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The Etiology of Individual Differences in Maths beyond IQ: Insights from 12-year Old Twins

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Abstract

This study investigated the etiology of individual differences in mathematics and the nature of the relationship of mathematics with reading and *g*. A sample of 13,262 12-year-old twins from the Twins Early Development Study (TEDS) was assessed on 11 measures of mathematics, reading, and general cognitive abilities (*g*). A variable of 'Pure Mathematics' was obtained by removing the common variance with reading and *g* from mathematical scores. Controlling for reading and *g* did not reduce variability in mathematics but eliminated the influences of shared environment in the etiology of individual differences. Pure Mathematics remained moderately heritable (.44).

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Keywords: Mathematical ability; Heritability; Individual differences; Pure Mathematics; Reading, IQ

1. Introduction

The successful acquisition of mathematics relies on a number of cognitive abilities [1]. Evidence for this is provided by the fact that a selective impairment in any of these supporting cognitive mechanisms may give rise to mathematical difficulties. For example, reading difficulties and low mathematical performance often co-occur [2], [3]. Conversely, children with poor mathematical skills often show no impairment in non-verbal intelligence and language abilities [4]. Children with average IQ can have low mathematical skills [5]; however, children with various cognitive impairments among which mathematics, may show no difference in IQ compared to controls

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[4], [6]. Reading and language abilities have also shown association with mathematical development [7] and a number of studies have also shown comorbidity between poor mathematics and poor reading skills [2], [3].

The heterogeneity in the cognitive profile underlying poor and good mathematical ability encouraged researches to use different approaches when exploring the etiology of mathematical skills. By using the twin design, behavioural genetic studies can estimate the portion of variance in a trait that is attributed to genetic and environmental influences. These studies have found a moderate to substantial heritability of mathematical ability and achievement (between ~.42 and ~.68) consistently across development [8], [9], [10], [11] and across ages [12]. Small influences from shared environment (~.20) were also found. This suggests stability in the heritability of mathematics. Similarly, reading abilities show stability in the pattern of heritability estimates across ages and samples [13], [14]. Conversely, the heritability of *g* has shown to increase with development [15]. Behavioural genetic studies have shown that the covariation between mathematics and other abilities is largely due to genetic factors. For example, at the age of 7, the genetic correlation (indexing the overlap of genetic factors) between mathematics and reading was .74; and between mathematics and *g* was .67 [8]. This suggests that if a gene is involved in the development of mathematics, there is 74% of probability that the same gene is also involved in reading and 67% of chance that is involved in *g*. Other studies have shown large genetic overlaps among abilities [16], [17], [18], suggesting that different cognitive domains share much of the same etiology. This is referred to as the “Generalist Genes Hypothesis” [19]. Despite the common etiology, there is evidence that some genetic influences are trait-specific [8], [9], [10]. The mathematics-specific genetic influences seem to be stable, at least between the ages of 7 and 10. One important question is whether this independence from other abilities is maintained at later stages, when mathematical concepts become more complex and abstract. It is possible that different genetic influences get involved as a consequence of the change in mathematics, or new genetic influences arise with development.

The present study used a twin representative sample to address the following research questions: (1) Do the relative contributions of genetic and environmental factors to variation in mathematics remain similar to those previously reported at 10 years of age in the same sample? This question is relevant for three reasons. First, at least for some educationally-relevant traits, heritability has been shown to increase with age. Second, many biological changes occur in children over the two year period. Third, under the UK National Curriculum (NC), at 10 years of age, children are still in primary school and the same teacher is likely to teach most subjects including mathematics and reading. At 12, in secondary school, different subjects are taught by a specialist teacher. These factors may lead to an abrupt change in the relative contribution of genes and environments to the variation in mathematics. (2) How variable is mathematical ability at this age after controlling for variability in reading and *g*? This question is of major practical and scientific interest. As described above, a large portion of the mathematical variance has been shown to be shared with reading and *g* at previous developmental stages described in this sample. Do reading and intelligence become more closely associated with mathematics at 12, or does the independent variance in this trait emerge with the increased complexity of the subject? (3) What is the etiology of this “Pure Mathematics” variance? One hypothesis is that individual differences in mathematics, not associated with reading or *g*, would be highly genetic. On the other hand, with a specialist mathematics teacher providing mathematical education for the first time, the contribution of shared environment might become particularly important. As many children move to a different school between the ages of 10 and 12, an additional source of environmental, potentially non-shared influence may be new peers.

The etiology of “Pure Mathematics” was explored at 12 years of age. Univariate genetic analysis was used to estimate genetic and environmental influences on mathematical scores after controlling for the effects of reading and *g*. It was hypothesized that by removing the overlapping variance of reading and *g*, will lead to a change in the estimates of genetic and environmental influences on mathematical variation at this developmental stage.

