comparison, approximate magnitude, executive function, mathematics competence

Numeracy is important for outcomes across the lifespan, such as college attainment, employment earnings, and health and medical decision making (Dougherty, 2003; Reyna & Brainerd, 2007), and the relation between numeracy and life outcomes begins before formal schooling. Mathematics school-readiness skills (e.g., counting, understanding ordinal relations and relative numerical magnitude) are strong predictors of later academic achievement (Duncan et al., 2007). In particular, the ability to quickly and accurately compare digits (e.g., determine whether 8 or 2 is greater) has emerged as a robust, consistent predictor of mathematical achievement in children and adults (Schneider et al., 2017). Digit comparison has become commonplace across investigations of numerical cognition (Lyons et al., 2012; Maloney et al., 2010; Reike & Schwarz, 2016; Van Opstal et al., 2008; Verguts & Van Opstal, 2005) and its relation to mathematics achievement (De Smedt et al., 2013; Sasanguie, Lyons, et al., 2017; Schneider et al., 2017).

Traditionally, the task of comparing digits – here referred to as symbolic number comparison – has been used (among other tasks) to measure children’s and adults’ representations of numerical magnitude (Dehaene et al., 1998).

The task comprises several processes that include digit identification, digit-number word connections, ordinal understanding, and general comparison; the task may draw on associations among digits in long-term memory (Sasanguie, Lyons, et al., 2017). While research on symbolic number comparison most often involves single-digit comparison tasks, some studies have examined double-digit comparison (e.g., Nuerk et al., 2001). Task properties such as presentation mode (i.e., sequential or simultaneous presentation of the double-digit numbers) or number pairs (e.g., same-decade or different-decade) may engage different cognitive processes (e.g., Ganor-Stern et al., 2009). Studies suggest that when number pairs are displayed simultaneously, children and adults compare double-digit numbers componentially (Dehaene et al., 1990; Ganor-Stern et al., 2009; Nuerk, Kaufmann, et al., 2004). In other words, they may decompose the double-digit numbers into single-digit comparisons by decades and units and rely on the same long-term associations that single-digit comparisons engage (Verguts & De Moor, 2005). Taken together, studies suggest that single-digit and double-digit comparison tasks measure the processing of number symbols that is foundational to mathematics achievement.

Symbolic number comparison performance differs by age. Cross-sectional studies with single-digit comparison have shown that symbolic number comparison is faster and more accurate for older elementary school students (i.e., about 11 years old) than younger ones (i.e., 5-7 years old), and for adults compared to children (Defever et al., 2011; Duncan & McFarland, 1980; Holloway & Ansari, 2008, 2009; Sekuler & Mierkiewicz, 1977). Similarly, longitudinal research has shown improvement in symbolic number comparison over the first few years of schooling. On average, students in Kindergarten or Grade 1 (i.e., 5-6 years old) improve on symbolic number comparison over the course of a school year (Lyons et al., 2018; Matejko & Ansari, 2016), and across early grades, such as from Kindergarten to Grade 2 (Xenidou-Dervou et al., 2017). Differences in performance, or improvement over time, reflect greater fluency with processing digits. As examples, this processing may reflect the development of greater precision of numerical magnitude representations on the mental line (Dehaene et al., 1998) or fluency of accessing associations between numbers that are stored in long-term memory (Sasanguie, Lyons, et al., 2017).

Compared to younger children, relatively less is known about the development of symbolic number processing for older children. Research involving middle school students (i.e., Grade 6, about 11 years old) has shown that they have higher symbolic number comparison performance compared to younger students (Defever et al., 2011). However, because this relation was cross-sectional, it did not capture developmental change in symbolic number comparison performance. Whether students continue to improve or show stable symbolic number comparison performance beyond elementary school, and the extent of individual differences in any such change, remain open questions. Such knowledge will illuminate the developmental trajectory of symbolic number processing beyond elementary school.

Potential Factors Related to Symbolic Number Comparison Performance

If students' symbolic number comparison performance continues to improve over time, myriad factors may contribute. First, symbolic number comparison performance may relate to prior ability with similar numerical magnitude comparison tasks. In the traditional view, symbolic number comparison or comparison of nonsymbolic numerical magnitude (i.e., determining which of two dot arrays is more numerous) engages numerical representations on a mental number line (Dehaene et al., 1998; Feigenson et al., 2004; Moyer & Landauer, 1967; Restle, 1970). This view posits a strong overlap in the cognitive processes involved in symbolic number comparison and nonsymbolic numerical magnitude comparison (Dehaene, 2001; Piazza, 2010). Indeed, research suggests a correlation between symbolic and nonsymbolic task performance in both children and adults (Gilmore et al., 2014; Mussolin et al., 2012, 2014, 2016). From this view, prior symbolic and nonsymbolic number comparison performance would both relate to continued change in symbolic number comparison over time, as they both reflect foundational representations of numerical magnitude.

However, the cognitive processes underlying symbolic number comparison and nonsymbolic comparison performance may not overlap as much as traditionally thought. In the early grades, symbolic number comparison performance may predict nonsymbolic comparison performance, but not vice versa (Hutchison et al., 2020; Lyons et al., 2018; Matejko & Ansari, 2016; Mussolin et al., 2014; Sasanguie et al., 2014). Another possibility is that symbolic and nonsymbolic number comparison may influence each other reciprocally (Toll et al., 2015; for a review, see Goffin & Ansari, 2019). These possibilities suggest there may be distinct cognitive systems for processing symbolic and nonsymbolic numerical magnitude (Fazio et al., 2014). If so, whether they integrate later in development is still an open question (Kolkman et al., 2013; Lyons et al., 2012; Reynvoet & Sasanguie, 2016; Sasanguie, De Smedt, et al., 2017; Wilkey, Conrad, et al., 2020). From this alternative view, prior symbolic number comparison performance is likely to predict future symbolic number comparison performance. However, the role of nonsymbolic comparison performance is less certain, based on open questions about shared cognitive mechanisms across symbolic and nonsymbolic number processing.

Second, executive functions (EF) may contribute to change in symbolic number comparison performance during middle school. This contribution could be direct, since improvements in handling attentional and working memory task demands could drive improvements in task performance. Or, EF could contribute to change in symbolic number comparison indirectly. For example, given the interrelation of symbolic and nonsymbolic comparison performance, one indirect way may be through the relation between EF and nonsymbolic comparison performance. Nonsymbolic comparison tasks may engage EF skills, specifically inhibitory control (Clayton & Gilmore, 2015; Gilmore et al., 2013) and selective attention (Fuhs & McNeil, 2013), due to task-specific features. For example, tasks often include comparison of two dot arrays that vary not only in numerical magnitude, but other features that covary with magnitude, such as dot density, surface area, and convex hull, and that may influence comparison processes (Clayton et al., 2015; Gebuis & Reynvoet, 2011, 2013; Pekár & Kinder, 2020; Szűcs et al., 2013; Wilkey et al., 2017). In some nonsymbolic comparison trials, the features are congruent (e.g., greater numerical magnitude, dot density, surface area, and convex hull), while in other trials the features are incongruent (e.g., greater numerical magnitude, smaller dot density, surface area, and convex hull). Successful comparison in the latter case may require the ability to inhibit conflicting information and focus attention on numerical magnitude, rather than other stimulus features. Indeed, these EF skills may even underlie the relation between nonsymbolic magnitude processing and mathematics competence (Bugden & Ansari, 2016; Fuhs et al., 2016; Fuhs & McNeil, 2013; Gilmore et al., 2013; Wilkey, Pollack, et al., 2020). Ultimately, the influence of EF on nonsymbolic magnitude processing may relate to the development of symbolic number processing. A second way that EF may contribute to change in symbolic number comparison performance is through relations with more advanced mathematical skills. EF has a well-established relation to calculation ability and more advanced mathematics knowledge across age groups (Cragg & Gilmore, 2014; Yeniad et al., 2013). Taken together, this research suggests that EF, specifically inhibitory control, may play an important role in symbolic number comparison performance and its change over time.

