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Cognitive Ability and Academic Achievement in the Colorado Adoption Project: A Multivariate Genetic Analysis of Parent–Offspring and Sibling Data

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To test the hypothesis that the etiology of covariation among measures of cognitive ability and academic achievement is due at least in part to shared genetic influences, data from 198 adoptive and 220 nonadoptive families participating in the Colorado Adoption Project were subjected to multivariate behavioral genetic analyses. Data on measures of cognitive ability (verbal comprehension and perceptual organization) and academic achievement (reading recognition and mathematics achievement) from related and unrelated sibling pairs tested at age 7, as well as from adoptive and nonadoptive parents, were analyzed. Phenotypic analyses confirmed previous findings of moderate correlations among measures of cognitive ability and achievement, averaging about .35. Although 54% of the covariation between reading and mathematics achievement was due to influences shared with verbal ability, a significant proportion of this covariation was independent of the cognitive ability measures. Heritabilities for the various measures were moderate, ranging from .21 to .37. Moreover, genetic influences accounted for 33–64% of their phenotypic covariation; for example, 33–60% of the observed correlations between verbal comprehension and the achievement measures, 64% of those between perceptual organization and the achievement measures, and 63% of that between reading recognition and mathematics achievement were due to shared genetic influences. Similar to the results of the phenotypic analysis, nearly half of the genetic covariance between reading and mathematics achievement was independent of cognitive ability. Their remaining covariance was due primarily to nonshared environmental influences.

KEY WORDS: Cognitive ability; achievement; multivariate analysis; genetic; adoption; parent–offspring sibling.

INTRODUCTION

Measures of intelligence are highly correlated with measures of academic achievement. Thus, one of the primary uses of intelligence tests for school-aged children has been to predict and evaluate academic achievement (Eaves and Darch, 1990). Because expected levels of achievement are based on a student's IQ, intelligence tests are routinely used to assess under- or overachievement (Oakland and Stern, 1989; McCall *et al.*, 1992) and to diagnose learning disabilities (Rutter and Yule, 1975; Shepard, 1980; Pennington *et al.*, 1992). Controversy has arisen over the use of intelligence tests for these purposes (Shepard, 1980; Pennington *et al.*, 1992; Wong, 1989; Siegel, 1989); nevertheless, IQ is one of the best predictors of academic achievement (Jensen, 1972).

Although phenotypic correlations between IQ

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and various measures of scholastic achievement are substantial, relatively little is known regarding the etiology of this relationship (Cardon *et al.*, 1990). Because educational systems attempt to foster both ability and achievement, associations between IQ and achievement measures may be mediated environmentally. In addition, the home environment (including early childhood exposure to reading, arithmetic, and problem-solving games) may also influence both ability and achievement. Alternatively, given that both IQ and measures of academic achievement are moderately heritable (Loehlin and Nichols, 1976; Plomin and DeFries, 1979; Cherny and Cardon, 1994; McGue *et al.*, 1993; Wadsworth, 1994; Wadsworth *et al.*, in press), it is equally plausible that genetic factors which influence scores on tests of general cognitive ability may also affect performance on achievement tests. Recent twin and adoption studies provide support for this hypothesis.

In a study of 86 monozygotic (MZ) and 60 same-sex dizygotic (DZ) twin pairs participating in the Colorado Reading Project, Brooks *et al.* (1990) examined the relationship between scores on the Wechsler Intelligence Scale for Children—Revised (WISC-R) or the Wechsler Adult Intelligence Scale—Revised (WAIS-R) (Wechsler, 1974, 1981) and three subtests of the Peabody Individual Achievement Test (PIAT) (Dunn and Markwardt, 1970)—Reading Recognition (REC), Reading Comprehension (COMP), and Spelling (SPELL). Multivariate analyses yielded substantial heritability estimates for both IQ and REC, .57 and .45, respectively, with shared environment accounting for only a very small proportion of the variance in each measure (.18 and .07, respectively), COMP and SPELL were found to be somewhat less heritable (.27 and .21, respectively), with shared environment accounting for 36% of the variance in SPELL but only 19% of that in COMP. Genetic influences accounted for 59–77% of the observed covariation between IQ and the reading measures, suggesting that the relationship between intelligence and reading achievement in this sample of twins is largely genetic in origin. Furthermore, there was significant genetic and environmental covariation among the reading measures independent of IQ.