2. Methods

2.1. Participants, measures and analyses

The Twins Early Development Study (TEDS) is a sample of twins born in the United Kingdom (UK) between 1994 and 1996 [20]. TEDS sample is considered a good representative of the UK population in terms of ethnicity and socio-economic status [9]. At the age of 12 the twins were assessed using a web-based battery. Mathematical skills assessed achievement levels required by the UK NC [21]. Teachers filled questionnaires providing an additional measure of the children mathematical achievement on 4 mathematical aspects. Reading was assessed with 2 tests of reading comprehension (PIAT [22]; GOAL [23]) and 2 tests of reading fluency (WJ-III [24]; TOWRE-words and non-words subtests [25]). General cognitive ability (*g*) was assessed with two verbal tests (General Knowledge and Vocabulary from WISC-III-PI [26]) and two non-verbal ability tests (Picture Completion [27]; Raven's Standard Progressive Matrices [28]). Prior to any analysis, all the twins with severe medical problems such as cerebral palsy, Down syndrome or autism and for which English was not the first language, were excluded from the analysis. The final sample was constituted of 13,262 twins (6,631 pairs), of which 4,636 were MZ (2,318 pairs), 8,626 (4,313 pairs) were DZ, with a mean age of 11.71. Twin analyses were conducted using standard ACE univariate model-fitting in OpenMx software [29]. The twin method and model-fitting procedures are described elsewhere [30].

2.2. Results

Mean and standard deviation on unstandardised data were as follow: Mathematics web test, M=67.11, SD=14.78 out of 95 trials; PIAT, M=58.03, SD=10.64 out of 82; GOAL, M=23.53, SD=6.37 out of 36; WJ-III, M=58.41, SD=13.38 out of 98; TOWRE, M=71.71, SD=10.87 out of 54 trials for the word-subtest and M=41.95, SD=11.41 out of 85 for non-words; General Knowledge, M=21.37, SD=4.22 out of 30; Vocabulary, M=39.77, SD= 10.12 out of 30; Picture Completion, M=19.99, SD=3.88 out of 30; Raven, M=10.81, SD=3.50 out of 24.

Phenotypic correlations of all unstandardised scores ranged between .33 and .55 ($p<.01$, 2-tailed). The magnitudes of these correlations justified the creation of composite variables. First, all the scores were standardised, then distinct composite-variables of cognitive ability, *g*, and of reading were obtained by averaging the standardised means of the 4 general cognitive tests and of the 5 reading scales. The correlation between the Mathematical web test with reading and *g* composites was .55 and .61 respectively. Between reading composite and *g* the correlation was .54 ($p<.01$, 2-tailed). Mathematics Teachers' rating questionnaires correlated among each other between .93 and .96 ($p<.01$, 2-tailed); therefore a unique score of Mathematics Teachers' Rating was obtained from the unrotated first principal component of the 4 questionnaires. This factor explained 95.7% of the total variance. The correlation between Mathematics web scores and Mathematics Teachers' Rating was .55 ($p<.01$, 2-tailed). Therefore, a composite score was created averaging the standardised means of the Mathematical web test scores and the composite from the teachers' ratings. The variance in common with reading and *g* was removed from this new composite of mathematics and from the Mathematical web scores. This created two 'Pure Mathematics' variables: Pure Mathematics web and Pure Mathematics web+teacher. Twins are perfectly correlated in age and sex and this correlation can inflate estimates of the shared environment [31]. For this reason variables and the composite scores were corrected for age and sex. Scores outside +/-3 standard deviations were considered outliers and removed from the analyses. A series of ANOVAs tested the significance of the mean effects of sex and zygosity and their interaction on all variables. No effects of sex or interaction with zygosity were significant in any of the measures. The effects of zygosity were significant on both reading and *g* composites, with MZ twins showing lower average performance than DZ twins. However, the effects size were very small, with zygosity accounting for less than 1% of the variance ($\eta^2=.00$).

The intraclass correlations, indexing twins' similarity on Mathematics and on the two Pure Mathematics variables, are shown in Table 1. MZ correlations were higher than DZ correlations for all variables, suggesting genetic influences. The significance of the genetic influences was indicated from the lack of overlap between the confidence intervals between MZ and DZ intraclass correlations.

Table 1. Intraclass correlation for Mathematics web scores and Pure Mathematics, parameter estimates and 95% Confidence Intervals

Measure	Model	Univariate model fitting				Intraclass Correlations		Parameter estimates & confidence intervals		
		-2LL	*df*	*(Δ-2LL)*	*AIC*	*MZ - I.C. (C.I)*	*DZ - I.C. (C.I)*	*Variance of A (C.I)*	*Variance of C (C.I)*	*Variance of E (C.I)*
Mathematics Web test	S.M.	23781.27	9269	--	5243.27	.66	.42	.52	.16	.32
	ACE	**23787.29**	**9275**	**-6.02**	**5237.27**	(.64 - .69)	(.39 – 45)	(.44 - .59)	(.10 - .22)	(.30 - .35)
	AE	23812.62	9276	-31.35	5260.63					
Pure Mathematics web test	S.M..	18083.38	6764	--	4555.38	.44	.21	.44	N/A	.56
	ACE	18087.66	6670	-4.28	4547.66	(.39 - .49)	(.17 – 25)	(.40 - .48)		(.52 - .60)
	AE	**18087.66**	**6671**	**-4.28**	**4545.66**					
Pure Mathematics web+teacher	S.M..	10902.61	4087	--	2728.61	.59	.29	.62	N/A	.38
	ACE	10904.82	4093	2.21	2718.83	(.54 - .64)	(.24 - .35)	(.57 - .66)		(.34 - .43)
	AE	**10904.82**	**4094**	**2.21**	**2716.83**					

