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Confirmatory Factor Analysis of Reading and Mathematics Performance: A Twin Study

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Abstract. Reading and mathematics performance data from a sample of 264 reading-disabled twin pairs and 182 matched control twin pairs were subjected to multivariate behavior genetic analysis. The factor structure of reading and math performance measures was found to be highly similar for both groups. Consistent with previous findings obtained using alternative methods, a significant heritable component to individual differences in reading performance was found both within the reading-disabled ($h^2 = 0.78$) and control ($h^2 = 0.74$) twin samples. In addition, a substantial genetic influence on mathematics performance was found ($h^2 = 0.51$ and 0.60 in the reading-disabled and control samples, respectively), although shared environmental influences common to both members of a twin pair also contribute significantly to the variance in math scores of both groups ($c^2 = 0.44$ and 0.37). Moreover, genetic influences accounted for 98% of the observed correlation between reading and math performance within the sample of reading-disabled twin pairs, and for 55% of the observed correlation in the control sample. Thus, individual differences in both reading and mathematics perfomance are highly heritable and appear to be caused by many of the same genetic influences.

Key words: Confirmatory factor analysis, Genetic correlation, Heritability, Math performance, Reading disability, Twins.

INTRODUCTION

A major goal of the Colorado Reading Project [8] has been to use the methodology of behavioral genetics to assess the genetic and environmental etiologies of reading disability. Since 1982, a test battery that includes measures of cognitive abilities and of reading and language processes has been administered to a sample of identical (monozygotic, MZ) and fraternal (dizygotic, DZ) twins in which at least one member of each pair is reading disabled, and to members of MZ and DZ twin pairs in which the children are normal readers. Twin pairs are systematically and objectively ascertained from cooperating school districts within the state of Colorado. Irrespective of reading status, all twin pairs within a school district are identified and permission is sought from parents to review the twins' school records for evidence of reading problems. If either member of a pair manifests a positive school history of a reading problem (eg, a low reading achievement test score or referral to a reading therapist because of low reading performance), both members of the pair are invited to complete an extensive test battery that includes measures of reading and mathematics performance. A discriminant function score is computed for each individual employing discriminant weights estimated from an analysis of Peabody Individual Achievement Test (PIAT) on Reading Recognition, Reading Comprehension, and Spelling data [11] obtained from an independent sample of 140 children with reading disability and 140 control nontwin children [3]. Twin pairs are included in the proband sample if at least one member of the pair with a positive history of reading problems is also classified as affected by the discriminant score, has a Verbal or Performance IQ score of at least 90, and has no evidence of neurological, emotional or behavioral problems, and no uncorrected visual or auditory acuity deficits. A comparison sample of control twin pairs (matched to probands on the basis of age, gender, and school district) is also tested.

As of June 30, 1992, a total of 133 pairs of MZ twins and 98 pairs of same-sex DZ twins met the criteria for inclusion in the proband sample (ie, at least one member of the pair of twins was reading disabled). These twins ranged from 8 to 20 years of age at the time of testing and all had been reared in English-speaking, middle-class homes. Discriminant function score data (a composite measure of reading performance) from the proband sample were recently subjected to multiple regression analysis [10].

Multiple regression analysis of selected twin data offers a highly flexible and statistically powerful method of testing for genetic etiology. The logic of the multiple regression approach stems from the fact that MZ twin pairs share 100% of their genes, whereas DZ twin pairs share, on average, 50% of their segregating genes. If probands are selected due to deviant scores on a continuous measure such as reading performance, the scores of both MZ and DZ cotwins are expected to regress toward the mean of the unselected population. However, MZ and DZ cotwins will show differential regression to the unselected population mean, if genetic factors are important in the etiology of reading performance. Thus, to the extent that reading performance is heritable, the scores of DZ cotwins should regress more toward the unselected population mean than those of MZ cotwins.