Third, students' prior mathematics achievement may relate to their symbolic number comparison performance and its change over time. The majority of prior research has examined how symbolic number comparison predicts mathematics competence and has shown a consistent positive relation (Fazio et al., 2014; Sasanguie, Lyons, et al., 2017; Schneider et al., 2017). Therefore, students that enter middle school with higher mathematics competence are likely to also have higher performance on symbolic number comparison. Students with higher mathematics competence may also have a greater rate of improvement in symbolic number comparison performance, as relatively higher prior achievement may facilitate how quickly students' master mathematics tasks. This potential relation may be similar to the way that acquisition of formal mathematics and improvement in symbolic number has been shown to improve nonsymbolic number comparison performance (Nys et al., 2013; Piazza et al., 2013). To our knowledge, mathematics competence as a factor related to change over time in basic symbolic number processing has not been characterized previously.

In sum, children improve in symbolic number comparison performance throughout the early years of developing fluency with number symbols, and adults have higher performance compared to children. However, a characterization of symbolic number comparison performance and its change over time beyond early elementary school has yet to be established. Further, while it is clear from prior research that symbolic number comparison predicts later mathematics competence, it is unknown how related constructs, such as nonsymbolic comparison, EF, and mathematics knowledge are associated with symbolic number comparison performance and its change over time after students have acquired fluency with number symbols. Research on symbolic number comparison performance and its change over time in older students, such as middle school students, is necessary to characterize a developmental trajectory of symbolic number comparison that bridges our understanding of symbolic number comparison performance across early grades and adulthood. Further, an understanding of what contributes to symbolic number comparison performance and its change over time can clarify the cognitive processes measured by symbolic number comparison tasks and thereby illuminate their connection to numerical and mathematics competence.

Present Study

In the present study, we investigated symbolic number comparison performance and its change over time during Grades 5-8. To do so, we used the first year of data (i.e., Grade 5 [mean age about 11 years]) to predict symbolic number comparison performance in Grade 8 and its change over time in Grades 6-8. This approach characterizes within-student variability in symbolic number comparison performance across grades, between-student variability in Grade 8 and rate of change over Grades 6-8, as well as predictors of each. We first asked: Does symbolic number comparison performance change over middle school? We hypothesized that, on average, students would improve from Grades 6-8. Second, we asked: How do prior symbolic and nonsymbolic comparison ability, EF ability, and mathematics competence relate to Grade 8 symbolic number comparison performance and symbolic number comparison rate of change from Grades 6-8? We hypothesized that Grade 5 symbolic number comparison, Grade 5 EF, and Grade 5 mathematics competence would predict symbolic number comparison performance at Grade 8 and from Grades 6-8. Based on the uncertain relation between symbolic and nonsymbolic numerical magnitude processing, we did not have a strong hypothesis for the role of Grade 5 nonsymbolic comparison ability.

Materials and Method

Sample

Students are a subset of a larger sample who took part in an initial longitudinal study of early mathematical skills (Hofer et al., 2013), and a follow-up study for students who attended public school in the same district in both middle school (students about 11-14 years old) and Pre-K (Price & Wilkey, 2017; Rittle-Johnson et al., 2017). Starting in the 2013-2014 school year, 519 students across 65 schools participated in the follow-up study. All participants had parental consent and gave assent. The Vanderbilt University IRB approved the study.

The analytic sample consists of a subset of students (n = 394) from the follow-up study. Starting with the full follow-up sample (n = 519), we excluded 125 students based on several criteria. We excluded students who had been retained (n = 94, approximately 14% of the full follow-up sample), since these students had a qualitatively different educational experience that is outside the scope of this study. For example, retained students change cohorts and stay in a school a year longer. Retention is associated with behavioral and emotional challenges and lower academic achievement (Jimerson & Ferguson, 2007; Meisels & Liaw, 1993), including mathematics learning trajectories (Zilanawala et al., 2018), and a higher probability of dropping out of high school (Hughes et al., 2018). We excluded one student who belonged to an older cohort, since that student had a different level of knowledge than the other students. We excluded 23 students who were missing data on the outcome (i.e., symbolic number comparison in Grades 6-8). We also excluded seven students who did not advance past the nonsymbolic comparison practice (students had to correctly answer five of six easy ratio trials) despite three attempts and example trials prior to each attempt, and because these students had no subsequent nonsymbolic comparison scores. The total analytic sample was 394 students across 65 schools. Most schools were public with a small number that were charter schools (i.e., independently-run public schools) or designated for additional resources to support student performance. At the first time of testing (i.e., Grade 5), students had a mean age of 11.02 years (SD = 0.32). The ethnic/racial composition of the sample was 78.17% African American, 8.88% Hispanic, 8.38% White, 4.57% Other. The sample was 40.61% male; 90.82% qualified for free or reduced lunch, defined as a family income less than 1.85 times the U.S. Federal income poverty guideline.

Measures

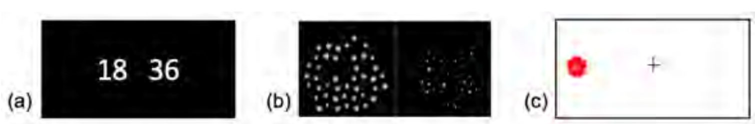
Symbolic Number Comparison

In Grade 5, students completed single-digit symbolic number comparison. We chose this because it is a standard number comparison task that correlates with math ability across a wide range of ages (e.g., Schneider et al., 2017). There were 96 trials, in which students saw two single-digit numbers (i.e., 1-9) for 1200 ms and selected which was larger via number pad button press. Response time and accuracy were recorded for each trial and the position of the larger number was counterbalanced across trials. A trial ended with an 1800 ms inter-stimulus interval (ISI). Before starting the task, students had to correctly answer five of six practice trials. Table A1 in the Appendix lists the digit pairs and associated ratios.

