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Persistent Genetic and Family-Wide Environmental Contributions to Early Number Knowledge and Later Achievement in Mathematics

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Abstract

This study investigated the stable and transient genetic and environmental contributions to individual differences in number knowledge in the transition from preschool (age 5) to Grade 1 (age 7) and to the predictive association between early number knowledge and later math achievement (age 10–12). We conducted genetic simplex modeling across these three time points. Genetic variance was transmitted from preschool number knowledge to late-elementary math achievement; in addition, significant genetic innovation (i.e., new influence) occurred at ages 10 through 12 years. The shared and nonshared environmental contributions decreased during the transition from preschool to school entry, but shared and nonshared environment contributed to the continuity across time from preschool number knowledge to subsequent number knowledge and math achievement. There was no new environmental contribution at time points subsequent to preschool. Results are discussed in light of their practical implications for children who have difficulties with mathematics, as well as for preventive intervention.

Keywords

number knowledge, mathematics achievement, longitudinal study, genetically sensitive design, innovations, continuity

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Early number knowledge forecasts later achievement in mathematics (Duncan et al., 2007; Göbel, Watson, Lervåg, & Hulme, 2014; Nguyen et al., 2016; Watts, Duncan, Siegler, & Davis-Kean, 2014). Core components of number knowledge, such as ability to compare magnitudes and count, underlie the development of effective counting strategies (LeFevre et al., 2010), which provide the foundation for solving complex problems, such as algebraic equations and multistep arithmetic problems (Gersten, Clarke, & Jordan, 2007; Göbel et al., 2014). Population-based longitudinal studies of children and studies of children showing learning disabilities in mathematics both indicate that number knowledge at school entry predicts later mathematics achievement in elementary school (Duncan et al., 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Nguyen et al., 2016) and subsequently, up to age 15 years (Watts, Duncan, Clements, & Sarama, 2017).

This predictive association raises questions regarding the underlying mechanisms, including questions about the individual and family factors accounting for interindividual differences in number knowledge and later math achievement. Previous studies found that achievement in mathematics is associated with family income (Jordan & Levine, 2009; Siegler, 2009), parental involvement in the child’s education (LeFevre et al., 2009), and the quality of educational experiences (Ramani, Siegler, & Hitti, 2012). Those family and schoolwide factors are typically shared by children of the same family, whereas other factors, such as birth complications or illnesses, are usually individual-specific (i.e., not shared by children of the same family; Plomin, Asbury, & Dunn, 2011). It is important to understand how these factors combine with children’s early cognitive abilities, such as visuospatial skills or memory span

(Garon-Carrier et al., 2017; Soto-Calvo, Simmons, Willis, & Adams, 2015), to foster number knowledge and math achievement, and to understand the extent to which number knowledge and math achievement are genetically and environmentally linked over time.

Previous studies have provided mixed results regarding the genetic and environmental underpinnings of achievement in mathematics. One of the first twin studies examined mathematics skills of 6- to 12-year-old twins and found that achievement in mathematics was only modestly heritable; shared and nonshared environment accounted for most of the variation (Thompson, Detterman, & Plomin, 1991). The large age range and the absence of correction for age and sex in this study may explain the large shared environmental component. In contrast, another study of twins ages 8 to 20 years showed a heritability of .90 for math achievement and negligible environmental contribution (Alarcón, Knopik, & DeFries, 2000).

These inconsistencies across studies likely resulted from variations in age both within and between studies. They may also be related to variations in assessments; some studies used teachers' ratings of math achievement (Kovas et al., 2007; Oliver et al., 2004), whereas others used math subtests of standardized scholastic achievement tests (Alarcón et al., 2000; Thompson et al., 1991); in addition, scores on verbal and nonverbal geometry and trigonometry subtests were combined (Alarcón et al., 2000), and sometimes tests were administered through online batteries rather than in person (Davis, Haworth, & Plomin, 2009).

The most important limitation of previous studies is their cross-sectional nature. Only a few twin studies have taken advantage of a longitudinal design to disentangle the genetic and environmental contributions to mathematics achievement over time (Haworth, Kovas, Petrill, & Plomin, 2007; Kovas et al., 2007). Two studies based on the Twins Early Development Study found substantial heritability (ranging between .62 and .72) in mathematics performance in children ages 7 to 9 years (Haworth et al., 2007) and ages 7 to 10 years (Kovas et al., 2007). Moreover, about .50 of the genetic contribution to math achievement at age 10 years was present at age 7 years. Other new genetic contributions were time-specific, emerging at ages 9 and 10. Shared environment accounted for a small but significant part of continuity in mathematics performance (.07 from age 7 to age 9 and .05 from age 7 to age 10), whereas nonshared environment uniquely contributed to age-specific variation (Kovas et al., 2007). These results suggest that genetic factors account for most developmental continuity in mathematics achievement in elementary school, but that experiences shared by twins of the same family also play a unique significant role.

