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

**Short title:** Etiology of math knowledge and skills development

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Author note

This research was supported by grants from the Québec Ministry of Health, the FQRSC, SSHRC, CIHR, and FRQS, the National Health Research Development Program, CHU Sainte-Justine Research Center, the Canada Research Chair Program, and the Government of the Russian Federation [grant 11.G34.31.0043]. We are grateful to the parents of the twin participants, and we thank the GRIP staff for data collection and management.

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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 its predictive association with 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, with significant genetic innovation (i.e. new) at ages 10-12 years. The shared and non-shared environmental contributions decreased during the transition from preschool to school entry, but entirely contributed to the continuity across time from preschool number knowledge to subsequent number knowledge and math achievement. There was no additional environmental contribution at time points subsequent to preschool. Results are discussed in light of their practical implications for children with mathematic difficulties as well as for preventive intervention.

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

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

Early number knowledge forecasts later achievement in mathematics (Duncan et al., 2007; Nguyen et al., 2016; Watts, Duncan, Siegler, & Davis-Kean, 2014; Goebel, Watson, Lervag, & Hulme, 2014). Core components of number knowledge, such as magnitude comparisons and counting abilities, underlie the development of effective counting strategies (LeFevre et al., 2010), which provides the foundation for solving complex operations, such as algebraic equations and multi-step arithmetic problems (Gersten, Clarke, & Jordan, 2007; Göbel et al., 2014).

There is indeed evidence of continuity from early number knowledge to later achievement in mathematics (Duncan et al., 2007; Nguyen et al., 2016; Watts, Duncan, Clements, & Sarama, 2017; Watts et al., 2014; Jordan, Kaplan, Ramineni, & Locuniak, 2009). Population-based longitudinal studies of children, and of children showing learning disabilities in mathematics both indicate that number knowledge at school entry predicts later mathematics achievement (Duncan et al., 2007; Jordan et al., 2009; Nguyen et al., 2016) up to age 15 years (Watts et al., 2017).

This predictive association from early number knowledge to later math achievement raises questions regarding the underlying mechanisms, starting with the individual and family factors accounting for inter-individual differences in number knowledge and later math achievement. Previous studies found achievement in mathematics to be associated with family income (Jordan & Levine, 2009; Siegler, 2009), parental involvement in child’s education (LeFevre et al., 2009), and quality of educational experiences (Ramani, Siegler, & Hitti, 2012). Those family/school-wide factors are typically shared by children of the same family, while others, such as birth complications or illnesses are usually individual-specifics (i.e. non-shared by children of the same family; Plomin, Asbury, & Dunn, 2011). It is important to understand how these experiences combine with child early cognitive abilities, such as visual-spatial skills or memory span (Soto-Calvo, Simmons, Willis, & Adams, 2015; Garon-Carrier et al., submitted), to foster number knowledge and math achievement, and the extent to which they are genetically and environmentally linked over time.

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

These inconsistencies across studies likely result from variations in age within studies, as well as between studies. They may also be related to variations in assessments; some studies used teacher ratings of math achievement (Oliver et al., 2004; Kovas et al., 2007), while others used math subtests of standardized scholastic achievement tests (Thompson et al., 1991; Alarcόn, et al., 2000), in some cases, combining scores of verbal and non-verbal arithmetic and math subtests of geometry and trigonometry (Alarcόn, et al., 2000), sometimes through online batteries (Davis, Haworth, & Plomin, 2009).

Most importantly, previous findings were limited by their cross-sectional nature. Only a few twin studies previously took advantage of a longitudinal design to disentangle the genetic and environmental contributions to mathematics over time (Haworth, Kovas, Petrill, & Plomin, 2007; Kovas et al., 2007). Based on the Twin Early Development Study, two studies found substantial heritability (ranging between .62-.72) in mathematical performance in children aged 7 to 9 years (Haworth et al., 2007), and then aged 7 to 10 (Kovas et al., 2007). Moreover, about .50 of the genetic contribution to math at age 10 years was present at age 7 years. Other new genetic contributions were time-specific, emerging at 9 and 10 years respectively. Quite interestingly, shared environment accounted for a small but significant part of continuity in mathematical performance (7% from age 7 to 9 years, and 5% from age 7 to 10 years), whereas non-shared environment uniquely contributed to age-specific variation (Kovas et al., 2007). These results suggest that genetic factors account for most developmental continuity in mathematics in elementary school, but that experiences shared by twins of the same family also played a unique significant role.