Students completed double-digit number comparison in Grades 6-8. Double-digit numbers were used to ensure adequate variation in symbolic number comparison and avoid ceiling effects in accuracy in subsequent years of data collection, based on high accuracy rates for single-digit comparison for Grade 5 students. The task comprised 70 trials. For each trial, students saw a pair of double-digit numbers for 1200 ms and indicated which number was larger via number pad button press. The pairs were unit-decade incompatible (i.e., the unit in the larger number was smaller than the unit in the smaller number, such as in 18 versus 54), so that tens and units did not convey the same information about which digit was larger. Decade-unit compatibility further ensured adequate task difficulty, since decade-unit compatible trials facilitate faster response time and higher accuracy (e.g., Nuerk et al., 2001). Finally, we chose decade-unit incompatible trials to align task properties (i.e., number of trials, ratios) with additional measures in the larger longitudinal study. The inclusion of decade-unit compatible and same-decade trials would have been preferable as part of the double-digit comparison task. However, in this case, the selection of decade-incompatible trials provided a measure of symbolic number processing at an adequate level of task difficulty that additionally conformed to the parameters of the larger longitudinal study. We modeled ratios, stimulus presentation times, and order of presentation after a version of the nonsymbolic number comparison task designed by Odic et al. (2014). Whether the correct answer was on the left or right side of the screen was counterbalanced. Each trial ended with an 1800 ms ISI. Accuracy and response time data were recorded for each trial. Before the task, students had up to three attempts to complete a six-trial practice. To advance beyond the practice, students had to respond correctly to five trials. Figure 1a shows an example stimulus and Table A1 in the Appendix lists all comparison pairs.

Figure 1

Example Stimuli From (a) Double-Digit Symbolic Number Comparison, (b) Grade 5 Dot Comparison, and (c) the Grade 5 Hearts and Flowers Task



Grade 5 Nonsymbolic Number Comparison

In this task (Grade 5 Dots), students viewed two simultaneously presented nonsymbolic dot arrays and indicated via number pad button press which array had more dots. We adopted ratios from Piazza et al. (2013). There were 100 trials total, ten each of ten ratios that ranged from .625 to .941 (see Table A1). Dot sets ranged in numerosity from 10 to 44. Dot arrays were gray on a black background and separated by a vertical gray line. For each trial, the dot arrays displayed for 1000 ms with a 2000 ms ISI. To construct the dot arrays, we adapted Gebuis and Reynvoet's (2011) MATLAB code to control visual properties that covary with numerosity (i.e., convex hull, total surface area, average dot diameter, total circumference, density). Response sides were fully counterbalanced. Figure 1b shows an example trial. Prior to starting the task, students had to correctly answer at least four of six trials in a practice round, with up to three practice rounds. Accuracy and response time were recorded for each trial.

Grade 5 Executive Function (EF)

Students completed three blocks of the Hearts and Flowers task (Wright & Diamond, 2014) as a measure of EF. In the first block, students completed 12 trials in which they saw a heart on the left or right side of the screen and pressed a number pad button corresponding to the same side. In the second block, students completed 12 trials in which they saw a flower on one side of the screen and pressed a number pad button corresponding to the opposite side. In the third mixed block, students completed 48 trials in which they saw a heart or flower, and pressed the corresponding number pad button according to the rules from previous blocks (see Figure 1c for an example image).

As a measure of EF, we used accuracy on the mixed block, which captures inhibitory control, working memory, and task switching (Diamond, 2013). Eighteen students were missing data on the Grade 5 Hearts and Flowers measure, but completed this task in Grade 6. To include these children in the analytic sample, we used single imputation by substituting their Grade 6 mixed block accuracy scores. To keep the relative position of students' performance, we first standardized Grade 5 and Grade 6 scores separately, imputed the Grade 6 scores for the 18 students, and used the *z*-scores for all analyses. We adopted this analytic approach from a prior study that used a similar data set to examine the relations among non-symbolic number comparison, executive functioning, and dyscalculia (Wilkey, Pollack, et al., 2020).

Grade 5 KeyMath-3

Students completed the KeyMath-3 (Connolly, 2007), a norm-referenced assessment of mathematics competence. For the present analysis, students' scores comprised an average of age-scaled scores on the Numeration, Algebra, and Geometry subscales from the Basic Concepts section, which focuses on conceptual knowledge. Items on the Numeration subtest cover students' ability to identify, represent, compare, and round whole and rational numbers. Numeration subtest items substantially differ from the symbolic and nonsymbolic comparison tasks; example topics include number combinations, fraction estimation, word problems, percents, and ordering fractions and integers. Items on the Algebra subtest cover topics including sorting, classifying, ordering, patterns, functions, number sentences, and operational properties. Items on the Geometry subtest cover topics including properties of two- and three-dimensional shapes, spatial relations, symmetry, and coordinates. A composite score across these three subtests has been used in prior studies of mathematical development from the same data set, and have shown that alternate analyses using individual subtest scores produce consistent results with the composite measure (Price & Wilkey, 2017; Rittle-Johnson et al., 2017).

Data Analysis

Variables

We measured student performance on symbolic and nonsymbolic number comparison using Lyons et al.'s (2014) performance metric $P = RT(1 + 2ER)$. Here, RT represents response time in milliseconds and ER represents error rate. The performance metric adjusts response time for error rate and a greater P score indicates worse performance. For students without errors, response time is unchanged. For students who perform at chance (i.e., error rate of 50%), response time is doubled. We used the performance metric as an outcome because it combines response time and accuracy, and it adjusts for speed-accuracy trade-offs. We calculated error rate using all trials and calculated mean response time using correct trials. We excluded outlier trials that were +/-3 standard deviations from each student's average response time.

Modeling Approach

We used the multi-level model for change (Singer & Willett, 2003) to investigate change in symbolic number comparison performance over Grades 6-8. This approach models within- and between-student variation at different levels of a multi-level model. Since students are additionally nested within schools, we calculated the percentage of school-level variation in symbolic number comparison at each of Grades 6-8 [i.e., the intra-class correlation (ICC), $\widehat{\rho} = \widehat{\sigma}_u^2/\left(\widehat{\sigma}_u^2 + \widehat{\sigma}_\varepsilon^2\right)$]. The ICC showed there was not a statistically significant amount of variation at the school level for symbolic number comparison at Grade 6 ($\widehat{\rho}$ = .002, z = .091, p = .93), Grade 7 ($\widehat{\rho}$ = .029, z = 1.07, p = .28), or Grade 8 ($\widehat{\rho}$ = .029, z = 1.12, p = .26), which suggests modeling the school-level is not necessary. Accordingly, the models focused on within- and between-student variation in symbolic number comparison across Grades 6-8.