Whether these joint contributions of genetics and shared environment to mathematics achievement can be traced back to the early (preschool) development of mathematics skills is still unknown. Yet over the period from preschool to late elementary school, there is substantial change in both the learning context and the developmental processes underlying math performance, including motivational (Garon-Carrier et al., 2016), cognitive (Decker & Roberts, 2015), and emotional (e.g., self-regulation, Krapohl et al., 2014) processes. Accordingly, twins should be followed longitudinally and from an early age~~,~~ to adequately capture (a) stability and changes in skills (i.e., “mathematics skills” may subsume core and persistent skills, as well as capacities that emerge with age) and (b) stable as well as new genetic and environmental contributions during development. Such new contributions may be related to changes associated with maturation, (e.g., puberty, socializing; Santos, Vaughn, Peceguina, Daniel, & Shin, 2014; Wehkalampi et al., 2008) and changes in the learning context. Examining whether number knowledge and math achievement share common etiological factors is a first step toward understanding the developmental pathways from number knowledge to math achievement in school.

The Present Study

This study is the first to investigate the genetic and environmental contributions to the continuity and time-specific variation in number knowledge during the transition from preschool to Grade 1, and the potential extension of these early contributions to achievement in mathematics in late elementary school. We used an ongoing longitudinal twin study covering an extended developmental window (from preschool to late elementary school) and involving substantial changes in the learning context, as well as in physical and psychological development. The following research questions were addressed: (a) What are the genetic and environmental contributions to preschool number knowledge (i.e., before school entry, at age 5), to Grade 1 number knowledge (age 7), and to late-elementary math achievement (age 10–12)? (b) To what extent are these contributions stable over time (vs. age-specific), such that early influences contribute to later achievement in mathematics?

These questions were examined through a simplex design (Boomsma, Martin, & Molenaar, 1989; Neale & Cardon, 1992). The simplex design takes into account the longitudinal nature of the data, typically when analog constructs are measured on the same participants over time. Its chief advantage is that it partitions genetic and environmental sources of variation transmitted across adjacent time points through autoregressive paths and estimates new genetic and environmental contributions (i.e., innovations) at each time point. The Cholesky decomposition is another approach to estimate the extent to which genetic and environmental contributions extend to different time points. However, it does not take full advantage of the prospective time-series and directional nature of the longitudinal data (Boomsma et al., 1989) or the assumption that development proceeds mainly through strong autoregressive paths. For these reasons, we preferred the simplex model over the Cholesky model.

Method

Participants

Participants were pairs of twins born in the greater Montreal area, in Canada. They were recruited between April 1995 and December 1998 to participate in the ongoing Quebec Newborn Twin Study (Boivin et al., 2013). Of the 989 families initially contacted, 662 (67%) agreed to participate. This initial sample, which included both same-sex and opposite-sex twin pairs, was followed longitudinally from the age of 5 months onward and assessed on various child and family characteristics. Parental informed consent was obtained at each assessment. Zygosity was ascertained using the Zygosity Questionnaire for Young Twins (Goldsmith, 1991) when the twins were 5 and 20 months of age. Results obtained with this method were 91.90% and 93.80% concordant, respectively, with those derived from DNA samples in a subsample of the twin pairs (*n* = 123 pairs at age 5 months, *n* = 113 pairs at age 20 months; Forget-Dubois et al., 2003). Zygosity was established for a total of 248 monozygotic (MZ) pairs and 405 dizygotic (DZ) pairs, including 196 opposite-sex pairs. Nine twin pairs did not have their zygosity diagnosed, and 70 twin pairs were lost through attrition and were not included in the analyses.

The children's number knowledge was assessed at age 5 (*M* = 5.30 years, *SD* = 0.26) and age 7 (*M* = 7.06 years, *SD* = 0.27), and their mathematics achievement was assessed when they were in Grade 4 (*M* = 10.00 years, *SD* = 0.28) and Grade 6 (*M* = 12.09 years, *SD* = 0.29). The two members of most of the twin pairs were in different classrooms (75.60%, 70.30%, and 60.30% for ages 7, 10, and 12 years, respectively).

Measures and procedure

Number knowledge.

A trained research assistant assessed number knowledge during a face-to-face interview when the children were ages 5 (preschool) and 7 (Grade 1). An adapted version of the Number Knowledge Test (Okamoto & Case, 1996) was used. This test measures aspects of numerical competence, such as counting and basic arithmetic skills. The test questions have four levels of difficulty (Gersten et al., 2007), and the score on this measure is the total number of correct items across all levels. In our sample, scores varied between 0 and 18 at age 5 and between 0 and 35 at age 7. Gersten et al. (2007) reported high internal consistency (.94), for this measure, and the stability of the measure was good in the present study (r = .55, 95% CI = [.47, .62]).

Achievement in mathematics.

In the spring of both Grade 4 (age 10) and Grade 6 (age 12), teachers rated each child's achievement in mathematics relative to his or her classmates, using a 5-point scale ranging from 1 (lowest achievers) to 5 (highest achievers). Two sets of skills were assessed:

In your opinion, how does this child's achievement in the following subjects compare with other children of the same age? (1) mathematical calculations (ability to carry out basic mathematical operations at his/her level), and (2) mathematical problem solving (ability to grasp the elements of the problem, choose a method and carry out the operations needed).