Whether this joint genetic and shared environment contributions to mathematic achievement can be traced back to the early (preschool) development of mathematic skills is still unknown. Yet, there is substantial change in both the learning context and developmental processes underlying math performance over this period, including motivational (Garon-Carrier et al., 2016), cognitive (Decker & Roberts, 2015), and emotional processes (e.g. self-regulation, Krapohl et al., 2014). Accordingly, twins should be followed early and longitudinally~~,~~ to adequately capture (1) stability and changes in skills, i.e., ‘mathematics’ may subsume core and persistent skills, as well as emergent capacities with age, and (2) stable as well as new genetic and environmental contributions during development, i.e., changes associated with maturation/development (e.g., puberty, socializing; [Wehkalampi](http://www.ncbi.nlm.nih.gov/pubmed/?term=Wehkalampi%20K%5Bauth%5D) et al. 2008; Santos, Vaughn, Peceguina, Daniel, & Shin, 2014) and 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 was 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) involving substantial changes in the learning context, as well as in physical and psychological development. The following research questions were addressed: (1) What are the genetic and environmental contributions to preschool number knowledge, that is, before school entry (age 5), to grade 1 number knowledge (age 7), and to late elementary math achievement (10-12 years)? (2) To what extent are these contributions stable, i.e., extending over time versus age specific; and do they 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 the partitioning of genetic and environmental source of variation transmitted across adjacent time-points through auto-regressive paths, and the estimation of 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), and the assumption that development mainly proceed through strong auto-regressive paths. For this reason, the simplex model was preferred over the Cholesky model.

**Methods**

**Participants**

Participants were pairs of twins born in the greater Montreal area, Canada, who 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 5 months onward, and assessed on various child and family characteristics. Parental informed consent was obtained at each assessment. Twins’ zygosity was established with the Zygosity Questionnaire for Young Twins (Goldsmith, 1991), and was derived from DNA samples for 123 and 113 twin pairs respectively. The two methods converged at 91.90% at 5 months, and 93.80% at 20 months (Forget-Dubois et al., 2003). Zygosity was established for a total of 667 twin pairs (254 MZ and 413 DZ pairs including 203 opposite-sex pairs). Of the 667 families with zygosity information, 70 were lost through attrition and were not included in the analyses.

Children’s number knowledge was assessed at 5 (M= 5.30, SD= .26) and 7 (M= 7.06, SD= .27) years respectively, and their mathematics achievement, in grade 4 (M= 10.00 years, SD= .28) and 6 (M= 12.09, SD= .29). Most twins of the same family were in different classrooms, that is, 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 at age 5 (preschool) and 7 years (grade 1) using an adapted version of the Number Knowledge Test (Okamoto & Case, 1996). This test measures aspects of numerical competence, such as counting and basic arithmetic skills. The test has 4 levels of difficulty ranging from 0 to 3 (Gersten et al., 2007). The score consisted of the total number of correct items across a level, and varied between 0 and 18 at age 5, and between 0 and 35 at age 7. Reported internal consistency was .94 (Gersten et al., 2007), and the stability was good in the present study (see results).

**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/her classmates on a 5-point scale ranging from 1 (lower achievers) to 5 (higher achievers), using two items: “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 at .63 the association between their assessment of student’s academic achievement and actual test performance, (Südkamp, Kaiser, & Möller, 2012). We found moderate correlation (between .43 and .48) between such ratings and concurrent standardized test of math in a study of singleton children (Garon-Carrier et al., submitted), as well as similar, if not higher figures predicting these ratings from early number knowledge in the actual study (see results). All of this provides convincing evidence of the validity of teacher ratings of mathematics achievement.

The correlations between the two items (i.e. math calculation and math problem solving) were .87 in grade 4, and .89 in grade 6. The stability across ages (and different teachers) were .60 and .67 for calculations and problem solving, respectively. Given these high correlations, the items were averaged across age to serve as a reliable score of mathematics achievement in late elementary school.