Equations (1), (2), and (3) show a hypothesized model, in which Grade 5 Symbolic number comparison and Dots performance, EF, and mathematics competence predict Symbolic number comparison performance at Grade 8 and rate of change in performance from Grades 6-8. The first level of the model [see (1)] captures within-student variation over time. It includes an intercept that captures Symbolic number comparison performance at Grade 8 (i.e., π_{0i} for student i), a parameter for the rate of change in Symbolic number comparison performance across Grades 6-8 (i.e., π_{1i} for student i), and the level 1 residual (i.e., ε_{ij} for student i at Grade j). The second and third equations together model between-student variability. The second equation [see (2)] models the between-student variation in Symbolic number comparison performance at Grade 8 (i.e., π_{0i}), in which $SNC5_i$ represents student i's Symbolic number comparison performance at Grade 5, $DOTS5_i$ represents student i's Dots performance at Grade 5, $EF5_i$ represents student i's accuracy on the Hearts and Flowers task at Grade 5, $KM5_i$ represents student i's age-scaled score composite KeyMath-3 score at Grade 5, and vector $\boldsymbol{X}_i$ represents student i's covariates of free/reduced lunch and gender. The model includes the level 2 residual for student i's Symbolic number comparison performance at Grade 8 (i.e., ζ_{0i}). Analogously, the third equation [see (3)] models between-student variation in the rate of change in Symbolic number comparison performance across Grades 6-8 (i.e., π_{1i}) as a function of the same Grade 5 predictors as in the second equation.

$$SNC_{ij} = \pi_{0i} + \pi_{1i}GRADE_{ij} + \varepsilon_{ij} \tag{1}$$

$$\pi_{0i} = \gamma_{00} + \gamma_{01}SNC5_i + \gamma_{02}DOTS5_i + \gamma_{03}EF5_i + \gamma_{04}KM5_i + \gamma_{05}\boldsymbol{X}_i + \zeta_{0i} \tag{2}$$

$$\pi_{1i} = \gamma_{10} + \gamma_{11}SNC5_i + \gamma_{12}DOTS5_i + \gamma_{13}EF5_i + \gamma_{14}KM5_i + \gamma_{15}\boldsymbol{X}_i + \zeta_{1i} \tag{3}$$

In examining longitudinal change in symbolic number comparison, we used the first wave of data (i.e., Grade 5) as predictor variables for symbolic number comparison performance across Grades 6-8 for two main reasons. First, students completed single-digit comparison in Grade 5 and double-digit comparison in Grades 6-8. Modeling change in symbolic number comparison over Grades 6-8 allowed us to use a consistent measure of symbolic number comparison across the three time points and to examine how prior digit comparison ability with single-digit numbers related to double-digit symbolic number comparison performance over three grades. Second, by selecting predictors from Grade 5, we avoid the reciprocal causation issues that occur from including predictors that are collected contemporaneously with the outcome (Singer & Willett, 2003). To facilitate interpretation of parameter estimates, including intercepts, we standardized all predictors prior to model fitting. We centered Grade on the final time point (i.e., Grade 8), such that values for Grades 6-8 were -2, -1, and 0, respectively. Therefore, parameter estimates associated with the intercept show the relation between Grade 5 predictors and symbolic number comparison performance at the end of middle school. For the general modeling approach, we first examined whether students' symbolic number comparison performance changed over time generally. We then stepwise investigated the effects of Grade 5 Symbolic number comparison performance and Dots performance, EF, and mathematics competence on Grade 8 Symbolic number comparison performance and rate of change in Symbolic number comparison performance from Grades 6-8. The stepwise approach incorporates constructs in order of most proximal (i.e., Grade 5 Symbolic number comparison performance) to most distal (i.e., Grade 5 mathematics competence) with respect to symbolic number comparison.

Results

Ratio Effects for Double-Digit Symbolic Number Comparison

To determine if the double-digit symbolic number comparison task functioned as expected, we examined whether students showed ratio effects for accuracy and response time at each grade. For each student, we regressed accuracy on ratio and response time on ratio, separately, to obtain a slope. Table A2 in the Appendix shows descriptive statistics by outcome and grade. On average, students showed a negative slope for accuracy, indicating that accuracy was lower when ratio was higher. For response time, students showed a positive slope on average, indicating that higher-ratio comparisons took longer than lower-ratio comparisons. One-sample *t*-tests showed that average accuracy and response time slopes for each grade were statistically significantly different from zero (see Table A2). Together, these results suggest the task elicited a ratio effect as intended.

Descriptive Statistics and Simple Correlations

Table 1 presents descriptive statistics for each comparison measure, and the EF and mathematics measures. As shown in the table, students' average Symbolic number comparison performance improved from Grades 6-8. Performance was better (i.e., lower P) on average for Grade 5 Symbolic number comparison, likely due to double-digit comparison in Grades 6-8 and single-digit comparison in Grade 5.

Table 1

Descriptive Statistics for Symbolic Number Comparison (SNC) Across the Four Time Points and Grade 5 Dots, Hearts and Flowers, and KeyMath-3 Performance (n = 394)

Measure	*M*	*SD*	Range
SNC Performance, Double-Digit (ms)			
Grade 6	1007	242	648 – 2113
Grade 7	911	202	582 – 1874
Grade 8	838	168	546 – 1816
Grade 5 Predictors			
SNC Performance (ms)	795	227	467 – 1917
Dots Performance (ms)	1463	395	713 – 3376
Hearts and Flowers (Percent accuracy, Mixed trials)	67.34	13.86	35.42 – 95.83
KeyMath-3 (Composite)	8.29	2.36	2.67 – 16.00

Note. All Symbolic number comparison (SNC) and Dots performance values reflect the performance metric *P*, which is milliseconds adjusted for accuracy (see Variables section).

To characterize the relations among the predictor variables and each year of symbolic number comparison, we calculated Pearson correlation coefficients for Grade 5 Symbolic number comparison, Dots, and EF, and Symbolic number comparison for Grades 6-8. As Table 2 shows, there were moderate to strong positive correlations among Symbolic number comparison performance across Grades 6-8. Both Grade 5 Symbolic number comparison and Dots had positive correlations with Symbolic number comparison across Grades 6-8, but the relation was stronger for Grade 5 Symbolic number comparison. Additionally, there was a strong positive correlation between Grade 5 Symbolic number comparison and Grade 5 Dots. There were negative correlations of Symbolic number comparison in Grades 6-8 with EF and with Grade 5 KeyMath-3 scores, such that greater EF skills and math knowledge were associated with better Symbolic number comparison performance (i.e., lower ms).

Table 2

Pearson Correlations Among Symbolic Number Comparison (SNC) Performance Across Grades 6-8, and Grade 5 Symbolic Number Comparison (SNC), Dots, and EF (n = 394)

Measure	1	2	3	4	5	6	7
1. Grade 6 SNC	1.00						
2. Grade 7 SNC	0.63***	1.00					
3. Grade 8 SNC	0.45***	0.74***	1.00				
4. Grade 5 SNC	0.47***	0.51***	0.41***	1.00			
5. Grade 5 Dots	0.27***	0.26***	0.12*	0.64***	1.00		
6. Grade 5 EF	-0.13**	-0.20***	-0.20***	-0.11*	0.09	1.00	
7. Grade 5 KM-3	-0.14**	-0.21***	-0.24***	-0.12*	0.12*	0.27***	1.00

*$p < .05$. **$p < .01$. ***$p < .001$.

Symbolic Number Comparison Performance Over Grades 6-8

Table 3 displays a taxonomy of five models, including parameter estimates (*PE*) and standard errors (*SE*), variance components, deviance statistics, and *pseudo*-R^2 statistics. The first model (i.e., Model 1) shows that across all students for Grades 6-8, average Symbolic number comparison performance was about 919 ms. The variance components in Model 1 also allow for estimation of the ICC, which shows that approximately 47% of the variation in Symbolic number comparison performance was due to between-student differences.