Teachers generally provide a reliable assessment of achievement; a recent meta-analysis estimated that the association between their assessment of students' academic achievement and actual test performance is .63 (Südkamp, Kaiser, & Möller, 2012). We found a moderate correlation (between .43 and .48) between teachers' ratings and concurrent scores on a standardized math test in a study of singleton children (Garon-Carrier et al., 2017), as well as similar, if not higher associations between teachers' ratings and early number knowledge in the present study (see the Results section). Thus, we are convinced of the validity of teachers' ratings of mathematics achievement.

The correlations between the two ratings (i.e., for calculation and problem solving) were .87 in Grade 4 and .89 in Grade 6. The stability (*r*) of the ratings across ages (and different teachers) was .60 for calculation and .67 for problem solving. Given these high correlations, we averaged each child's ratings across the two items and two ages to obtain a reliable score of mathematics achievement in late elementary school.

The twin method

As natural experiments, twin studies allow researchers to disentangling genetic from environmental sources of variation in a given phenotype, by comparing intrapair correlations of identical (MZ) twins, who share 100% of their genes, with intrapair correlations of nonidentical (DZ) twins, who share 50% of their genes, on average. Higher phenotypic similarity for MZ than for DZ twins reflects genetic sources of variance (i.e., heritability, or additive genetic effects, typically labeled *A*), whereas equal phenotypic similarity between MZ and DZ twin pairs points to shared environmental sources of variance (shared environment, or *C*). *Shared environment* refers to experiences that potentially create similarity among twins of the same family, such as socioeconomic status, home environment, and school factors. Nonshared environment (typically labeled *E*) refers to contexts and events that each member of a twin pair experiences differently (e.g., different relationships with classmates, treatment by parents and teachers, and perceived experiences) and that result in increased dissimilarity. The *E* component also includes measurement error.

Analyses

Treatment of missing data.

Attrition from age 5 to age 12 was less than 10% (about 1.5% per wave), although it varied slightly across measures and analyses (*n* = 396–448 twin pairs. According to Little's (1988) missing-completely-at-random (MCAR) test, participating twins differed from those lost through attrition with regard to mathematics achievement, $\chi^2(9, N = 888) = 19.63$, $p = .020$, and socioeconomic measures, $\chi^2(28, N = 869) = 74.67$, $p = .000$. A series of *t* tests showed that, compared with children who remained in the study, those who were lost at ages 5, 7 and 12 had been from lower socioeconomic status at age 5 months, and those who were lost at ages 5 and 7 had lower math achievement at age 10. Accordingly, we used the full information maximum likelihood (FIML) approach of the Mplus 7.11 statistical package (Muthén & Muthén, 2012) to make full use of the available data and minimize biases due to attrition (Peugh & Enders, 2004). All statistics reported were estimated using FIML.

Twin analyses.

A univariate genetic analysis was first fitted to the data to examine the genetic and environmental sources of variance in preschool and Grade 1 number knowledge and later math achievement. *ACE*, *CE*, and *AE* models were tested, and the best-fitting model at each age was selected using Akaike's information criterion (AIC). We also examined sex differences in the genetic and environmental contributions to number knowledge and math achievement, by testing a sex-limitation model (i.e., a model positing sex invariance regarding these estimates).

Next, to examine the transmission of initial genetic and environmental contributions over time, we fitted a simplex model to the data (Boomsma et al., 1989; Neale & Cardon, 1992). This autoregressive model posits a latent variable at time *i* to be causally related with the immediately preceding latent variable, at time $i – 1$, through a linear relation (transmission coefficient). Innovation (time-specific influence) is the part of the latent factor at time *i* that is not caused by the latent factor at time $i – 1$, but is part of every subsequent transmission coefficient (see

Gillespie et al., 2004, for a more detailed description).

Our simplex model tested the degree to which individual differences in preschool number knowledge and later math achievement were accounted for by continuous and transient effects. It estimated 16 parameters: three innovation parameters (*o*, *p*, and *q*) and two transmission coefficients (*b*) for each source of variance (*A*, *C*, and *E*) and one parameter for measurement error (*u*), which was constrained to equality across ages (see Fig. 1). The factor loadings of the observed variables on the latent factors were set to 1 for the model to fit the data. The variance in number knowledge and later math achievement that was accounted for by innovation and transmission was estimated. Confidence intervals, which allowed us to determine the significance of the parameters, were obtained by bootstrapping the sample 1,000 times. The proportions of genetic, shared environmental, and nonshared environmental influences that were transmitted to later time points and the proportions of these influences that were specific to Grade 1 number knowledge and to late-elementary math achievement (innovation) were derived using the formulas presented in the Supplemental Material available online.

[TS: Please insert Figure 1 about here.]