Two other twin studies yielded highly similar results. Thompson *et al.* (1991) examined scores of 146 MZ and 132 same-sex DZ twin pairs on measures of specific cognitive abilities (verbal, spatial, perceptual speed, and memory) as well as on the Metropolitan Achievement Test (MAT), including measures of reading, mathematics, and language skills. Although each of the measures of specific cognitive abilities evidenced moderate to high heritabilities (ranging from .37 for memory to .74 for spatial ability), the achievement measures were less heritable, with heritabilities of .27 for reading, .17 for math, and .19 for language. However, genetic correlations among the measures of achievement and specific cognitive ability were high, averaging about .85 between verbal ability and the scholastic achievement measures. Similarly, genetic correlations between spatial ability and the achievement measures averaged .79. In contrast, the average shared environmental correlation between the measures of ability and achievement was zero. These results suggest that the phenotypic correlations among these measures of specific cognitive abilities and scholastic achievement are almost entirely genetically mediated.

In a recent study by Gillis (1993), the etiology of the interrelationships among the Kaufman Verbal Comprehension factor (VERB) (Kaufman, 1975) of the WISC-R or WAIS-R (Wechsler, 1974, 1981), phonological coding (PHON), and reading and mathematics achievement was assessed using data from 227 control twin pairs (134 MZ and 93 same-sex DZ pairs) participating in the Colorado Reading Project. Reading achievement (READ) was assessed using a composite of the PIAT Reading Recognition, Reading Comprehension, and Spelling subtests (Dunn and Markwardt, 1970). Mathematics achievement (MATH) was assessed using a composite of the PIAT Mathematics subtest (Dunn and Markwardt, 1970) and the Arithmetic subtest of the WISC-R or WAIS-R (Wechsler, 1974, 1981). Genetic analysis yielded heritability estimates of .28, .68, .42, and .69 for VERB, PHON, READ, and MATH, respectively. Shared environmental influences accounted for 49% of the variance in VERB and 26% of the variance in READ but only 1% of the variance in PHON and 6% of the variance in MATH. Furthermore, results of this study suggest that over half of the phenotypic covariation among measures of IQ and achievement is due to shared genetic influences.

Results from two recent analyses of adoption data provide further support for this hypothesis. Examining data from a sample of 119 adoptive and

120 nonadoptive families participating in the Colorado Adoption Project (CAP), Cardon *et al.* (1990) investigated the etiology of the relationship between IQ and Reading Recognition employing a multivariate parent–offspring adoption model. Two sets of analyses were performed: (1) a bivariate analysis examining the relationship between WISC-R or WAIS-R Full Scale IQ (FSIQ) (Wechsler, 1974, 1981) and PIAT Reading Recognition (REC) (Dunn and Markwardt, 1970) and (2) a trivariate analysis involving both Verbal and Performance IQ (VIQ and PIQ, respectively) and REC. Genetic analyses yielded heritability estimates of .36 for FSIQ and VIQ, .38 for REC, and .41 for PIQ, suggesting a moderate influence of genotype on individual differences in each of these measures. Moreover, genetic influences accounted for 78% of the phenotypic correlation between REC and VIQ and for 67% of that between REC and PIQ. Environmental influences were specific to each measure and contributed little to the covariance among the measures. Thus, results of this study again indicate that the IQ–achievement relationship may be due largely to common genetic influences.