Table 3

A Taxonomy of Multilevel Models for Change Including Parameter Estimates, Standard Errors (in Parentheses), Variance Components, Deviance, and Pseudo-R^2 Statistics for the Relation Between Symbolic Number Comparison (SNC) Performance in Grades 6-8 and Grade 5 Symbolic Number Comparison (SNC), Dots, EF, and Math Skills

Predictor	Parameter	Model 1	Model 2	Model 3	Model 4	Model 5
Fixed Effects						
SNC Intercept, π_{0i}						
Intercept	$\hat{\gamma}_{00}$	918.543*** (8.794)	833.742*** (8.855)	833.742*** (7.933)	832.525*** (7.860)	832.774*** (7.785)
Grade 5 SNC Performance	$\hat{\gamma}_{01}$			96.884*** (10.322)	90.376*** (10.425)	84.671*** (10.512)
Grade 5 Dots Performance	$\hat{\gamma}_{02}$			-38.228*** (10.322)	-32.038** (10.405)	-26.291* (10.495)
Grade 5 EF	$\hat{\gamma}_{03}$				-21.927** (6.995)	-17.446* (7.094)
Grade 5 KeyMath-3[a]	$\hat{\gamma}_{04}$					-21.317** (7.383)
SNC Rate of Change, π_{1i}						
Intercept	$\hat{\gamma}_{10}$		-84.801*** (5.608)	-84.801*** (5.462)	-84.801*** (5.462)	-84.801*** (5.462)
Grade 5 SNC Performance	$\hat{\gamma}_{11}$			-14.244* (7.107)	-14.244* (7.107)	-14.244* (7.107)
Grade 5 Dots Performance	$\hat{\gamma}_{12}$			-13.719† (7.107)	-13.719† (7.107)	-13.719† (7.107)
Variance Components						
Level 1						
Within person	$\hat{\sigma}^2_\varepsilon$	25028.40***	10888.59***	10888.60***	10888.60***	10888.59***
Level 2						
In Intercept	$\hat{\sigma}^2_0$	22129.96***	21819.97***	15718.62***	15210.04***	14745.89***
In Rate of Change	$\hat{\sigma}^2_1$		6948.56***	6309.49***	6309.49***	6309.49***
Covariance	$\hat{\sigma}^2_{01}$		962.65	2315.84**	2293.09**	2242.25**
Deviance		15835.79	15464.75	15310.68	15300.97	15292.73
Pseudo-R^2 Statistics						
R^2_ε			0.565	0.565	0.565	0.565
R^2_0				0.280	0.303	0.324
R^2_1				0.092	0.092	0.092

Note. The first panel of fixed effects shows the relation between each predictor and Grade 8 Symbolic number comparison performance. The second panel of fixed effects shows the relation between each predictor and rate of change in Symbolic number comparison performance over Grades 6-8 (n = 394).

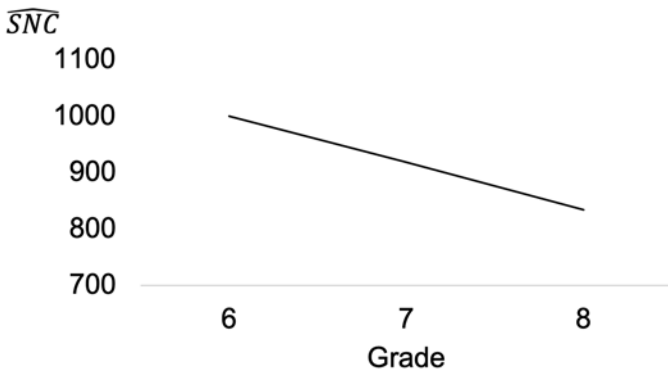
[a]Age-standard composite scores.

†$p < .06$. *$p < .05$. **$p < .01$. ***$p < .001$.

Model 2 shows parameter estimates and associated standard errors for the unconditional effect of Grade, that is, whether students' Symbolic number comparison performance changed over Grades 6-8. Model 2 shows that on average, students' Symbolic number comparison performance improved (i.e., P decreased) over Grades 6-8, by about 85 ms each year. The covariance (i.e., $\hat{\sigma}^2_{01}$) of the level-2 residuals from Model 2 quantifies the covariance between Symbolic number comparison performance in Grade 8 and rate of change from Grades 6-8, in the population. It shows that there is not a statistically significant correlation between performance in Grade 8 and rate of change from Grades 6-8 ($\hat{\rho}_{01}$= .08, p = .38). Figure 2 illustrates students' average change in Symbolic number comparison performance across Grades 6-8.

Figure 2

Fitted Growth Trajectory for Symbolic Number Comparison (SNC) Performance (Adjusted ms) Across Grades 6-8 as Estimated in Model 2 (See Table 3)



Note. On average, Grade 6 Symbolic number comparison performance was about 999 ms, with an improvement of about 85 ms per year. Note that separate standard errors for the Grade 6 intercept and the slope from Grades 6-8 are presented with their associated parameter estimates in Model 2 of Table 3.

Predictors for Grade 8 Symbolic Number Comparison Performance and Grades 6-8 Rate of Change

Model 3 shows the effects of Grade 5 Symbolic number comparison performance and Dots performance. As shown in Table 3, both Grade 5 Symbolic number comparison and Dots performance were statistically significant predictors of Grade 8 Symbolic number comparison. One standard deviation increment in Grade 5 Symbolic number comparison performance was associated with a 97 ms increment in Grade 8 performance, controlling for Grade 5 Dots performance. One standard deviation increment in Grade 5 Dots performance was associated with a 38 ms decrement in Grade 8 Symbolic number comparison, controlling for Grade 5 Symbolic number comparison performance. For rate of change, the magnitude of the relations with Grade 5 Symbolic number comparison performance and with Grade 5 Dots performance were similar. One standard deviation increment in either Grade 5 Symbolic number comparison or Grade 5 Dots was associated with a 14 ms decrement in Symbolic number comparison performance over Grades 6-8. However, while the relation between Grade 5 Symbolic number comparison and rate of change was statistically significant (p = .045), the relation between Grade 5 Dots and rate of change did not meet the threshold for statistical significance (p = .054). In sum, Model 3 suggests that Grade 5 Symbolic number comparison has a positive association with Grade 8 Symbolic number comparison, Grade 5 Dots has a negative relation with Grade 8 Symbolic number comparison, and both Grade 5 measures have similar negative relations with rate of change in Symbolic number comparison across Grades 6-8.