The simplex model with parameter estimates for genetic (*A*), shared environmental (*C*), and nonshared environmental (*E*) contributions to variance in preschool and Grade 1 number knowledge (NK) and late-elementary math achievement. For each time point, parameters were estimated for innovations (*o*, *p*, and *q* for genetic, shared environmental, and nonshared environmental contributions, respectively) and for transmission (b_A, b_C, and b_E for genetic, shared environmental, and nonshared environmental contributions, respectively). In addition, measurement error (*u*) was constrained to be equal across ages. Circles indicate latent factors, rectangles indicate observed variables, and number subscripts refer to the time of measurement

(1 = preschool, 2 = Grade 1, 3 = late elementary school).

Results

Phenotypic analyses of individual differences

Descriptive statistics and analysis of variance results by sex and zygosity are presented in Table 1. No sex differences were found in preschool number knowledge or in math achievement during late elementary school. However, in Grade 1, boys' number knowledge was significantly better than girls'. No significant zygosity differences or sex-by-zygosity interactions were found for preschool number knowledge, Grade 1 number knowledge, and late-elementary math achievement.

[TS: Please insert Table 1 about here.]

Moderate predictive associations were found between preschool and Grade 1 number knowledge (r = .55, 95% CI = [.47, .62]), between preschool number knowledge and late-elementary math achievement (r = .47, 95% CI = [.38, .54]), and between Grade 1 number knowledge and late-elementary math achievement (r = .57, 95% CI = [.49, .63]). These correlations suggest stable prediction from preschool number knowledge to late-elementary math achievement.

Genetic univariate analyses

Prior to performing the genetic analyses, we standardized the number-knowledge and math scores and corrected them for age and sex. The univariate twin analyses, reported in Table 2, revealed low heritability for preschool number knowledge (.18), but moderate heritability for Grade 1 number knowledge (.49) and later math achievement (.52). Shared environment contributed moderately to preschool number knowledge (.35), but weakly to Grade 1 number knowledge (.18) and to later math achievement (.21). The contribution of nonshared environment was moderate for preschool number knowledge (.47), but decreased for Grade 1 number knowledge (.33) and later math achievement (.27). All the estimated parameters were significant at all the ages. Given these significant estimates, and the fact that the fit of the *ACE* models at all three ages did not differ statistically from the corresponding saturated models (yet were more parsimonious, i.e., had lower AICs; see Table S1 in the Supplemental Material), they were selected (over the *CE* and *AE* models) as the best-fitting models for preschool, Grade 1, and late elementary school.

[TS: Please insert Table 2 about here.]

The sex-limitation models revealed no sex differences in the genetic and environmental contributions to preschool and Grade 1 number knowledge and to later math achievement (see Table S2 in the Supplemental Material).

We also examined whether the estimated parameters for Grade 1 number knowledge, and math achievement at ages 10 and 12 years (separately) (a) were the same for twin pairs whose members were in the same classroom as for those whose members were in different classrooms and (b) were the same for same-sex twin pairs as for the entire sample(i.e., including opposite-sex twin pairs). With the sole exception of a lower *E* estimate for math achievement at age 10 for twins in the same classroom (vs. different classrooms), the results generally indicated that the *ACE* parameters were similar regardless of whether twins were in the same or different classrooms (see Table S3 in the Supplemental Material). The *ACE* parameters estimated for same-sex pairs differed only slightly from those estimated for all pairs, but many did not reach significance, most likely because of power issues (see Table S4 in the Supplemental Material).

Genetic longitudinal analyses

The simplex model, presented in Figure 2, provided an adequate fit to the observed data, as shown by a nonsignificant χ^2 value (p = .61), a high comparative fit index (1.00), and a high Tucker-Lewis index (1.00), as well as a very small root-mean-square error of approximation (0.00, 95% CI = [0.00, 0.041]; Hu & Bentler, 1999).

[TS: Please insert Figure 2 about here.]

Results of the simplex model: estimates of transmission and innovation in the genetic (*A*), shared environmental (*C*), and nonshared environmental (*E*) contributions to preschool and Grade 1 number knowledge (NK) and to late-elementary math achievement(see Fig. 1 for an explanation of the model). Asterisks indicate significant values ($p < .05$).

Table 3 shows the proportion of the transmission from preschool number knowledge to late-elementary math achievement, and the proportion of innovation for Grade 1 number knowledge and late-elementary math achievement. There was a large additive genetic transmission from preschool to Grade 1 number knowledge; .37 of the genetic variance at age 7 was transmitted from the previous age, and there was no significant genetic innovation in Grade 1. A substantial part of this genetic transmission from early number knowledge persisted to later math achievement. Specifically, .23 of the variance in math achievement in Grades 4 and 6 was accounted for by genetic contributions transmitted from previous number knowledge. However, a significant genetic age-specific contribution (i.e., innovation; .31 of the variance) was also found. In other words, a significant part of the genetic variance in math achievement, over and above persistent genetic variance associated with previous number knowledge, was due to new genes being expressed.

[TS: Please insert Table 3 about here.]

The shared environmental contributions to Grade 1 number knowledge and later math achievement were essentially transmitted from shared environmental factors associated with preschool number knowledge. Indeed, .12 of the variance in Grade 1 number knowledge was transmitted from the shared environmental contribution to preschool number knowledge, whereas .20 of the variance in later math achievement originated from shared environmental contributions to both preschool and Grade 1 number knowledge. No significant shared environmental innovations were found in Grade 1 number knowledge and in later math achievement.