DeFries and Fulker [4,6] formulated two regression models:

$$C = B_1P + B_2R + A, \qquad (1)$$

and

$$C = B_3P + B_4R + B_5PR + A, \qquad (2)$$

where C is the cotwin's score, P is the proband's score, R is the coefficient of relationship (R = 1.0 for MZ twin pairs and 0.5 for DZ twin pairs), and PR is the product of the proband's score and relationship. The B_2 coefficient is the partial regression of the cotwin's score on the coefficient of relationship and equals twice the difference between the MZ and DZ cotwin means, after covariance adjustment for any difference between MZ and DZ proband means. Thus, the B_2 coefficient provides a direct test for genetic etiology. Transformation of the data, prior to multiple regression analysis [7], facilitates a direct estimate of h^2_g, the extent to which the observed proband reading deficit is heritable. When equation 2 is fit to twin data, the B_3 coefficient provides a direct estimate of c^2, that is, the extent to which individual differences in reading performance in the normal range are due to environmental influences shared by both members of a twin pair. Similarly, the B_5 coefficient provides an estimate of h^2, the extent to which individual differences in reading performance in the normal range are due to heritable influences.

In the Colorado Reading Project, the average discriminant scores of the MZ and DZ probands are highly similar and over 2.5 standard deviations below the mean of the unaffected control twins. However, scores of MZ and DZ cotwins regressed differentially toward the population mean. Scores of MZ cotwins regressed, on average, 0.24 standard deviations toward the control mean, whereas those of DZ cotwins regressed 0.87 standard deviations units. When equation 1 was fitted to transformed discriminant function data from the proband sample, $h^2_g = 0.50 \pm 0.11$ ($p < 0.001$), suggesting that about one-half of the reading performance deficit of the probands was due to heritable influences. When equation 2 was fitted to the discriminant function data from the proband sample, $B_5 = h^2 = 0.73 \pm 0.35$ ($p < 0.05$) and $B_3 = c^2 = 0.11 \pm 0.29$ ($p < = 0.71$). These results suggest that genetic factors are an important cause of the individual differences in reading performance within the selected group, but that environmental influences shared by members of twin pairs are not an important source of variation.

Co-investigators of the Colorado Reading Project recently initiated a new Learning Disabilities Research Center [9]. A major goal of this more comprehensive research program is to assess the genetic and environmental etiologies of both reading and mathematics disabilities, as well as their covariation with measures of reading and language processes, ADHD, and executive functions. The etiology of the comorbidity of reading and mathematics disabilities is of special interest. Although the majority of learning-disabled (LD) students manifest deficits in reading, about 10% have a specific deficit in mathematics or quantitative reasoning. In about 50% of LD children, reading and math problems are concurrent [17,19,24]. The overlap between reading and mathematics performance within learning disabled populations has been well-documented [2,16,19,24]. However, the nature of the relationship between reading and mathematics within these populations is not well understood. Bryant and Bradley [1] found that in problem readers the cognitive and neuropsychological predictors of reading achievement are highly similar to those that predict arithmetic achievement. A number of studies focusing on reading and/or math disabled children have reported that verbal ability plays a stronger role in learning disabilities in mathematics than previously hypothesized. Specifically, the data suggest that poor achievement in mathematics may be largely attributable to the same language-based deficits that underlie poor reading achievement [16,25,26]. For example, Muth [20] suggests that poor arithmetic achievement may be due to poor reading skills in general. By experimentally manipulating the computational and reading demands of a series of arithmetic problems, she found that

14% of the variance explained was uniquely attributable to reading skills, 8% was attributable to computational skills, and 32% to joint variance. Similarly, Rourke and Strang [24] argue that the difficulties reading-and-math-disabled children have memorizing tables and memorizing procedural steps in problem solving are reflections of verbal impairments.

In order to begin to assess the etiology of covariation between reading and mathematics performance measures, we recently subjected data from proband and control twin pairs to multivariate behavior genetic analysis. The purpose of the present study is to reportes h^2 and c^2 estimates for measures of both reading and math performance, as well as to examine the covariation between reading and mathematics scores using the structural modeling program LISREL.