S. M. = Saturated Model; ACE, AE = nested models; -2LL = minus 2log-likelihood; df = degrees of freedom; Δ-2LL = difference in log likelihood between the Saturated Model and the nested models; MZ = monozygotic twins; DZ = dizygotic twins; I.C. = Intraclass correlation; C.I. = 95% confidence intervals (in brackets); A = variance explained by genetic factors, C = variance explained by shared environmental factors, E = variance explained by non shared factors plus the error model; AIC = Akaike's information criterion. For Mathematics web scores, the best fit is provided by the ACE model. For the two Pure Mathematics variables, the best fits are the AE models: with no significant decrease in likelihood (Δ-2LL) two estimated parameters fit the data as well as three estimated parameters. The better fit is confirmed by the smaller AIC index. Better fitting models are indicated in bold characters.

The influences of genetic, shared and non-shared environmental factors were estimated carrying out a univariate genetic analysis, the parameter estimates are reported in Table 1. Summary of the model fit comparison is also presented in Table 1. Individual differences in Mathematics web test scores (which included the variance in common with reading and *g*) were explained mostly by genetic influences (.52), with non-shared environment of .32 and very modest but significant influence of shared environment (.16). Shared environmental influences on the Pure Mathematical scores (web test, and web+teacher composite) were non-significant. Individual differences in Pure Mathematical web scores were explained by genetic and non-shared environmental influence in almost equal measure (.44 and .56 respectively). In the Pure Mathematics web+teacher composite, there was a stronger genetic contribution (.62) compared to non-shared environmental influences (.38).

3. Discussion

The aim of this study was to use quantitative genetics to investigate the etiology of individual differences in Mathematics and in Pure Mathematics (a variable obtained by removing the phenotypic variance shared by mathematics with reading and g). The results revealed that at 12 years of age, mathematics is a heritable trait (.52), with moderate non-shared environment (.32) and very modest shared environmental influences. These heritability estimates are consistent with previous TEDS estimates, suggesting stable genetic influences in mathematics across development. The concepts involved in mathematics become more abstract and more complex as children progress in their academic journey. However, the results of this investigation show that genetic influences in mathematics are highly similar at ages 12, 10 and 7. Stable genetic influences indicate that environmental influences do not become more or less important in mathematics, despite the changes in the trait of study. Starting at the age of 12, in the UK school mathematical education is delivered by specialist mathematical teachers. This change in the objective-mathematical environment does not seem to contribute to a change in the amount of objectively relevant environments (shared environments) to individual differences in mathematics. It is possible that the structured UK National Curriculum and the homogeneous training of mathematical teachers contribute to the stability of the trait, whereas genetic influences contribute to individual differences. The experiences unique to each individual (non-shared environments) also contribute to children's differences, almost in the same amount, at the ages of 7, 10 and 12. Given the genetic and phenotypic overlap of mathematics with other abilities, it is also important to understand whether the observed stability in heritability estimates is mediated by other abilities. It is possible that later mathematical ability is supported more by reading skills, reasoning, and general intelligence than earlier mathematics. Our results suggest that this is not the case. After removing the variance shared between mathematics, reading and *g*, what is left in terms of mathematical variation, is still heritable. This means that similarly to what was previously found for mathematics at the age of 7 and 10 [8], [9], some genetic influences are specific to mathematics at the age of 12. This study reported higher mathematics-specific genetic influences compared to the ones reported at the age 7 and 10. It is possible that later mathematics (at 12) shares less genetic influences with other domains than the earlier mathematics. Alternatively, the different estimates may be partially due to the different mathematical components assessed at the different ages [10], [32]. Pure Mathematics of web scores was less heritable than when teacher-rated school achievement was included in the composite. This difference may reflect the wider range of skills assessed by school achievement over time compare to web tests. Alternatively, a rating bias of teachers may inflate MZ correlation - resulting in higher heritability estimates. Despite some discrepancy in genetic estimates, that involved web and teacher rating, the measures of "Pure Mathematics" showed the absence of shared environmental influences. Only individual-specific, rather than family or school-wide environmental experiences showed influences on unique variance in mathematics

The existence of mathematical variance independent from other reading and *g*, calls for more research aiming at identifying the sources of such variance. It is possible that some of this variance may be shared with other abilities not measured in this study. This hypothesis would be in line with the Generalist Genes Hypothesis, however it is not excluded that some of this unexplained variance may be mathematics specific. Future research should address this issue. Comprehension of the sources of mathematical skills that are independent from other abilities, could clarify the mechanisms that facilitate mathematical acquisition. In turn, this information could guide changes in the way we conceptualise and teach mathematics. It could also lead to efficient screening for predicting individual variation in mathematics skills and apply suitable individualized environmental interventions.

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