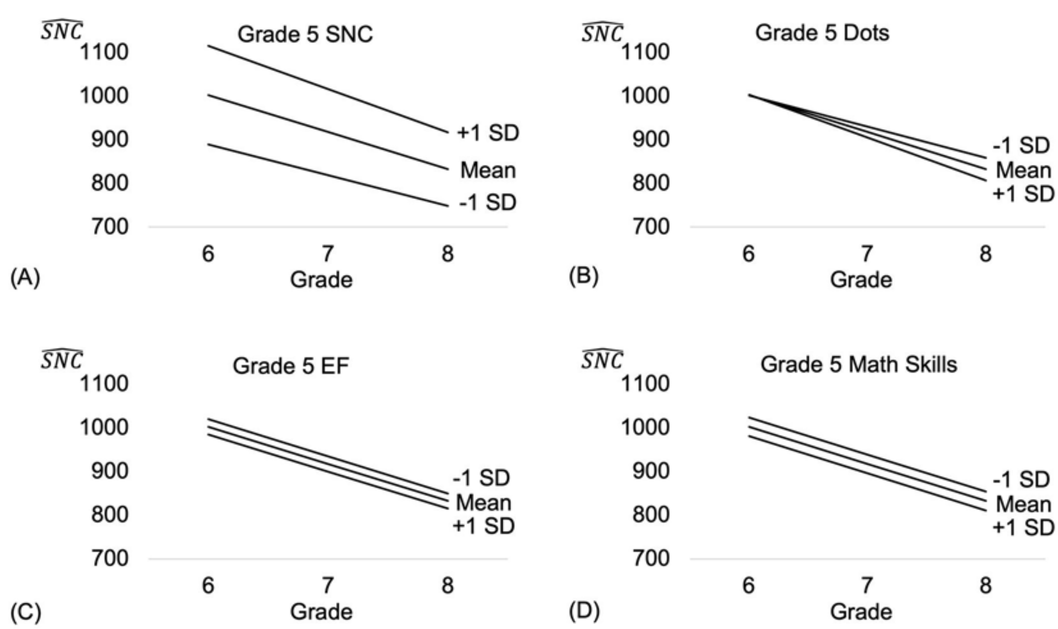
We next examined the effect of Grade 5 EF on Grade 8 Symbolic number comparison and rate of change from Grades 6-8. As Model 4 in Table 3 shows, Grade 5 EF was a statistically significant predictor of Grade 8 Symbolic number comparison. Controlling for Grade 5 Symbolic number comparison and Dot performance, one standard deviation increment in EF accuracy was associated with better Grade 8 Symbolic number comparison performance by about 22 ms. Additionally, Model 4 shows that with the addition of EF as a predictor, the parameter estimates for Grade 5 Symbolic number comparison performance and Dots performance are essentially unchanged. Intermediate models showed that EF was not a statistically significant predictor of Symbolic number comparison rate of change from Grades 6-8 (*PE* = -1.04, *SE* = 5.47, p = .85), controlling for Grade 5 Symbolic number comparison and Dots performance, and that there were no statistically significant interactions of Grade 5 EF with Grade 5 Symbolic number comparison (*PE* = -1.34, *SE* = 7.77, p = 86) or Grade 5 Dots (*PE* = -8.11, *SE* = 8.23, p = .33).

In Model 5, we examined the relation between Grade 5 mathematics competence and Symbolic number comparison performance, controlling for Grade 5 Symbolic number comparison, Dots, and EF. As Table 3 shows, the relation was statistically significant, such that a one standard deviation increment in Grade 5 mathematics scores was associated with a 21 ms decrement in Grade 8 Symbolic number comparison. However, Grade 5 mathematics competence was not a statistically significant predictor of Symbolic number comparison rate of change from Grades 6-8 (PE = -2.83, SE = 5.70, p = .62). Further, subsequent models showed there were no statistically significant interactions with Grade 5 mathematics competence (ps > .2) and neither gender nor free/reduced lunch status were statistically significant predictors (ps > .2). The covariance of the level-2 residuals from Model 5 shows a small, statistically significant correlation between intercepts and slopes ($\widehat{\rho}_{01}$ = .23, p = .03).

To illustrate the relations in Model 5, Figure 3 shows fitted trajectories for change in Symbolic number comparison performance over Grades 6-8 for different levels of Grade 5 Symbolic number comparison (Panel A), Grade 5 Dots (Panel B), Grade 5 EF (Panel C), and Grade 5 mathematics competence (Panel D). Each panel shows the effect of one predictor from Model 5, controlling for the remaining predictors in that model. Panel A shows the fitted relation between Grade 5 Symbolic number comparison and Symbolic number comparison performance across Grades 6-8, for students of average Grade 5 Dots, EF, and mathematics competence. Students who had relatively better Grade 5 Symbolic number comparison performance (e.g., -1 SD) also had relatively better Symbolic number comparison performance from Grades 6-8, though they improved at a slower rate. Students who did relatively worse on Grade 5 Symbolic number comparison (e.g., +1 SD) had relatively worse Symbolic number comparison performance from Grades 6-8, but improved their Symbolic number comparison performance at a comparatively faster rate (about 14 ms per year on average). For example, as Panel A illustrates, a difference of 1 SD in Grade 5 Symbolic number comparison was associated with an estimated 113 ms difference in Grade 6 Symbolic number comparison performance, but an 85 ms difference in Grade 8 Symbolic number comparison performance.

Figure 3

Fitted Growth Trajectories for Change in Symbolic Number Comparison (SNC) Performance (Adjusted ms) Over Grades 6-8 for Different Levels of Grade 5 Symbolic Number Comparison (A), Grade 5 Dots (B), Grade 5 EF (C), and Grade 5 Math Skills (D) as Estimated in Model 5 (n = 394)



Note. Panel A shows the relation between estimated Symbolic number comparison performance and Grade 5 Symbolic number comparison, with Grade 5 Dots and EF set to their sample means. Panel B shows the relation between estimated Symbolic number comparison performance and Grade 5 Dots, with Grade 5 Symbolic number comparison and EF set to their sample means. In both Panels A and B, -1 SD is associated with better performance. Panel C shows the relation between estimated Symbolic number comparison performance and Grade 5 EF, with Grade 5 Symbolic number comparison and Dots set to their sample means. Panel D shows the relation between estimated Symbolic number comparison performance and Grade 5 Math skills, with Grade 5 Symbolic number comparison, Dots, and EF set to their sample means. In both Panels C and D, -1 SD is associated with worse performance.

Panel B shows the fitted relation between Grade 5 Dots and Symbolic number comparison performance, for students of average Grade 5 Symbolic number comparison, EF, and mathematics competence. Panel B illustrates that students with relatively worse Grade 5 Dots performance tended to have better Grade 8 Symbolic number comparison performance. Panel B also shows that children with relatively better Grade 5 Dots performance improved in Symbolic number comparison at a comparatively slower rate. While this relation did not meet the threshold for statistical significance, the magnitude and direction of the relation are very similar to the relation between Grade 5 Symbolic number comparison and Symbolic number comparison from Grades 6-8.

Panel C shows the fitted relation between Grade 5 EF and Symbolic number comparison performance, for students with average Grade 5 Symbolic number comparison, Dots, and mathematics competence. Students who had relatively better Grade 5 EF (e.g., +1 *SD*) also had relatively better Symbolic number comparison performance from Grades 6-8. Students with relatively worse Grade 5 EF (e.g., -1 *SD*) had relatively worse Symbolic number comparison performance from Grades 6-8. All else equal, an increment of 1 *SD* in Grade 5 EF was associated with about a 17 ms increment in Symbolic number comparison performance, on average. Since Grade 5 EF did not predict a difference in the rate of change in Symbolic number comparison performance from Grades 6-8, the three estimated trajectories in Panel C are parallel.