METHOD

Subjects

Subjects in the present study included twin pairs in the Colorado Reading Project (CRP) [3] for whom complete reading and math performance measures were available. Twin pairs in the CRP were identified from 27 cooperating school districts within a 150-mile radius of Denver, Colorado. Once a pair was identified, parental permission was sought to examine the twins' school records for evidence of reading problems (eg, low standardized test scores, referral to a remedial reading program, or referrals from classroom teachers or school psychologists). Twin pairs were then invited to come to the University of Colorado where they were administered an extensive battery of psychometric tests. Included in this were the Wechsler Intelligence Scale for Children-Revised (WISC-R) or the Wechsler Adult Intelligence Scale-Revised (WAIS-R) and the PIAT [30,31,11]. For the present study, the reading-disabled sample includes twin pairs in which at least one member had a positive history of reading problems in school, no diagnosed neurological, emotional, or behavioral problems and no uncorrected auditory or visual problems which could account for low reading performance. The control twin sample was matched to the reading-disabled sample on the basis of age, gender and school district, and includes twin pairs in which both members had a negative history of reading problems in school. Zygosity of the twin pairs was determined using selected items from the Nichols and Bilbro zygosity questionnaire [23] which has a reported accuracy of 95%. In doubtful cases, zygosity was determined by blood sample analysis. All twins participating in the Colorado Reading Project were school-age at the time of testing and all came from middle-class homes in which English was the primary language spoken.

In the present study, 150 MZ twin pairs and 114 same-sex DZ twin pairs had at least one member in each pair with evident reading problems in school. Complete reading and mathematics performance data were available for all. The matched control twin sample includes 108 MZ and 74 same-sex DZ twin pairs having complete reading and mathematics data.

Tests

An exploratory factor analysis of the subtests of the Colorado test battery was undertaken separately for the reading-disabled and control twin data. The reading measures included three subtests of the PIAT [11], Reading Recognition, Reading Comprehension, and Spelling. In the Reading Recognition subtest, subjects are asked to read a series of words aloud and are scored on correct pronunciation. In the Reading Comprehension subtest, subjects read a series of short passages silently after which they must choose one of four pictures best illustrating the passage they have just read. In the Spelling subtest, testers orally present words and subjects must choose the correctly spelled word from four possible choices. The subtests chosen to measure mathematics performance included the PIAT Mathematics subtest, the Arithmetic subtest of the WISC-R or WAIS-R [30,31] and the Spatial Relations subtest of the Primary Mental Abilities Test (PMA) [29]. In the Mathematics subtest of the PIAT, math problems are read aloud and subjects must select the correct answer from four possibilities. In the Arithmetic subtest of the WISC-R or WAIS-R, testers again read math problems aloud, but in this instance, subjects must generate the correct answer without the help of a visual aid. Lastly, in the Spatial Relations subtest, subjects are shown a 2-dimensional line drawing and five similar line drawings which may be in a different orientation. Subjects must select those drawings which are in a simple clockwise rotation of the original line drawing.

Analyses

Covariance matrices (6×6) were computed among the reading and math performance measures for reading-disabled and control twins separately. The resultant data were fit to a phenotypic model (see Fig. 1) in LISREL [12] using the method of maximum likelihood. It allowed for two latent factors underlying the 6 observed measures, as well as 6 specific error variances. Because reading and mathematics performance is correlated, the latent factors were also allowed to be correlated. This model provides a confirmatory factor analysis of the fit of the model to the observed data. The model was fit to the reading-disabled and control twin data separately, yielding a χ^2 and goodness-of-fit index for each group. A general model was then fit to the combined data sets that yielded separate parameter estimates for the two groups. Then, the parameter estimates for the phenotypic model were constrained to be equal across the reading-disabled and control groups. A comparison of the χ^2 value from the general model, estimating separate parameters for the two groups, with the χ^2 obtained from the nested model, equating the parameters across groups, facilitated a test of the hypothesis that the factor structure, underlying reading and math performance measures at the phenotypic level, is the same for a group of reading-disabled twins and for a matched sample of control twins. Although LISREL is not entirely appropriate for the analysis of data from selected samples, minimal selection criteria were used to ascertain the reading-disabled subjects (positive school history of reading problems). Furthermore, the reading and math performance measures were normally distributed within both the reading-disabled and control samples.