Finally, the coefficients for transmission of nonshared environmental influences were significant, but very small; only .03 of the variance due to nonshared environmental factors was transmitted from preschool and Grade 1 number knowledge to later math achievement. No significant nonshared environmental innovations were found in either Grade 1 number knowledge or later math achievement.

Discussion

This study is the first to longitudinally document the stable and transient genetic and environmental sources of variance in preschool and Grade 1 number knowledge, and their associations with achievement in mathematics during late elementary school. Our results revealed increasing heritability across the ages examined, from .18 in preschool number knowledge to .52 in late-elementary math achievement, but substantial genetic continuity from preschool number knowledge to late-elementary math achievement, with additional, new genetic contributions appearing in late-elementary math achievement. In contrast, shared and nonshared environmental contributions decreased from age 5 to ages 10 through 12, from .35 to .21 in the case of shared environment and from .47 to .27 in the case of nonshared environment. Most important, shared environmental influences contributed substantially to the continuity from preschool number knowledge to late-elementary math achievement.

The finding of substantial (shared and nonshared) environmental sources of variance in preschool number knowledge is consistent with previous studies showing that preschool number knowledge develops largely through informal exposure to numbers and instructions received from parents, siblings, or teachers (LeFevre et al., 2009; Ramani et al., 2012). In contrast, whereas environmental sources accounted for most of the variance in preschool number knowledge, genetic factors explained half of the variance in Grade 1 number knowledge and late-elementary-school math achievement. This pattern of results has also been observed for vocabulary (Hart et al., 2009; Olson et al., 2011). One potential explanation for the increased heritability we observed is the timing of the assessments. The first transition coincided with the children's entry into formal education, which might have affected the genetic and environmental contributions by creating a more homogeneous learning environment across the sample, especially in Quebec, where the school curriculum is unified and standardized. Specifically, in Quebec, the elementary-school curriculum in mathematics is based on three main components that children master progressively: solving situational problems related to math, reasoning using math concepts and processes, and using proper math language (Ministère de l'Education et Enseignement supérieur, 2016). In Grades 1 and 2 (age 7–8), children learn to add and subtract natural numbers represented in simple concrete situations. Then, in Grades 3 and 4 (age 9–10), they learn and apply the four basic operations (addition, subtraction, multiplication, and division). In Grades 5 and 6 (age 11–12), they start to add and subtract fractions, to multiply fractions by natural numbers, and to estimate length, surface, volume, and angles.

Exposure to this common math curriculum may have reduced environmental variance, leaving more room for genetic factors to drive differences in mathematics achievement (Krapohl et al., 2014). Consistent with this view is the finding that this increased heritability of number knowledge at school entry was not driven by new genetic factors (i.e., there was no significant genetic innovation); rather, the same genetic factors that were important in preschool number knowledge continued to play a role, but their role increased relative to that of the environment. By contrast, the increased heritability in late-elementary-school math achievement seemed to be due to the activation of new genes relevant to mathematics. The contribution of age-specific genetic factors may reflect maturation that occurs around ages 10 through 12 years, as well as the growing complexity of mathematical concepts presented in the curriculum in late elementary school. Arithmetic reasoning and abstract ways of thinking usually rise around age 12 (Susac, Bubic, Vrbanc, & Planinic, 2014), and math achievement becomes increasingly differentiated from achievement in other school subjects at this age.

It is important to note that this new genetic contribution at ages 10 through 12 may not be specific to mathematics. For instance, strong genetic correlations between mathematics achievement and general intelligence, and between mathematics achievement and reading, have been reported at age 7 (Kovas, Harlaar, Petrill, & Plomin, 2005) and at age 10 (Davis et al., 2008). These findings suggest that the same genes account for most of these associations (Kovas et al., 2007). Improvements in basic cognitive abilities, such as visuospatial skills and memory span, themselves partly genetically influenced (van Leeuwen, van den Berg, Hoekstra, & Boomsma, 2009), could lead to more complex mental computation abilities with age. Late elementary school roughly coincides with a period of qualitative change in children’s cognitive development, when most children progress from the concrete operational stage of thinking to the far more abstract formal operational stage (Piaget, 1977). This change in cognitive development is supported by age-related brain maturation, which allows for multitasking, enhanced problem-solving ability, and the capability to process more complex information (Arain et al., 2013). The cognitive abilities that are most important for mathematics problem solving change as children develop higher-level math skills (Decker & Roberts, 2015), and the genetic contribution to these cognitive abilities has been found to increase with age, from .41 at age 9 years to .66 at age 17 years (Haworth et al., 2010).