**The Twin Method**

As natural experiments, twin studies allow to disentangling genetic from environmental source of variation in a given phenotype, by comparing intra-pair correlations of identical twins (monozygotic, MZ) who share 100% of their genes, to non-identical twins (dizygotic, DZ) who share 50% of their genes on average. Higher phenotypic similarity for MZ over 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 point 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 socio-economic status, home environment, and school factors. Non-shared environment (typically labeled E) refers to contexts/events that each twin of a pair experiences differently (e.g., different peers/classmates relationship, treatment by parents and teachers, and perceived experiences), and result in increased dissimilarity (including measurement error).

**Analyses**

**Treatment of Missing Data.** Attrition from ages 5 to 12 years was less than 10 % (about 1.5 % per wave), although it varied slightly across measures and analyses (between 396 and 448 twin pairs; see Table 1). According to Little**’**s missing completely at random (MCAR) test, participating twins differed from those lost due to attrition with regard to mathematics achievement and socioeconomic measures (χ2= 176.76, *df*= 73, *p*= .000). A series of *t* tests showed that missing children at ages 5, 7 and 12 were from lower socioeconomic status at age 5 months, and those missing 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, 1998-2012) to make full use of 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 data to examine the genetic and environmental sources of variance in preschool and grade 1 number knowledge, and math achievement. ACE, CE and AE models were tested, and the best fitting model was derived based on the lowest Akaike information criterion (AIC), which reflects the parsimony of the model. 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.

Second, to examine the transmission of initial genetic and environmental contributions over time, a simplex model was fitted to the data. The simplex model specifically tests the degree to which individual differences in preschool number knowledge and later math achievement are accounted for by continuous or transient effects (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 (i – 1) through a linear relation (transmission coefficients). The innovations (time-specific influence) are part of the latent factor at time (i) that is not caused by the latent factor at time (i-1), but are part of every subsequent transmission coefficient time point (see Gillespie et al., 2004, for a more detailed description).

In this study, the simplex model estimated 16 parameters, i.e., three innovations (o, p, q) and two transmission coefficients (b) for each source of variance (A, C and E), and one measurement error (u) parameter, the latter constrained to equality across ages (see Figure 1). The factor loadings of the observed variables to the latent factors were set to 1 for the model to be identified. The variance of the innovation terms and the transmission coefficients were estimated. Confidence intervals were obtained by bootstrapping the sample 1000 times, which allowed to determine the significance of the parameters.

The proportion of genetic, shared and non-shared environmental source of transmission, and innovation specific to grade 1 number knowledge and to math achievement were derived using the formulas presented in Supplementary material.

**Results**

**Phenotypic Analyses of Individual Differences**

Descriptive statistics and ANOVA results by sex and zygosity are presented in Table 1. These descriptive statistics are reported for one twin of each pair selected randomly. No sex differences were found in preschool number knowledge and math achievement during late elementary school. However, boys performed significantly better than girls in grade 1 number knowledge. No significant zygosity differences, nor sex by zygosity interactions were found in preschool, grade 1 number knowledge, and math achievement.

Moderate predictive associations were found between preschool and grade 1 number knowledge (*r*= .54) and math achievement (*r*= .47), and between grade 1 number knowledge and math achievement (*r*= .56). These correlations suggest stable prediction from preschool number knowledge to late elementary math achievement.

**Genetic Univariate Analyses**

Prior to genetic analyses, number knowledge and math scores were standardized and corrected 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 math achievement (52%). Shared environmental contribution to preschool number knowledge was moderate (35%), but weak to grade 1 number knowledge (18%) and to later math achievement (21%). Non-shared environmental contribution 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 ages. Given these significant estimates, and that all three ACE model fits did not statistically differ from their corresponding saturated model (yet more parsimonious, i.e., lower AIC; see Table S1 in Supplementary material), they were selected as the best-fitting models in preschool, grade 1, and late elementary school.

The sex-limitation models revealed no sex differences in the genetic and environmental contributions to both preschool and grade 1 number knowledge, and to later math achievement (see Table S2 in Supplementary material).