As shown in Fig. 2, the phenotypic model was then decomposed to include genetic, common environmental, and specific environmental influences on reading and math performance, and on their covariance. The latent reading and math factors are correlated at the genetic, common environmental, and specific environmental levels through *aa'*, *bb'*, and *cc'*, respectively. Thus, these influences are common to both reading and math performance. In contrast, the *d'*, *e'*, and *f'* paths represent genetic and environmental influences on math performance that are independent of reading performance.

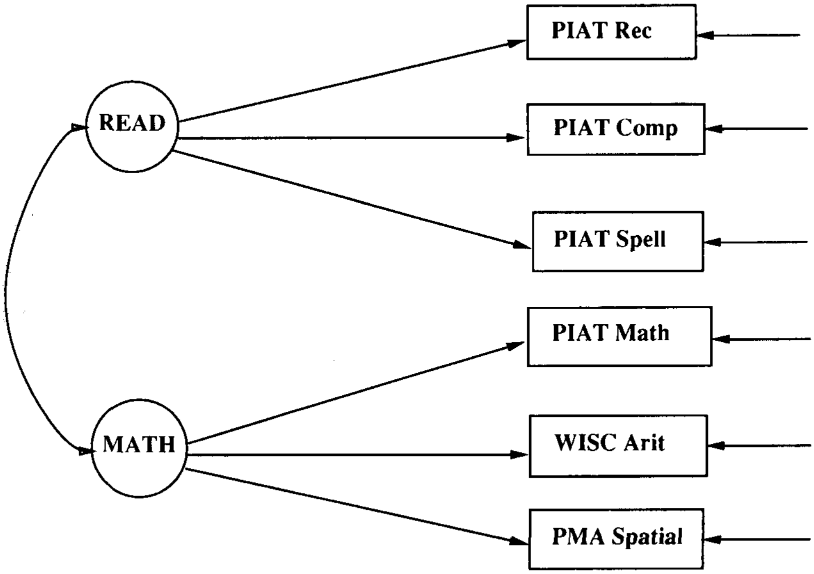

Fig. 1. Phenotypic factor structure of reading and mathematics performance measures.

From this model, we obtain estimates of the proportion of variance in reading and mathematics performance scores that are due to genetic, shared environmental, and specific environmental influences.

Two 12×12 covariance matrices (one for MZ and one for DZ twin pairs) were computed among Twin 1 and Twin 2 reading and math performance measures. Again, a general model was fit to data from the combined sample of reading-disabled and control twin pairs. The resulting χ^2 estimate was then compared to χ^2 estimates obtained from a series of nested submodels. Specifically, we tested (1) a model equating all the parameters across the reading-disabled and control groups, (2) models in which we dropped the genetic influences common to reading and math, (3) models in which we dropped the shared environmental influences common to reading and math, and (4) a model in which we dropped the genetic influence on math that is independent of reading.