Wadsworth *et al.* (in press) analyzed cognitive ability and achievement data from 100 related and 90 unrelated sibling pairs participating in the CAP at age 7. Measures included the Kaufman Verbal Comprehension (VERB) and Perceptual Organization (PERCEP) factors (Kaufman, 1975) of the WISC-R (Wechsler, 1974), the Reading Recognition subtest (REC) of the PIAT (Dunn and Markwardt, 1970), and a composite measure of mathematics achievement (MATH) based on the Numeration, Addition, and Subtraction subtests of the KeyMath Diagnostic Arithmetic Test (Connolly *et al.*, 1976) and the Arithmetic subtest of the WISC-R (Wechsler, 1974). Genetic influences accounted for 33–60% of the phenotypic covariance among the variables, with much of the genetic covariation being due to influences shared with verbal ability. The environmental variance was due primarily to nonshared influences specific to each of the measures, with shared environmental influences accounting for no more than 20% of the variance of any measure and 28% of the covariances among the measures. The results of this study, therefore, suggest that much of the covariance between cognitive ability and academic achievement is due to shared genetic influences. Furthermore, significant genetic and environmental covariation was found between reading and mathematics achievement, independent of general cognitive ability. Similar results were obtained from analysis of a subset of these data, using Verbal and Performance IQ (WISC-R, Wechsler, 1974) rather than the Kaufman factors (Wadsworth, 1994).

These previous studies utilized parent–offspring, sibling, or twin data to examine the relationships among a variety of cognitive ability and academic achievement measures. The purpose of the current study is to extend and complement these previous studies by analyzing simultaneously parent–offspring and sibling data from the CAP. This design facilitates analyses of data from both adoptive and nonadoptive parents and their children, as well as from related and unrelated siblings. Although the sibling data used by Wadsworth *et al.* (in press) are included in the current analyses, a different math measure is used. In addition, the results of these two studies are compared to address the issues of isomorphism of the measures and stability of genetic and environmental influences throughout development. Based on the results of previous studies, we hypothesized that the relationships among the measures of cognitive ability and academic achievement are due at least in part to common genetic influences.

METHODS

Subjects

The subjects included in this study are participants in the CAP, an ongoing longitudinal study of genetic and environmental influences on behavioral development. Adoptive families were recruited through two adoption agencies in Denver, Colorado. Data from a wide variety of measures were collected from both adoptive and biological parents and are currently being obtained from adopted children and their unrelated siblings. All adopted children were separated from their biological parents within a few days of birth and placed in adoptive homes within one month. The children were tested yearly, using in-home tests and interviews at ages 1–4 and telephone tests and interviews at ages 5 and 6. At age 7, they were administered an extensive battery of tests in the CAP laboratory at the Institute for Behavioral Genetics, University of Colorado, Boulder. The CAP

Table I. Sample Sizes

Type of individual	Number of subjects
Parents	
Adoptive fathers (A_F)	187
Adoptive mothers (A_M)	193
Nonadoptive control fathers (C_F)	211
Nonadoptive control mothers (C_M)	220
Offspring	
Adopted probands (A_1)	198
Nonadopted control probands (C_1)	215
Siblings	
Adopted siblings of adoptees (A_2)	66
Nonadopted siblings of adoptees (S_2)	24
Full siblings of nonadoptees (C_2)	100

sample consists of 245 adoptive families and 245 nonadoptive control families which are matched to the adoptive families according to age, education, and occupational status of the fathers, gender of the adopted child, and number of children in the family. There are, additionally, test and questionnaire data on 280 biological mothers and 58 biological fathers. Detailed descriptions of the CAP design and sample have been provided by Plomin and DeFries (1985), Plomin *et al.* (1988), and DeFries *et al.* (1994).

For the present study, cognitive ability and achievement data from adopted children and their unrelated siblings, as well as from nonadopted control children and their related siblings, were collected during the summer following first grade (average age, 7.4 years). Unrelated siblings of adoptees may be either adopted or nonadopted. Adoptive and control parents were tested during the summer following the proband's completion of first grade. Sample sizes, by family and individual type, are provided in Table I.