Lastly, Panel D shows the fitted relation between Grade 5 mathematics competence and Symbolic number comparison performance for students with average Grade 5 Symbolic number comparison, Dots, and EF. Students with relatively higher levels of Grade 5 mathematics competence (e.g., +1 *SD*) had relatively better performance on Symbolic number comparison from Grades 6-8 (e.g., -1 *SD*), by approximately 21 ms. This estimated relation is consistent across Grades 6-8, since mathematics competence did not predict rate of change in Symbolic number comparison.

Discussion

In the present study, we examined longitudinal change in middle school students' symbolic number comparison, and how Grade 5 numerical magnitude processing, EF, and mathematics competence relate to the rate of this change. We found that from Grades 6-8, students continued to improve in Symbolic number comparison performance, on average. Grade 5 Symbolic number comparison performance, Dots performance, EF skills, and mathematics competence all predicted Symbolic number comparison performance in Grade 8. Grade 5 Symbolic number comparison and Dots performance had similar relations with rate of change in Symbolic number comparison from Grades 6-8, though only Symbolic number comparison was a statistically significant predictor of Symbolic number comparison improvement rate from Grades 6-8.

Students Improve Across Grades 6-8

Middle school students' continued improvement in symbolic number comparison performance bridges existing literature on the developmental trajectory of symbolic number comparison. In addition to students' improvement in basic symbolic number processing when developing fluency with digits (Matejko & Ansari, 2016), the present study suggests that students continue to refine their basic number processing skills even after working with number symbols for several years. Further, the present study sheds light on symbolic number comparison skills in early adolescence, complementing the literature that shows better symbolic number comparison performance for young adults (i.e., college undergraduates) compared to elementary school students (Cantlon et al., 2009; Holloway & Ansari, 2008). Together, prior research and the present study suggest that even when students' mathematics education has advanced well beyond developing basic number processing skills, those skills continue to improve.

The present results appear to differ from Sekuler and Mierkiewicz (1977), who found that average response time for symbolic number comparison is comparable in Grade 4 students, Grade 7 students, and young adults. Their findings suggest there may be a lower bound of performance (e.g., minimum average response time) that students reach relatively soon after achieving fluency with digits. Since Sekuler and Mierkiewicz's (1977) task used single digits, it could be that by upper elementary and middle school, students have levels of single-digit symbolic number comparison performance compared to adults, but also continue to improve on symbolic number comparison, as shown in the present study with double-digit comparison. Whether the cognitive processes involved in double- and single-digit symbolic number comparison differ may depend on task-specific properties such as number orientation and number pairs (Dehaene, Dupoux, & Mehler, 1990; Ganor-Stern, Pinhas, & Tzelgov, 2009; Moeller, Fischer, Nuerk, & Willmes, 2009; Moeller, Klein, Nuerk, & Willmes, 2013; Nuerk, Weger, & Willmes, 2001, 2004; Verguts & De Moor, 2005; Zhang & Wang, 2005). However, both single-digit and double-digit symbolic number comparison have a positive relation with mathematics achievement (Brankaer et al., 2017). As a measure of symbolic number comparison, single-digit comparison may not be sensitive enough to detect change in symbolic number comparison skills beyond early elementary school. The present study suggests that double-digit symbolic number comparison may provide a means to capture students' longitudinal improvement in symbolic number comparison ability beyond the early grades.

Grade 5 Symbolic Number Comparison Performance Predicts Grade 8 Symbolic Number Comparison and Rate of Change

Grade 5 symbolic number comparison performance predicted Grade 8 symbolic number comparison performance, controlling for nonsymbolic number comparison performance, EF, and prior mathematics competence. This suggests that some of the component skills involved in symbolic number comparison – digit identification, digit-number word matching, ordering, and comparing (Sasanguie, Lyons, et al., 2017) – were similar across single- and double-digit comparison, and that students who were adept at symbolic number processing with smaller numbers also tended to be adept at processing larger ones.

Further, all else equal, relatively worse Grade 5 symbolic number comparison performance predicted a greater rate of improvement in symbolic number comparison performance from Grades 6-8, controlling for nonsymbolic comparison performance, EF, and prior mathematics competence. Students with relatively worse Grade 5 performance may begin to catch-up to their peers over middle school. Alternatively, similar to Sekuler and Mierkiewicz (1977), there may be a lower bound for symbolic number comparison improvement, such that students who perform relatively worse in Grade 5 (i.e., higher adjusted response time), have more room to improve to approach that lower bound. In addition, it is possible that improvements closer to that lower bound are more difficult to make. Regardless, the current results suggest that prior symbolic number comparison ability should be considered when examining symbolic number comparison performance and rate of improvement or change in that performance.

Grade 5 Dots Performance Predicts Grade 8 Symbolic Number Comparison

Grade 5 Dots performance predicted Grade 8 symbolic number comparison, controlling for Grade 5 symbolic number comparison, EF, and mathematics competence (see Table 2). Compared to Grade 5 symbolic number comparison, the effect of nonsymbolic comparison performance was similarly inverse, but smaller in magnitude. This suggests that simple (i.e., single digit) processing has a stronger relation to later, more complex symbolic number processing (i.e., fluency processing double-digit numbers) than did nonsymbolic processing. These findings align with prior research suggesting that when considered simultaneously, symbolic number processing is often more predictive of mathematics skills than is nonsymbolic processing (Chu et al., 2018; Schneider et al., 2017; Xenidou-Dervou et al., 2017), and that the relation between nonsymbolic numerical magnitude processing and mathematics competence may decline over time (Fazio et al., 2014; Gimbert et al., 2019; Xenidou-Dervou et al., 2017). The present results suggest this pattern may also hold for more foundational tasks, such as processing double-digit numbers. Further, while nonsymbolic comparison in Grade 5 was not a statistically significant predictor of symbolic number comparison rate of change, this relation was almost identical in magnitude and direction (and *p*-value) to the relation between Grade 5 Symbolic number comparison and symbolic number comparison rate of change. This suggests that when considering rate of change in symbolic number comparison in the middle grades, both nonsymbolic and symbolic processing may contribute.

The inverse relation between Grade 5 nonsymbolic comparison and Grade 8 symbolic number comparison may also suggest that the Grade 5 Dots task measures additional domain-general mechanisms important for symbolic number comparison, beyond inhibitory control (Gilmore et al., 2013), and beyond the mechanisms that would be controlled for here (i.e., executive function, general response time). As one speculation, the Grade 5 Dots task may measure metacognitive processes like monitoring and control (e.g., Nelson & Narens, 1990), in which students may evaluate performance and adjust strategies. This could manifest as lower performance (i.e., greater adjusted response time) during Grade 5 nonsymbolic number comparison but be advantageous for proficiency with symbolic number comparison. In turn, this could suggest that cross-sectional differences in which adults perform better than children on single-digit comparison may reflect adults' proficiency with comparison or domain-general skills, rather than improved numerical magnitude processing of single digits. Indeed, prior research has suggested that symbolic number comparison task performance may reflect non-numerical processes associated with comparison itself (Sasanguie, Lyons, et al., 2017; Van Opstal et al., 2008; Verguts et al., 2005).