Shared environmental factors significantly contributed to continuity in individual differences from age 5 to ages 10 through 12, a finding in line with those of Kovas et al. (2007), while at the same time indicating even greater importance of these factors (.20 vs. .05 of the variance). This increased contribution is all the more noteworthy given the extended period our study covered (7 years), and the fact that the shared environmental contributions were essentially transmitted from preschool age to late-elementary age. The transmission of shared environmental influences from preschool to late elementary school suggests that the shared environmental sources of variation common to preschool number knowledge and later math achievement may involve enduring factors and contexts, such as socioeconomic status (Jordan & Levine, 2009), the quality of childcare (Choi & Dobbs-Oates, 2014), and parental involvement in children's education (LeFevre et al., 2009; Ramani et al., 2012), that somehow contribute to math performance (Bodovski & Youn, 2011).

Unique environmental sources of variance also contributed weakly to continuity in mathematics skill, but no age-specific innovations were identified. This latter finding may seem surprising, but not when one considers that measurement error, which is usually time-specific, was removed from the unique environmental factor in the simplex model.

Overall, our findings have implications for understanding the role of individual and family-wide factors in the stability of number knowledge and later math achievement, as well as for identifying children at risk and developing preventive interventions. The phenotypic correlation between preschool number knowledge and late-elementary math achievement suggests that the assessment of number knowledge could be a means to identify, before school entry, young children at risk for later math difficulties. Moreover, we found that both genetic factors and shared environment (exposure to family-wide environments and experiences) make enduring contributions that uniquely account for this association. The fact that these family-wide environmental influences could be traced back to preschool points to this period as a logical window for supportive and preventive interventions. At the same time, early interventions may not be enough. The effects of early interventions in mathematics have been shown to fade over time, as children who did not receive such interventions often tend to catch up to children who did (Bailey, Duncan, Odgers, & Yu, 2017). This suggests the need for sustained enrichment beyond preschool, in the form of booster or additional interventions aimed at helping children master a more advanced curriculum (see Bailey et al., 2017). Relevant to this point is the finding of genetic innovation for late-elementary math achievement, which may tap new, more complex math-relevant skills that could be the object of additional intervention. However, this is a topic for future research; although finding stable environmental variance points to the relevance of preschool interventions, it does not mean that intervention at a later age has no value.

Limitations and future directions

This study should be interpreted in the context of its limitations. First, it is possible that some effects were not detected because of the small sample size. Second, the simplex model makes the assumptions that there are no effects of nonadditive genetics and no gene-environment interaction. Thus, we did not test for specific interactions between individual genetic backgrounds and the environmental response. Third, some of the variance in math skills observed across the years might have been due to the measurement methods (standardized test of number knowledge administered in a laboratory vs. teachers' reports of math achievement) rather than genuine etiological change. However, the high phenotypic stability observed suggests that early number knowledge is a strong predictor of later math achievement, and the control for measurement-specific error in the simplex model may have been sufficient to minimize potential methodological bias.

Conclusion

In conclusion, this study provides new insights into the mechanisms that underlie the stability of (and change in) number knowledge, and that underlie its association with later math achievement. We found an etiological shift from preschool to late elementary school, with genetic influences—some of them new—becoming more important and environmental factors becoming less influential, possibly because of their standardization in formal schooling. Genetic factors accounted for both enduring and transient effects from preschool number knowledge to late-elementary math achievement. This suggests that certain genetic factors are needed to support the complex cognitive functions required for mathematical reasoning across development, but also that there are developmental changes in genetic expression, from preschool to late elementary school. Environmental factors were mostly involved in longitudinal continuity from number knowledge to math achievement; they contributed to early number knowledge and to its prediction of later math achievement. Future research is needed to identify specific genes and environments that are relevant for mathematics development.

Author Contributions

G. Garon-Carrier, M. Boivin, and G. Dionne conceived the study. M. Boivin, M. Brendgen, F. Vitaro, R. E. Tremblay, and G. Dionne selected the measures and planned the data collection, and B. Feng ran the analyses. G. Garon-Carrier and M. Boivin wrote the manuscript, and Y. Kovas, M. Brendgen, F. Vitaro, J. R. Séguin, R. E. Tremblay, and G. Dionne provided revisions. All the authors approved the final manuscript for submission.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797617721480