We also examined whether the estimated parameters for grade 1 number knowledge, and math achievement at ages 10 and 12 years (separately) could be equated (1) when comparing twins in same vs. different classrooms, and (2) when using same-sex twin pairs only vs. using all twin pairs (i.e. same-sex and opposite-sex twin pairs). With the sole exception of the lower non-shared E estimate for math achievement at age 10 for twins in same (vs. different) classroom, the results generally indicated that ACE parameters were similar for twins in same or different classrooms for all time-specific measures (see Table S3 in Supplementary material).

The ACE parameters estimated for same-sex pairs only slightly differed from those based on all pairs, but many did not reach significance, most likely due to power issues. These results are presented in Supplementary material, Table S4.

**Genetic Longitudinal Analyses**

The simplex model, presented in Figure 2, provided an adequate fit to the observed data, as shown by a non-significant χ2 value (*p* = .61), high comparative fit index (CFI = 1.00) and Tucker**–** Lewis index (TLI = 1.00), as well as very small root mean square error of approximation (RMSEA = 0.00 [0.00, 0.041]) (Hu & Bentler, 1999).

Table 3 shows the proportion (%) of the transmission coefficients and innovations at each time point. There was a large additive genetic transmission from preschool to grade 1 number knowledge, with 37% of the genetic variance at age 7 transmitted from previous age, and no genetic innovation in grade 1. A substantial part of this genetic transmission from early number knowledge persisted to later math achievement. Specifically, 22.5% 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 was due to new genes being expressed over and above persistent genetic variance associated with previous number knowledge.

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 was transmitted from preschool number knowledge shared environment, whereas 19.5% of the variance in math achievement originated from shared environmental contributions to both preschool and grade 1 number knowledge. No new significant shared environmental innovations were found in grade 1 number knowledge and in later math achievement.

Finally, non-shared environmental transmission coefficients were significant, but very small, with only 3% of non-shared environmental variance transmitted from preschool number knowledge to math achievement. Again, no significant non-shared environmental innovations were found in both grade 1 number knowledge and later math achievement.

**Discussion**

This study was the first to longitudinally document the stable and transient genetic and environmental sources of variance in preschool and grade 1 number knowledge, and of their associations to late elementary school achievement in mathematics. Our results revealed increasing heritability from number knowledge to math achievement, from 18% in preschool to 52% in late elementary school, but substantial genetic continuity from preschool number knowledge to late elementary math achievement, with additional genetic contributions appearing in later math achievement. In contrast, shared and non-shared environmental contributions decreased from 5 to 10-12 years, from 35% to 21% (shared environment) and from 47% to 27% (non-shared environment). Most importantly, shared environmental contributions substantially contributed to the continuity from preschool number knowledge to late elementary math achievement. These results were similar for both boys and girls.

The finding of substantial (shared and non-shared) environmental sources of variance in preschool number knowledge is consistent with previous studies showing that preschool number knowledge largely develops through informal exposure to numbers and instructions received from parents, siblings, or teachers (LeFevre et al., 2009; Ramani et al., 2012). In contrast, while environmental sources account 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 is the timing of the changes we observed. The first transition coincides with children**’**s entry into formal education. This transition might impact the genetic and environmental contributions by bringing a more homogeneous learning environment across children, especially in Quebec where the school curriculum is unified and standardized. Specifically in Quebec (Canada), the elementary school curriculum in mathematics is based on 3 main components that children learn and master progressively: solving situational problems related to math, reasoning using math concept and processes, and using math language to communicate (MEES, 2016). In grades 1 and 2 (age 7-8), children learn to add and subtract natural numbers from 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 (Krapohl et al., 2014). Consistent with this view was the finding that this increased heritability of number knowledge at school entry was not driven by new genetic factors (no significant genetic innovation); rather, the same genetic factors that were important in preschool number knowledge continued to play a role, but increased relative to the environment, in grade 1 number knowledge.

By contrast, the increased heritability in late elementary school math achievement seemed to reflect the activation of new genes relevant to mathematics. Mathematics achievement was found partly driven by age-specific genetic factors, which may reflect maturational factors around age 10-12 years, and the growing complexity of mathematical concepts. Arithmetic reasoning and growing abstract ways of thinking usually develop around age 12 years (Susac, Bubic, Vrbanc, & Planinic, 2014), with mathematics becoming increasingly differentiated from other school subjects at this age.