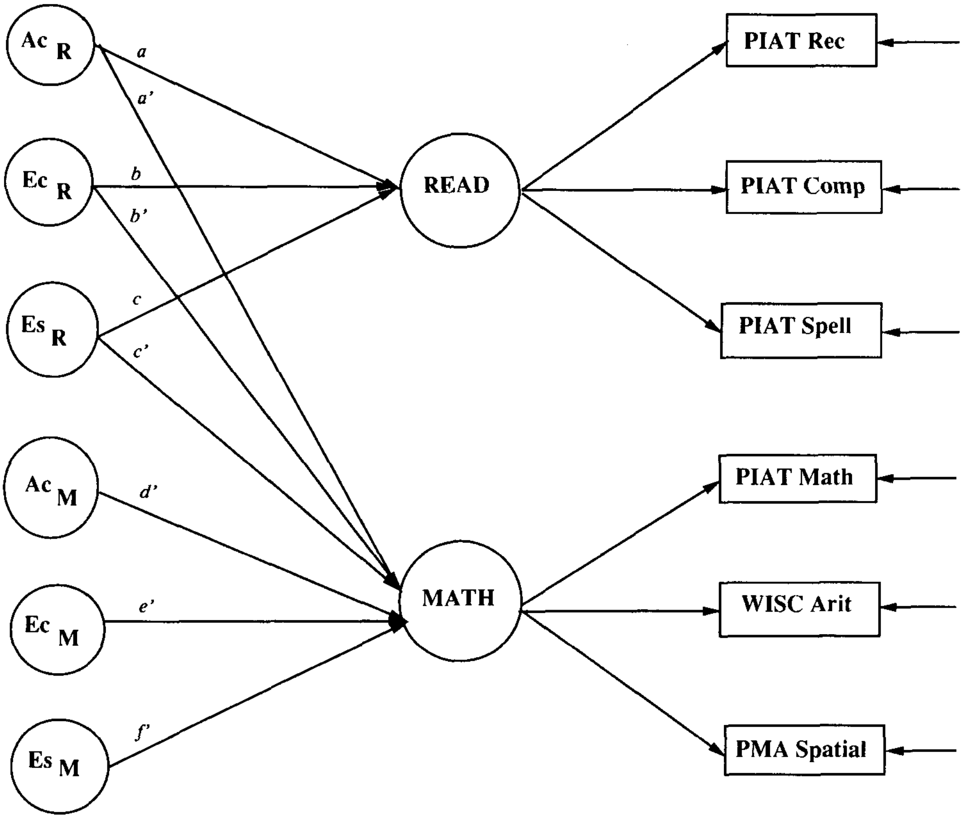

Fig. 2. Genetic and environmental factor structure of reading and mathematics performance data for one twin.

RESULTS

The phenotypic correlation between the reading and math factors was highly similar for the reading-disabled and control groups, 0.54 ($p<0.001$) and 0.55 ($p<0.001$), respectively. Other parameter estimates were also found to be highly similar for the reading-disabled and control groups. The goodness-of-fit statistic for this model was 0.98 in both groups, suggesting that the model adequately explains the observed data. Despite an adequate model fit, the chi-square estimates for the phenotypic model were significant. Because chi-square estimates are directly dependent on $\underline{N}$, the chi-square estimates of 36.44 (df = 8) and 22.28 (df = 8) reported for the RD and control groups, respectively, are primarily due to our large sample sizes [18]. The observed parameter estimates were then constrained across the RD and control groups without a significant deterioration in model fit ($\Delta\chi^2 = 18.80$, $\Delta df = 13$, $p > 0.05$). Parameter estimates from the equated model are shown in Fig. 3. The correlation between the reading and math factors in this model is 0.54 ($p < 0.001$). Thus, at the phenotypic level, the factor structures underlying reading and math performance appear to be congruent for a sample of reading-disabled probands and their cotwins and for a matched sample of control twin pairs.

The model was then partitioned into a genetic, common environmental, and specific environmental component. Again, separate parameter estimates were obtained for the reading-disabled and control twins. The proportions of variance in reading and math performance factors due to genetic (h^2), shared environmental (c^2), and specific environmental (e^2) influences were estimated and are summarized in Table 1. Consistent with previous analyses of reading performance data [5], we find a high heritability estimate for the reading factor in both the reading-disabled and control twin samples, 0.78 and 0.74, respectively. This suggests that individual differences in reading performance are substantially influenced by genetic factors regardless of reading ability. Moreover, shared environmental influences on reading appear to be negligible while specific environmental influences are moderate for both the reading-disabled and control groups. Thus, as was the case in the phenotypic model, parameter estimates for the reading-disabled and control groups are highly similar.