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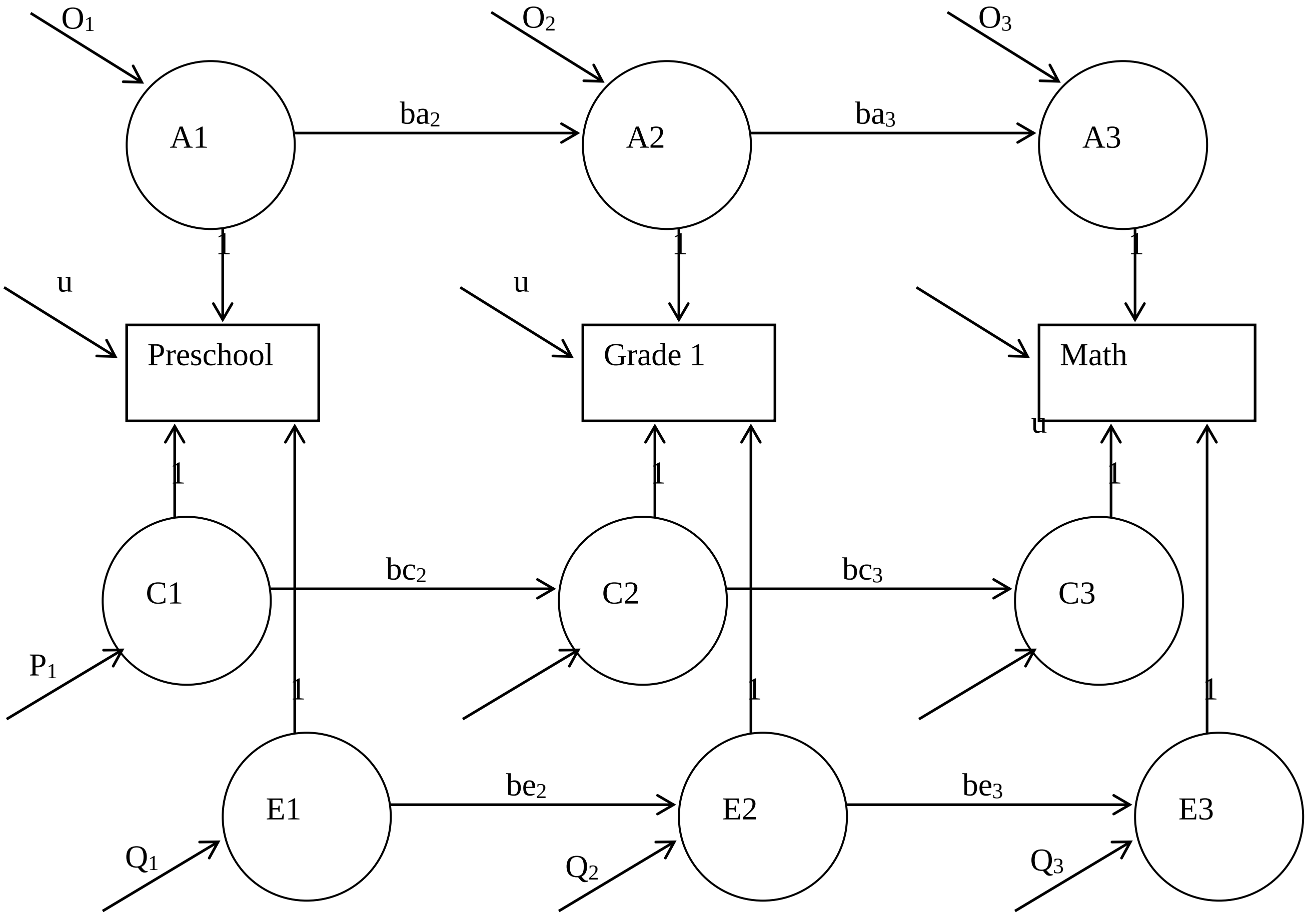

Figure 1. The simplex model with parameter estimates for genetic (*A*), shared environmental (*C*), and nonshared environmental (*E*) contributions to variance in preschool and Grade 1 number knowledge (NK) and late-elementary math achievement. For each time point, parameters were estimated for innovations (*o*, *p*, and *q* for genetic, shared environmental, and nonshared environmental contributions, respectively) and for transmission (b_A, b_C, and b_E for genetic, shared environmental, and nonshared environmental contributions, respectively). In addition, measurement error (*u*) was constrained to be equal across ages. Circles indicate latent factors, rectangles indicate observed variables, and number subscripts refer to the time of measurement (1 = preschool, 2 = Grade 1, 3 = late elementary school).