Measures

The current study examines scores of probands, siblings, and parents on measures of academic achievement and cognitive ability. The achievement measures include the Reading Recognition (REC) subtest of the Peabody Individual Achievement Test (PIAT) (Dunn and Markwardt, 1970) and the Arithmetic Subtest of the WISC-R or WAIS-R (Wechsler, 1974, 1981). Measures of cognitive ability include the Kaufman (1975) Verbal Comprehension (VERB) and Perceptual Organization (PERCEP) factors of the WISC-R or WAIS-R (Wechsler, 1974, 1981). VERB is computed as the sum of the scaled scores on the Information, Similarities, Vocabulary, and Comprehension subtests. PERCEP is computed as the sum of the scaled scores on the Picture Completion, Picture Arrangement, Block Design, and Object Assembly subtests. The Arithmetic subtest is omitted from these factors, permitting its use as a measure of mathematics achievement. Although inclusion of an independent measure of mathematics achievement would have been desirable, no other math measure is available for the parents in this study.

Analyses

Phenotypic Analysis

The current study employed the Cholesky decomposition (Neale and Cardon, 1992) to examine the phenotypic factor structure among the variables. Figure 1 depicts the phenotypic model, which was fitted to the data by the method of maximum-likelihood estimation using the MX Statistical Modeling package (Neale, 1991). The use of the Cholesky facilitates exploration of the factor structure among the variables, permitting a more thorough interpretation of their interrelationships. For example, using this model, we can determine the extent to which the observed relationship between the achievement measures is due to influences shared with verbal ability $(\lambda_{31} \times \lambda_{41}/r_{P_{\text{REC,ARITH}}})$, where

$$r_{P_{\text{REC,ARITH}}} = (\lambda_{31} \times \lambda_{41}) + (\lambda_{32} \times \lambda_{42}) + (\lambda_{33} \times \lambda_{43}) \qquad (1)$$

such that the total correlation between REC and ARITH is due to influences shared with VERB ($\lambda_{31} \times \lambda_{41}$), those shared with PERCEP but not VERB ($\lambda_{32} \times \lambda_{42}$), and those independent of either VERB or PERCEP ($\lambda_{33} \times \lambda_{43}$).

Because of the variability in patterns of missing data among families in the CAP, a maximum-likelihood pedigree approach was employed to make use of all available data, thereby increasing both the power to detect effects and the precision of parameter estimates. The pedigree approach in-