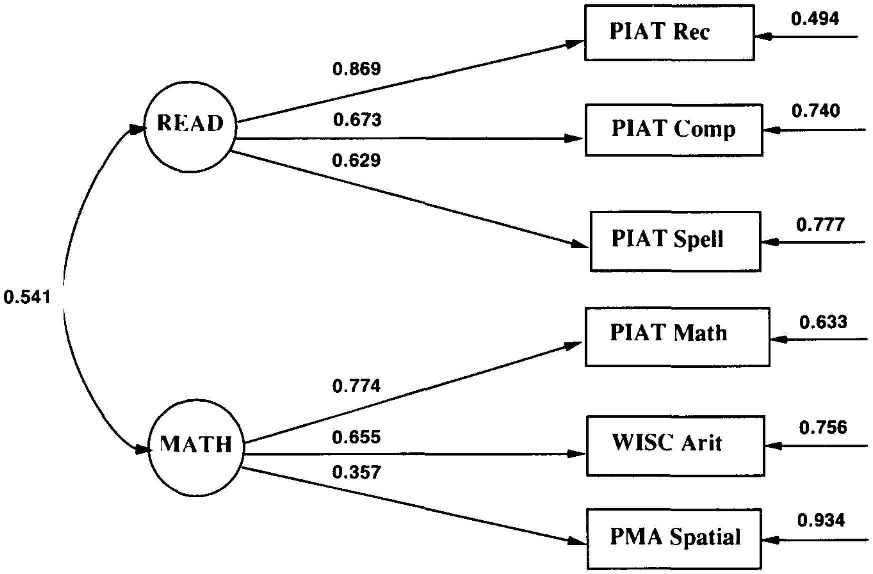

Fig. 3. Phenotypic factor structure of reading and mathematics performance measures with parameter estimates equated across reading-disabled and control twin samples.

With regard to math performance, the genetic, common environmental, and specific environmental influences are divided into those influences shared with reading (paths *a*', *b*', and *c*' in Fig. 2), and those influences independent of reading (paths *d*', *e*', and *f*'). Looking first at the environmental influences on mathematics, we note that both the

Table 1 - Proportion of variance in reading and mathematics performance factors due to genetic and environmental influences

	Reading-disabled No. pairs = 264			Control No. pairs = 182		
	h^2	c^2	e^2	h^2	c^2	e^2
Reading	0.78	0.04	0.18	0.74	0.09	0.17
Math[a]	0.37	0.44	0.05	0.12	0.37	0.03
Math[b]	0.14			0.48		

[a] Influences on math performance shared by reading performance.
[b] Influences on math performance independent of reading.

shared and specific environmental influences on mathematics, independent of reading, are negligible. Of the environmental influences on mathematics shared with reading, the common environmental influence is substantial, with c^2 estimates of 0.44 and 0.37 reported for the reading-disabled and control samples, respectively. In contrast, the specific environmental influence is negligible for both groups. Although the pattern of genetic influences on mathematics shared with reading and those independent of reading appear to be slightly different across the reading-disabled and control samples, there is a substantial overall genetic influence on mathematics performance scores in both the reading-disabled ($h^2 = 0.51$) and controls ($h^2 = 0.60$).

Phenotypically standardized correlations between reading and math performance factors are presented in Table 2. The phenotypically standardized genetic correlation, r_g, has been weighted by the square root of the heritability estimates for the two factors shown as paths *a* and *a*', respectively. Similarly, the shared environmental correlation (r_c) has been weighted by the square roots of the c^2 estimates, paths *b* and *b*', and the specific environmental correlation, (r_e), has been weighted by the square roots of the e^2 estimates, paths *c* and *c*'. Each phenotypically standardized correlation, when divided by the phenotypic corrrelation observed between the two factors, estimates the proportion of the observed correlation due to genetic, shared environmental, and specific environmental influences. For example, in the reading-disabled sample, the phenotypically

Table 2 - Phenotypically standardized genetic and environmental correlations between latent reading and mathematics performance factors

	r_g	r_c	r_e	N_{pairs}
Reading-disabled	0.53	-0.13	0.10	264
Control	0.30	0.18	0.07	182

standardized genetic correlation is 0.53. When divided by the phenotypic correlation observed in this sample, ie. 0.54, the resulting ratio of 0.98 suggests that the observed relationship between reading and math performance in this population is due almost entirely to genetic influences. Similarly, in the control group, the genetic correlation of 0.30 divided by the phenotypic correlation observed in this sample (0.55), suggests that genetic influences account for approximately 55% of the observed covariation between reading and math performance within the control twin sample.