It is important to note that this new genetic contribution at age 10-12 may not be specific to mathematics. For instance, strong genetic correlations were reported between mathematics and general intelligence, as well as with reading at ages 7 and 10 years (Kovas, Harlaar, Petrill, & Plomin, 2005; Davis et al., 2008), suggesting that the same genes account for most of their association (Kovas et al., 2007). Basic cognitive abilities, such as visual-spatial 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. Later elementary school roughly coincides with qualitative changes in children’s cognitive development, a period where 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 also supported by age-related brain maturational process in children and adolescents, allowing for multitasking, enhanced ability to solve problems, and the capability to process more complex information (Arain et al., 2013). Cognitive abilities involved in mathematics problem solving were indeed found to change in importance as children develop higher-level math skills (Decker & Roberts, 2015), and genetic contribution to these cognitive abilities was also found to increase with years, from 41% at age 9 years to 66% at age 17 years (Haworth et al., 2010).

Shared environmental factors significantly contributed to continuity from 5 to 10-12 years, a finding in line with those of Kovas et al. (2007), while at the same time raising the ante in terms of its importance (20% versus 5% of the variance). This increased contribution is all the more noteworthy given the extended time coverage (5-6 years), and the fact that the shared environmental contributions were essentially transmitted from preschool age to late elementary school years. This finding suggests that shared environmental sources of variation from preschool number knowledge to math achievement may involve enduring factors and contexts, such as socioeconomic status (Jordan & Levine, 2009), quality 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 & Young, 2011).

Unique environmental sources of variance also weakly contributed to continuity in mathematics; but no age-specific innovations were identified. This latter finding may appear surprising, but not when we consider the removal of measurement error from the unique environmental factor in the model.

Overall, these findings have implications for our understanding of the role of individual and family-wide factors in the stability of number knowledge and later math achievement, as well as for the identification of children at risk and preventive interventions. First, the strong phenotypic prediction from preschool number knowledge to late elementary math achievement suggests that the assessment of preschool number knowledge could be used to identify, before school entry, young children at risk for later math difficulties. Second and more distinctive to the present study is the finding that both the enduring contributions of genetic factors and exposure to family-wide environments and experiences (shared environment) uniquely accounted for this prediction. These family-wide environmental contributions could be traced back to preschool, thus pointing to this period as a logical window for supportive and preventive interventions. At the same time, this may not be enough. Early interventions in mathematics have been shown to fade over time, as children who did not receive the intervention often tend to catch up to children who did (Bailey, Duncan, Odgers, & Yu, 2017). This calls for sustained enrichment beyond preschool, under the form of booster or additional interventions aimed at helping children master a more advanced curriculum (see Bailey et al., 2017). Relevant to this is the finding of genetic innovation for math achievement which may tap new, more complex math-relevant skills that could be the object of additional intervention. However, this is the object of future research, the bottom line being that if finding stable environmental variance point to the relevance of preschool interventions, it does not preclude the value of intervention at a later age.

**Limitations and Future Directions**

This study should be interpreted in the context of its limitations. First, some effects were possibly not detected due to the small twin sample size. Second, the simplex model makes the assumptions that there are no effects of non-additive genetics, or gene–environment interaction. Even if we did not test for these specific effects, we should keep in mind that interactions between individual genetic backgrounds and their environmental response are possible. Third, some of the variations observed across the years might be due to measurement method (standardized test of number knowledge administered in laboratory vs. teachers report of math achievement) rather than genuine etiological change. However, the high phenotypic stability suggests great prediction from number knowledge to math achievement across ages and the control for measurement-specific error in the simplex model may have been sufficient to minimize potential methodological bias.