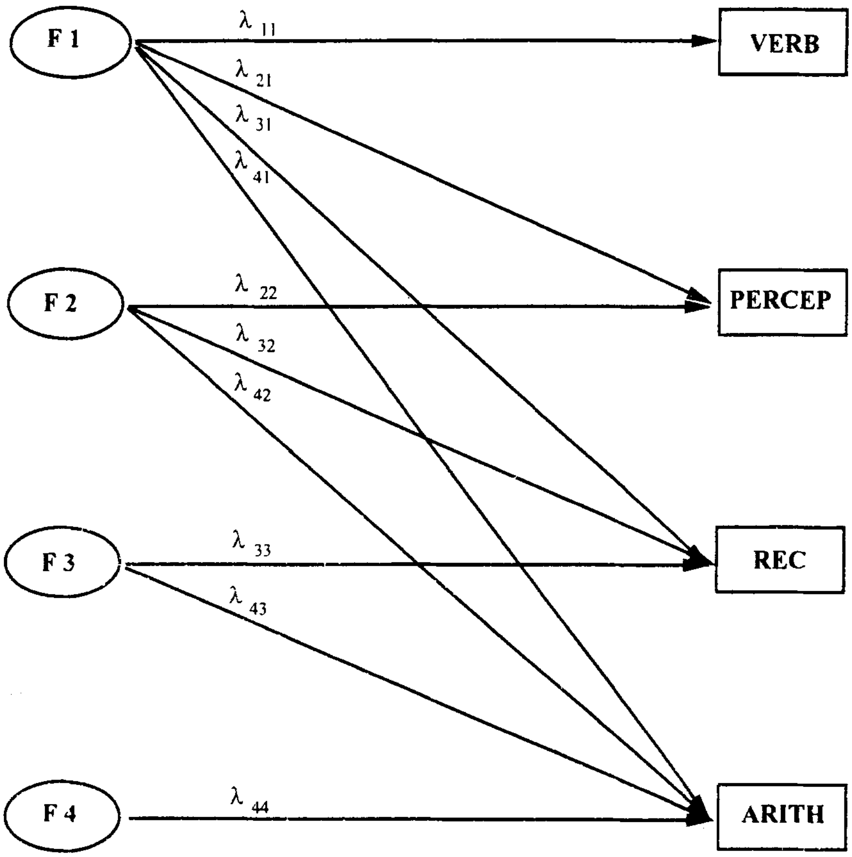

Fig. 1. Cholesky model of phenotypic factor structure among measures of Verbal Comprehension (VERB), Perceptual Organization (PERCEP), Reading (REC), and Mathematics (ARITH) performance.

volves the calculation of a log-likelihood for each family:

$$L_i = -\frac{1}{2}\ln|\Sigma_i| - \frac{1}{2}(\mathbf{x}_i - \mathrm{m})'\Sigma_i^{-1}(\mathbf{x}_i - \mathrm{m}) \quad (2)$$

where, for the i^{th} pedigree, Σ_i represents the matrix of expected covariances among scores of family members, **x** is a variable-length vector of observed family data, and m is a vector of expected means for each individual type (i.e., adoptive father, control mother, adoptive proband, control sibling, etc.). The appropriate mean vector μ and covariance matrix Σ are automatically created by MX for each pedigree (Neale, 1991). The L_i are summed across all pedigrees. For model comparisons, twice the difference between the log-likelihoods for the two models is distributed asymptotically as a chi-square, with degrees of freedom equal to the difference in the number of free parameters estimated in fitting each model.

Genetic Analysis

For the genetic analyses, the phenotypic model was partitioned to include genetic, shared environmental, and nonshared environmental contributions to the variance in each of the measures, as well as to the correlations between the measures. Figure 2 depicts the model, illustrating the genetic and environmental factor structures underlying measures of VERB, PERCEP, REC, and ARITH. Using this model, the etiology of the relationships among the measures of cognitive ability and achievement can be assessed, and the extent to which the correlation between the achievement variables is due to genetic and environmental influences shared with the cognitive ability factors can be quantified. In this manner, the model can provide evidence for common or independent genetic and environmental influences on the various measures. In addition, estimates of heritability, environmentality, and genetic and environmental correla-