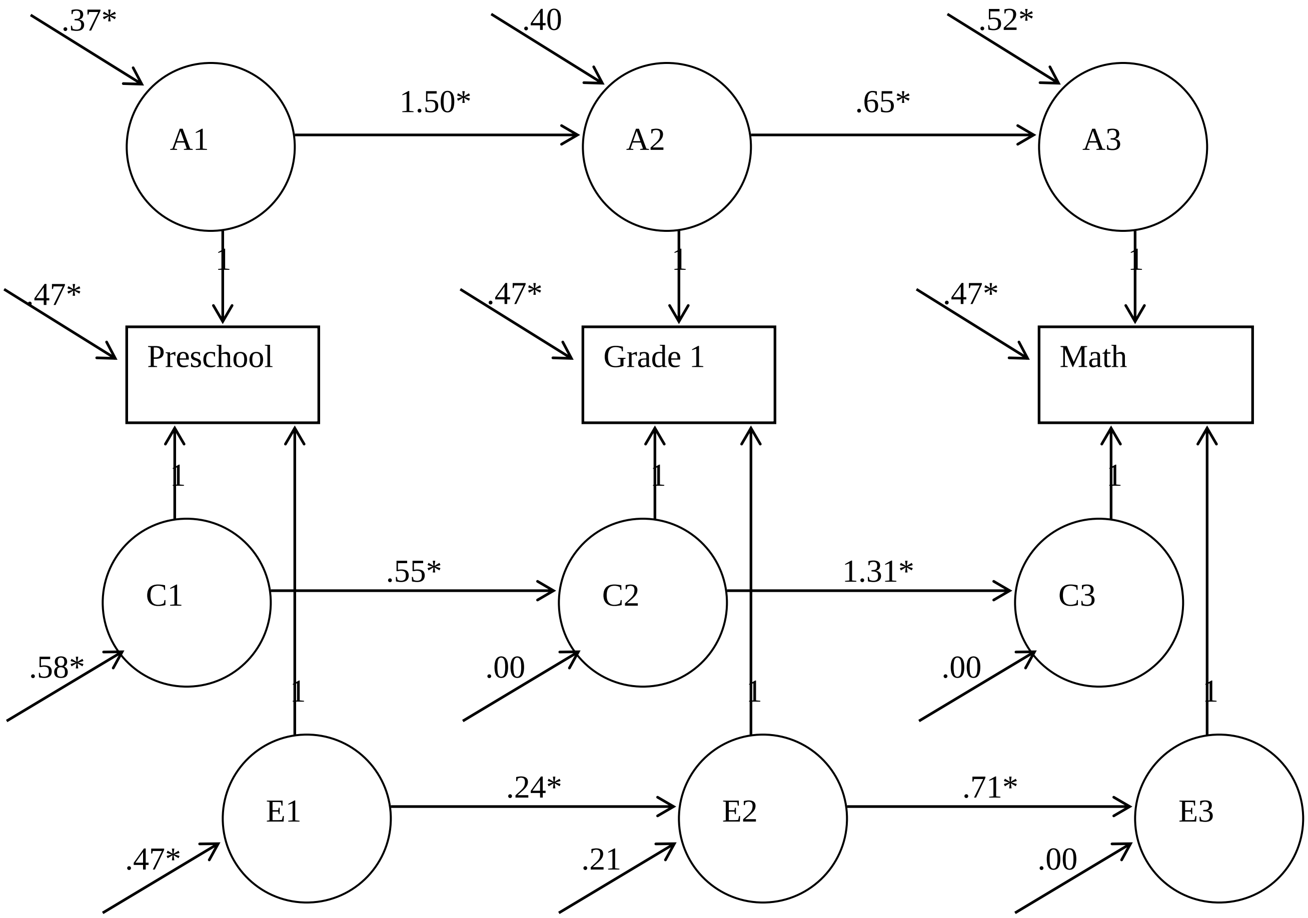

Figure 2. Results of the simplex model: unstandardized estimates of transmission and innovation in the genetic (*A*), shared environmental (*C*), and nonshared environmental (*E*) contributions to preschool and Grade 1 number knowledge (NK) and to late-elementary math achievement (see Fig. 1 for an explanation of the model). Asterisks indicate significant values ($p < .05$).

Table 1. Mean Raw Scores by Zygosity and Sex and Analysis of Variance Results

Measure	Zygosity		Sex		Analysis of variance results					
	MZ	DZ	Male	Female	Zygosity		Sex		Zygosity*Sex	
					p	η^2	p	η^2	p	η^2
Preschool NK	7.83 (3.87)	7.83 (4.37)	7.88 (0.30)	7.79 (0.29)	.97	.00	.42	.00	.84	.00
(n = 396)	n = 178	n = 218	n = 194	n = 202						
Grade 1 NK	14.40 (5.80)	14.40 (6.20)	15.32 (0.42)	13.56 (0.41)	.97	.00	.00	.02	.55	.00
(n = 418)	n = 182	n = 236	n = 204	n = 214						
Math achievement	3.19 (1.00)	3.17 (1.10)	3.17 (0.07)	3.18 (0.07)	.86	.00	.93	.00	.46	.00
(n= 449)	n = 186	n = 263	n = 217	n = 232						

Note: The data presented in this table are taken from one twin chosen at random within each pair. Numbers inside parentheses are standard deviations. NK = number knowledge; MZ = monozygotic; DZ = dizygotic.

Table 2. Parameter Estimates From the Univariate Twin Analyses

Measure	A	C	E
Preschool NK	.18 [.03, .39]	.35 [.17, .49]	.47 [.39, .56]
Grade 1 NK	.49 [.27, .69]	.18 [.01, .37]	.33 [.26, .41]
Math achievement	.52 [.36, .66]	.21 [.08, .35]	.27 [.22, .34]

Note: Values in brackets are 95% confidence intervals. *A* = additive genetic influences; *C* = shared environmental influences; *E* = nonshared environmental influences.

Table 3. Proportions of Variance in Number Knowledge and Math Achievement Explained by Genetic, Shared Environmental, and Nonshared Environmental Transmission and Innovation

Transmission or innovation influence	*A*	*C*	*E*
Transmission from preschool to Grade 1 number knowledge	**.37**	**.12**	**.01**
Transmission from preschool and Grade 1 number knowledge to late-elementary math achievement	**.23**	**.20**	**.03**
Innovation for Grade 1 number knowledge	.19	.00	.05
Innovation for late-elementary math achievement	**.31**	.00	.00

Note: The proportions presented in this table were derived using the formulas presented in the Supplemental Material. Significant proportions are highlighted in boldface. *A* = additive genetic influences; *C* = shared environmental influences; *E* = nonshared environmental influences.