The general model, which estimated separate parameter estimates for the RD and control groups, was first tested against a model which constrained the parameters to be equal across the two groups. As shown in Table 3, the parameter estimates could be equated across the reading-disabled and control groups without a significant loss in model fit ($\Delta\chi^2 = 26.12, \Delta df = 17$, $p > 0.05$). Resulting parameter estimates are shown in Fig. 4. This model was then compared to a series of nested submodels in order to assess more parsimonious models. Whereas shared environmental influences appear to be negligible for reading and can be dropped from the model without a significant loss in fit ($\Delta\chi^2 = 0.82, \Delta df = 1$, $p > 0.25$), they contribute significantly to the variance in mathematics performance scores ($\Delta\chi^2 = 7.73, \Delta df = 1$, $p < 0.01$). Consistent with our previous findings, the genetic influence on the variance in reading scores is significant ($p < 0.001$). Similarly, the genetic influence on math that is shared with reading is also significant ($\Delta\chi^2 = 24.54, \Delta df = 1$, $p < 0.001$). However, the genetic influence on math independent of reading is not significant and was dropped from the model ($\Delta\chi^2 = 3.63, \Delta df = 1$, $p > 0.05$). Thus, individual differences in math and reading performance appear to be due largely to the same genetic and environmental influences in both a sample of reading-disabled and matched control twin pairs.

Table 3 - Model fitting results

Model	df	Δdf	χ^2	$\Delta\chi^2$	p
Full model	278		653.91		<0.005
Equate model across groups	295	17	680.03	26.12	>0.05
Drop c Read (*b*)	296	1	680.85	0.82	>0.05
Drop c Math (*b*')	296	1	687.76	7.73	<0.01
Drop h Read (*a*)	296	1	733.88	53.85	<0.001
Drop h Math (*a*') (shared)	296	1	704.57	24.54	<0.001
Drop h Math (*d*') (specific)	296	1	683.66	3.63	>0.05

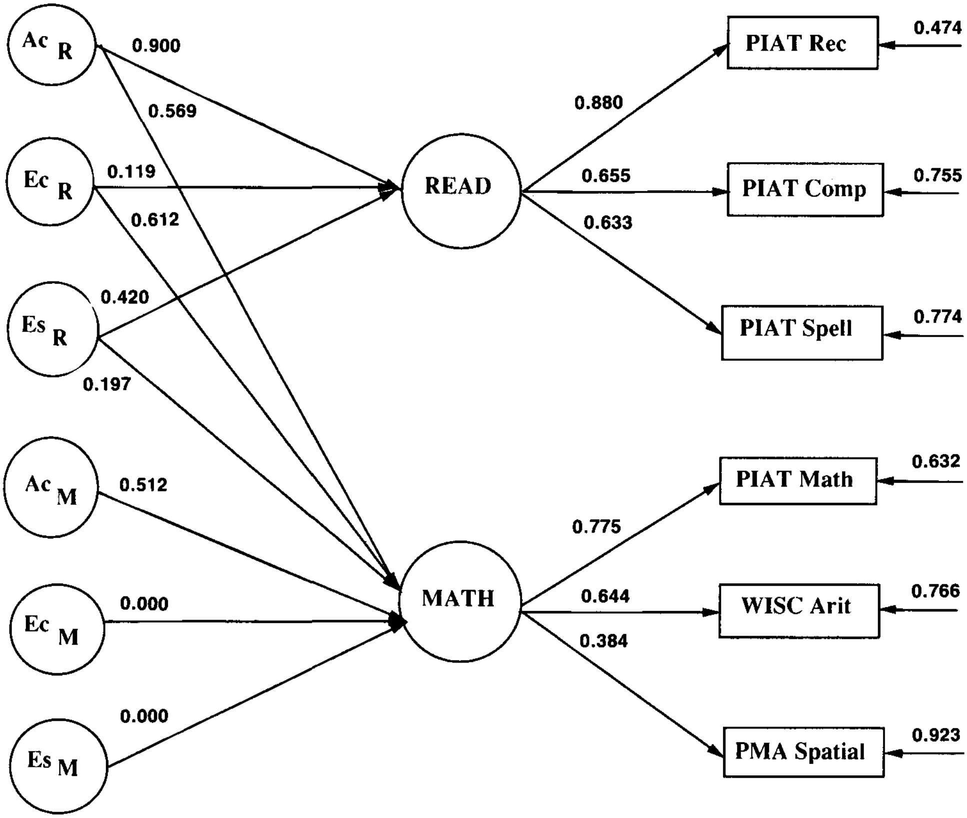

Fig. 4. Genetic and environmental factor structure of reading and mathematics performance measures after equating parameter estimates across reading-disabled and control twin samples.