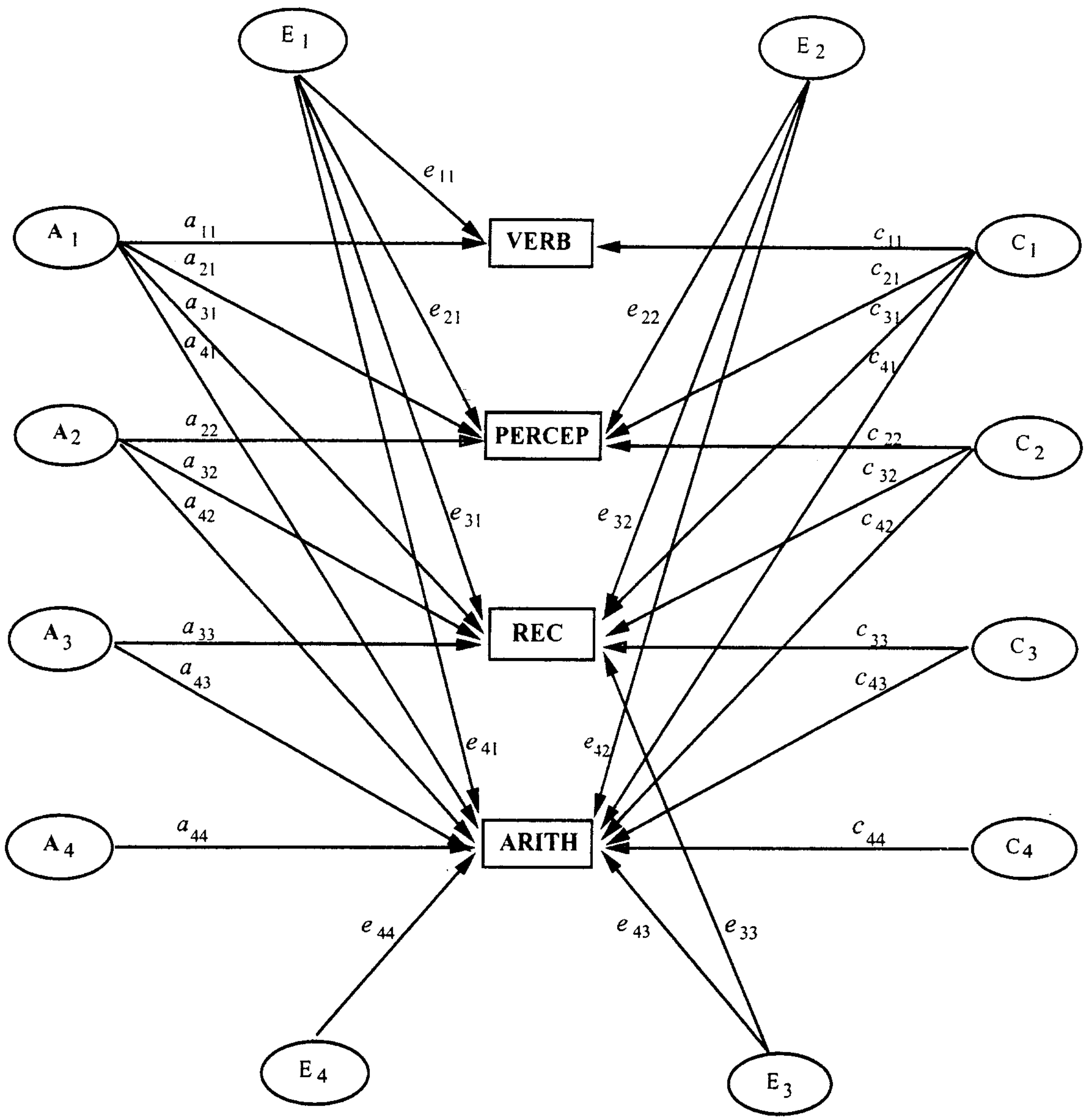

Fig. 2. Partitioning of the phenotypic Cholesky into genetic (A), shared environmental (C), and nonshared environmental (E) factors.

tions among the measures are computed with relative ease.

The basic CAP model of resemblance between parents and two offspring (DeFries *et al.*, 1987) allows simultaneous analysis of both parent–offspring covariances and those of related and unrelated sibling pairs. A multivariate extension of this model was suggested by Phillips (1988) and Phillips and Fulker (1989) (Fig. 3). Variables included in the model, along with their symbols, are listed in Table II, and matrix symbols and structures are presented in Table III. According to this model, cultural transmission is represented as an effect of the phenotype of the parents on the environment of the offspring (**m** or **f**), and mother's ($\mathbf{P_M}$) and father's ($\mathbf{P_F}$) phenotypes are allowed to contribute to varying degrees. Transmission of genetic and cultural influences from the parents induces covariances (*s*) between genetic (**A**) and shared environmental (**C**) factors. These genotype–environment