Grade 5 EF Predicts Grade 8 Symbolic Number Comparison

Students who scored more highly on the Grade 5 EF measure tended to have better Symbolic number comparison performance, though the magnitude of the effect of EF was smaller than the effects of Grade 5 Symbolic number comparison, Dots, and mathematics competence. This suggests a role for EF in double-digit symbolic number comparison beyond the EF skills that may also be captured by nonsymbolic comparison (Gilmore et al., 2013). For example, if students decompose double-digit numbers into decades and units instead of comparing holistically (Moeller et al., 2013; Verguts & De Moor, 2005), they may draw on strategies that require EF skills, such as inhibition, working memory, or selective attention. Accordingly, if double-digit comparison is used to measure symbolic number comparison performance (Brankaer et al., 2017), students' EF skills may be an important covariate to include.

Grade 5 EF did not predict rate of change in symbolic number comparison performance from Grades 6-8. It may be that other component skills that Grade 5 Symbolic number comparison or Dots captured, such as numerical magnitude processing or digit identification, may be more important for improvement in symbolic number comparison in the middle grades than general EF skills. Taken together, these findings suggest that performance on double-digit symbolic number comparison requires EF skills, but that improving symbolic number comparison performance is not associated with EF. This may suggest that during adolescence, a time when EF skills are developing (e.g., Best & Miller, 2010), rate of improvement on symbolic number comparison performance may not be a consequence of EF improvement. Therefore, rate of change in symbolic number comparison performance may reflect a change in cognitive mechanisms beyond those related to domain-general EF development.

Grade 5 Mathematics Predicts Grade 8 Symbolic Number Comparison

All else equal, Grade 5 mathematics competence predicted Grade 8 Symbolic number comparison. These results extend prior research showing that basic symbolic processing predicts mathematics competence (Schneider et al., 2017) to suggest the reverse is also true – that mathematics competence relates longitudinally to basic symbolic number processing. It may be that knowledge or skills captured by the KeyMath-3, beyond comparison or symbol processing generally (e.g., understanding of place value), may facilitate symbolic number comparison with double-digit numbers. The mechanisms that may contribute to this relation may be similar to those that support the positive relation between symbolic mathematics and later nonsymbolic numerical magnitude processing (Mussolin et al., 2014; Piazza et al., 2013; Suárez-Pellicioni & Booth, 2018). Further research can clarify candidate mechanisms that may underlie such relations.

Limitations and Next Steps

Results of the present study suggest that both symbolic and nonsymbolic numerical magnitude processing, EF, and prior mathematics competence are important predictors of symbolic number comparison performance. Results also suggest that students' prior numerical magnitude processing performance may be important for students' rate of symbolic number comparison improvement. However, there are additional cognitive abilities beyond the scope of this study that may also play a role. This notion is reflected in the final model (see Table 3, Model 5), whose variance components show additional unexplained variability in symbolic number comparison.

As one example, symbolic number comparison performance and its change over time may draw on both magnitude- and ordinal-related processing (Sasanguie, Lyons, et al., 2017; Turconi et al., 2006). The present study lacked a task that specifically measures ordinal processing (e.g., determine if a series of digits is ascending or descending) that we could use to predict Grade 8 symbolic number comparison performance or its rate of change from Grades 6-8. This precludes our ability to disentangle whether change in symbolic number comparison performance reflects changes in magnitude- or ordinal-related processing (or both). Future research on symbolic number comparison performance and its change over time should include separate measures of ordinal processing and numerical magnitude processing to further unpack the cognitive mechanisms that may underlie change in performance. As a second example, metacognitive processes captured in the Grade 5 Dots task that relate to lower performance (i.e., greater adjusted RT), may contribute to the relation between nonsymbolic comparison and change in symbolic number comparison performance. Future studies may investigate the role of metacognitive abilities in the relation between nonsymbolic and symbolic processing.

Finally, results of the present study raise questions for future study. Does symbolic number comparison performance stabilize? If so, when, and what might contribute to it? Results of the present study raise the possibility that symbolic number comparison performance could stabilize because numerical magnitude processing skills stabilize, or because of the constraints of current symbolic number comparison tasks (e.g., minimum response times, a lack of sensitivity from insufficient task difficulty). This in turn raises questions about what symbolic number comparison performance actually reflects, and if symbolic number comparison performance measures the same abilities over time.

The present study examined predictors of students' symbolic number comparison performance and its rate of change over middle school and showed that numerical magnitude processing, EF skills, and prior mathematics competence differentially contribute. In doing so, this study showed that symbolic number comparison performance continues to improve during adolescence, and that double-digit symbolic number comparison may be a more sensitive way to measure improvement in symbolic number comparison for those with several years of experience working with number symbols. This study also suggests that students' rate of improvement may draw on continued development of numerical magnitude processing. Taken together, results have illuminated the developmental trajectory of symbolic number processing, bridging extant knowledge on symbolic number comparison performance in elementary school and adulthood. Such contributions help to clarify the cognitive processes that relate to symbolic number comparison performance and how it changes over time, furthering our understanding of how symbolic number comparison may support mathematics competence.

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Appendix

Table A1

List of Digit and Dot Array Pairs for the Symbolic Number Comparison (SNC) and Dots Performance Tasks

Grades 6-8 SNC	Grade 5 SNC	Grade 5 Dots
.33 (18, 54)	.20 (1, 5)	.63 (10, 16; 12, 32)
.50 (36, 72)	.22 (2, 9)	.73 (16, 22; 32, 44)
.67 (18, 27)	.25 (1, 4)	.75 (16, 22; 32,44)
.80 (36, 45)	.25 (2, 8)	.75 (12, 6; 24, 32)
.86 (54, 63)	.50 (1, 2)	.80 (16, 28; 32, 40)
.88 (63, 72)	.50 (2, 4)	.81 (13, 16; 26, 32)
.89 (81, 72)	.50 (3, 6)	.84 (16, 19; 32, 38)
	.50 (4, 8)	.88 (16, 18; 32, 36)
	.56 (5, 9)	.94 (15, 16; 30, 32)
	.71 (5, 7)	.94 (16, 17; 32, 34)
	.75 (3, 4)	
	.75 (6, 8)	
	.78 (7, 9)	

Note. Each column displays the ratio followed by the number pair or dot count.

Table A2

Mean, Standard Deviation, and Range of Participants' Estimated Slopes of the Relation Between Accuracy (Top Panel) and Ratio, and Response Time (Bottom Panel) and Ratio During Double-Digit Comparison

Outcome	*M*	*SD*	Range	*t*	*p*
Accuracy					
Grade 6	-0.206	0.169	-0.904 – 0.345	-23.62	< .0001
Grade 7	-0.162	0.156	-0.839 – 0.344	-20.59	< .0001
Grade 8	-0.149	0.128	-0.550 – 0.204	-23.10	< .0001
RT					
Grade 6	293	174	-255 – 840	33.34	< .0001
Grade 7	266	150	-282 – 788	35.29	< .0001
Grade 8	254	135	-241 – 863	37.31	< .0001

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