In conclusion, the study provided new insights into the mechanisms that underlie the stability of (and change in) number knowledge, and its prediction of later math achievement. We found an etiological shift from preschool number knowledge to math achievement in late elementary school, with genetic influences – some of them new – becoming more important and environmental factors becoming less influential, possibly due to their standardization in formal school. Genetic factors accounted for both enduring and transient effects from preschool number knowledge to late elementary math achievement, suggesting that the same genetic factors are needed to support the complex cognitive functions required for mathematical reasoning across development, but also that developmental changes occur in genetic expression and/or in the phenotype in late elementary school (number knowledge vs. math; and measures at different ages). Environmental factors were mostly involved in longitudinal continuity from number knowledge to math achievement, highlighting their contribution in early number knowledge and of its prediction to math achievement. Therefore, future research is needed to identify specific genes and environments that are relevant for mathematics development.

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Table 1. Raw score means (SD) by zygosity and sex; and ANOVA results showing significance and effect size

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Measures** |  | **Zygosity** | | **Sex** | | **ANOVA** | | | | | |
|  | **MZ** | **DZ** | **Male** | **Female** | **Zygosity** | | **Sex** | | **Zygosity\*Sex** | |
|  | ***p*** | **η2** | ***p*** | **η2** | ***p*** | **η2** |
| Preschool NK | N= 396 | 7.83 (3.87) | 7.83 (4.37) | 7.88 (.30) | 7.79 (.29) | .97 | .00 | .42 | .00 | .84 | .00 |
| n = 178 | n = 218 | n = 194 | n = 202 |
| Grade 1  NK | N= 418 | 14.40 (5.80) | 14.40 (6.20) | 15.32 (.42) | 13.56 (.41) | .97 | .00 | **.00** | **.02** | .55 | .00 |
|  | n = 182 | n = 236 | n = 204 | n = 214 |  |  |  |  |  |  |
| Math achievement | N= 448 | 3.19 (1.00) | 3.17 (1.10) | 3.17 (.07) | 3.18 (.07) | .86 | .00 | .93 | .00 | .46 | .00 |
|  | n = 186 | n = 263 | n = 217 | n = 232 |  |  |  |  |  |  |

NK = number knowledge; MZ= monozygotic twins; DZ= dizygotic twins. The statistics are reported for one twin chosen at random from each pair.

Table 2. Genetic and environmental parameter estimates

|  |  |  |  |
| --- | --- | --- | --- |
| **Measures** | **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) |

NK = Number knowledge. 95% confidence intervals are presented in parentheses; genetic heritability (A), shared environmental (C) and non-shared environmental (E) parameter

estimates.

|  |  |  |  |
| --- | --- | --- | --- |
|  | A | C | E |
| Transmission T1 to T2 | **.370** | **.120** | **.014** |
| Transmission T1 & T2 to T3 | .**225** | **.195** | **.030** |
| Innovation T2 | .191 | .000 | .050 |
| Innovation T3 | **.306** | .000 | .000 |

Table 3. Proportion (%) of genetic, shared and non-shared environmental transmission and innovation

Significant proportion of transmission and/or innovation is indicated in bold character.

T1 = Preschool number knowledge

T2 = Grade 1 number knowledge

T3 = Math achievement

ba2

ba3

1

1

1

u

u

E1

E2

E3

P1

bc2

bc3

C1

C2

C3

1

1

1

Q1

be2

be3

1

1

1

A1

A2

A3

Preschool NK

Grade 1

NK

Math achievement

O1

O2

O3

u

P3

P2

Q3

Q2

**Figure 1.** The simplex model with 16 parameter estimates; genetic (A), shared environmental (C) and non-shared environmental (E) estimates for each time-point of measurement; innovations for genetic (O), shared (P) and non-shared environment (Q) parameters; transmission coefficients for each source of genetic (ba2 ba3), shared (bc2 bc3) and non-shared (be2 be3) environmental variance; and the measurement error (u) parameters. NK = number knowledge.

1.50\*

.65\*

1

1

1

.47\*

.47\*

.47\*

E1

E2

E3

.58\*

.55\*

1.31\*

C1

C2

C3

1

1

1

.00

.00

.47\*

.21

.00

.24\*

.71\*

1

1

1

A1

A2

A3

Preschool NK

Grade 1

NK

Math achievement

.37\*

.40

.52\*

**Figure 2.** Results of the simplex model; \* indicates significant unstandardized parameter estimates; genetic (heritability A), shared environmental (C) and non-shared environmental (E) parameter estimates. NK = number knowledge.