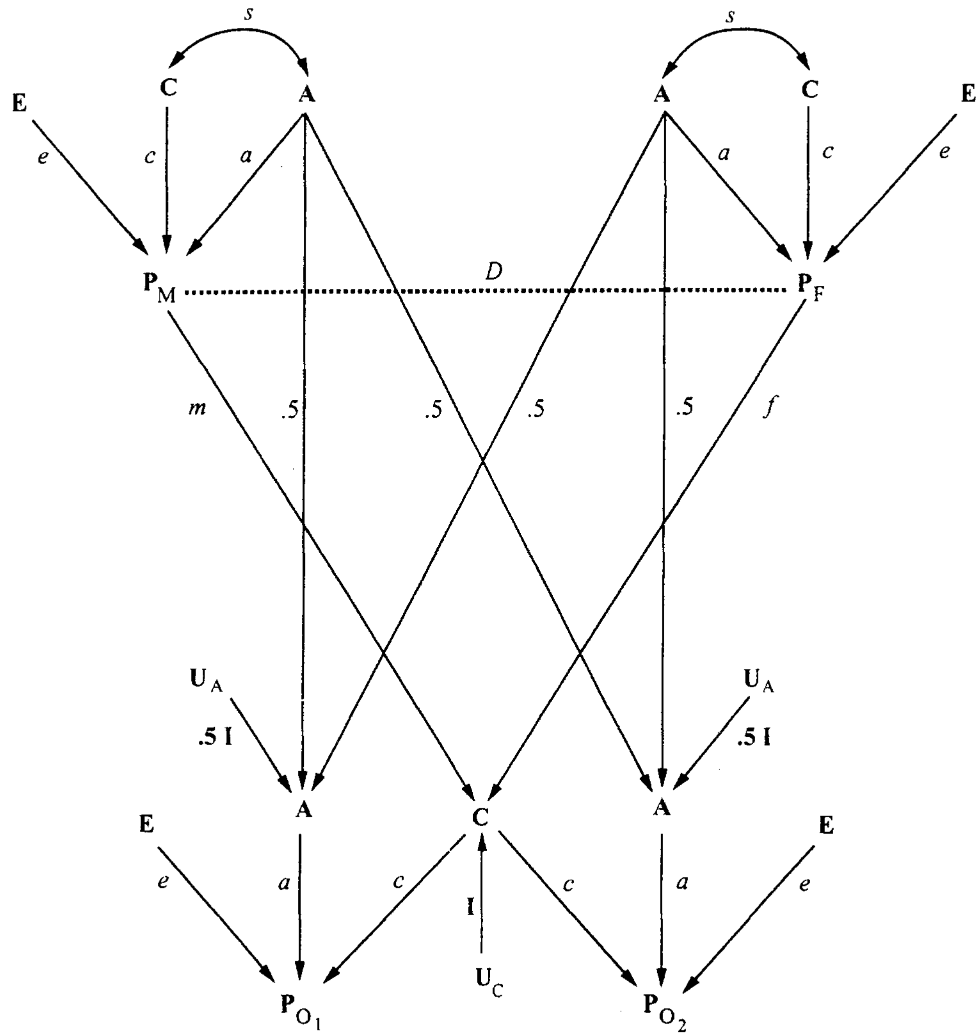

Fig. 3. Path diagram of resemblance between nonadoptive parents and two offspring, employing the method of delta paths (from Phillips, 1988; Phillips and Fulker, 1989).

covariances are assumed to be at equilibrium across generations, resulting in a set of nonlinear constraints,

$$\mathbf{s} = .5\mathbf{T}(\mathbf{m}' + \mathbf{f}' + \mathbf{D}\mathbf{R}_P\mathbf{m}' + \mathbf{D}'\mathbf{R}_P\mathbf{f}') \quad (3)$$

where $\mathbf{T} = \mathbf{R}_A\mathbf{a}' + \mathbf{s}\mathbf{c}'$, and $\mathbf{R}_P$ represents the within-person phenotypic covariance matrix. Parental assortative mating (**D**) is assumed to occur at the phenotypic level and is modeled using delta paths, as derived by Van Eerdewegh (1982) and described in detail by Phillips (1988, 1989). The current use of delta paths to model assortative mating is equivalent to that of Wright's (1968) reversed path coefficients, Cloninger's (1980) copaths, and Carey's (1986) conditional paths. Because biological parents of adopted-away offspring are not included in these analyses, selective placement is not modeled. However, the overall median selective placement correlation for educational level in the CAP is only .04 (Plomin *et al.*, 1988); therefore effects of selective placement on results of the current study are expected to be negligible.