DISCUSSION

Results of the present study suggest that the genetic and environmental influences underlying reading and math performance are similar for a sample of reading-disabled and matched control twin pairs. Heritability estimates for the reading factor are 0.78 and 0.74 for the reading-disabled and control sample, respectively, a result that is consistent with our previous findings [7,15]. Genetic influences on mathematics performance scores are also substantial, with heritability estimates of 0.51 and 0.60 for the reading-disabled and control groups, respectively. Of particular interest is the etiology of the observed covariance between reading and mathematics performance. The observed correlation between reading and mathematics (0.54) is due largely to genetic influences in both the reading-disabled and control sample, ie. genetic influences accounted for 98% of the correlation between reading and math in the reading-disabled sample, and for

55% of the correlation in the control sample. A similar finding was recently reported by Thompson et al [28] in a study of the genetic and environmental components of achievement and cognitive abilities in a school-age sample. In this study, the genetic correlation between reading and mathematics performance was 0.98, again suggesting that individual differences in reading and mathematics performance are due to the same genetic influences.

A bivariate form of the basic multiple regression model of DeFries and Fulker [4] can also be used to assess the etiology of observed differences in math performance between reading-disabled probands and controls. In the bivariate application, probands are selected for one variable (eg, low reading performance) and cotwins are measured for another variable (eg, math performance). When the basic regression model is fitted to such data, B_2 estimates the standardized genetic covariance between the two variables, ie. a measure of the extent to which the difference between probands and controls *in math performance is due to genes that also influence reading performance* [8]. The bivariate application of the multiple regression approach has recently been applied to reading and math performance measures from 103 MZ and 69 same-sex DZ twin pairs, in which, at least one member of the pair was reading-disabled (unpublished). The B_2 estimate of 0.20 ± 0.11 was significant ($p = 0.04$, one-tailed). This result is consistent with the findings of the present study and suggests that the observed phenotypic covariance between math scores and reading disability is due, at least in part, to genetic influences.

Another finding of the present study is the importance of shared environmental influences on the variance in math performance scores. The c^2 estimates for the math factor were 0.44 and 0.37 for the reading-disabled and control samples, respectively. Math performance encompasses a variety of independent skills which are learned sequentially, eg, skills such as addition/subtraction, multiplication/division, algebra, and geometry are taught during different developmental stages and performance on these tasks may be subject to shared environmental influences. In a recent summary of the current state of mathematics achievement in the United States, the National Center for Education Statistics [21] recently reported that «Students in homes with resource materials such as newspapers, magazines, and books had higher average mathematics proficiency, as did students who read more pages each day for school and homework». A number of studies have also reported that childrens' success in mathematics appears to be influenced by the instruction they receive in school [13]. Newman and Stevenson [22] found «student perceived performance on math tests, compared with reading tests, to be more strongly linked to whether they received sufficient help from the teacher in learning the material». Thus, environmental factors such as teaching protocol or parental support in academics may have important influences on one's later performance in mathematics.

A limitation of the present study is the lack of data on children with mathematics disabilities. Previous studies have reported distinct cognitive profiles for reading-disabled, specific math-disabled, and reading-and-math-disabled populations [14,25,27]. The underlying genetic and environmental influences affecting the relationship between reading and mathematics performance may also be different in these populations. We are currently collecting data on specific math-disabled and reading-and-math-disabled twin pairs in the Colorado Learning Disabilities Research Center. Thus, in the future, we will assess the etiology of mathematics deficits and their comorbidity with reading problems in more detail.

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