From this model, we can estimate additive genetic covariances among the factors ($\mathbf{R}_A$) which are a result of parental assortative mating (Phillips, 1988; Phillips and Fulker, 1989; Neale *et al.*, 1994) and assumed to be at equilibrium across generations. These are constrained as follows:

Table II. Variables Included in the Model

Symbol	Variable
	Observed (**P**)
C_m	Nonadoptive (control) mother
C_f	Nonadoptive (control) father
A_m	Adoptive mother
A_f	Adoptive father
C_1	Nonadopted proband
C_2	Nonadopted sibling
A_1	Adopted proband
A_2	Adopted sibling
S_2	Nonadopted sibling of A_1
	Latent
A	Genetic factors
C	Shared environmental factors
E	Nonshared environmental factors

Table III. Matrices Included in the Model

Matrix	Symbol	Structure
Additive genetic paths	**a**	Lower triangular
Additive genetic covariances	$\mathbf{R}_A$	Symmetric
Common environmental paths	**c**	Lower triangular
Common environmental covariances	$\mathbf{R}_C$	Symmetric
Specific environmental paths	**e**	Lower triangular
Phenotypic covariance	$\mathbf{R}_P$	Symmetric
Assortative mating delta paths	**D**	Full
A–C covariance	**s**	Full
Mother's cultural transmission	**m**	Full
Father's cultural transmission	**f**	Full
Mother–father covariance	**W**	Full
A–P covariance	**T**	Full

$$\mathbf{R}_A = .5 \otimes (\mathbf{R}_A + .5 \otimes \mathbf{T}(\mathbf{D} + \mathbf{D}')\mathbf{T}' + \mathbf{I}) \quad (4)$$

The effects of pleiotropy are modeled by the Cholesky (Neale *et al.*, 1994), where the first factor is pleiotropic for all variables, the second factor is pleiotropic for all except the first, etc.

Shared environmental factor covariances ($\mathbf{R}_C$), a result of cultural transmission and assortative mating, are also estimated, and assumed to be at equilibrium across generations, giving rise to a

Table IV. Summary, Derived, and Fixed Parameter Matrices

	Derivation formula
Matrix	
W	$\mathbf{R}_p\mathbf{D}\mathbf{R}_p$
T	$\mathbf{R}_A\mathbf{a}' + \mathbf{s}\mathbf{c}'$
$\mathbf{U}_A$	$.5\mathbf{I}$
$\mathbf{U}_e$	$\mathbf{I}$
Identifying constraints	
R_P	$\mathbf{a}\mathbf{R}_A\mathbf{a}' + \mathbf{c}\mathbf{R}_C\mathbf{c}' + \mathbf{e}\mathbf{e}' + \mathbf{a}\mathbf{s}\mathbf{c}' + \mathbf{c}\mathbf{s}'\mathbf{a}'$
R_A	$.5 \otimes (\mathbf{R}_A + .5 \otimes \mathbf{T}(\mathbf{D} + \mathbf{D}')\mathbf{T}' + \mathbf{I})$
R_C	$\mathbf{mRpm}' + \mathbf{fRpf}' + \mathbf{mWf}' + \mathbf{fW}'\mathbf{m}' + \mathbf{I}$
s	$.5\mathbf{T}(\mathbf{m}' + \mathbf{f}' + \mathbf{DRpm}' + \mathbf{D}'\mathbf{Rpf}')$

Table V. Expected Familial Covariances

Matrix	Predicted covariance
Control families	
C_m, C_f	**W**
C_m, C_1; C_m, C_2	$(\mathbf{Rpm}'+\mathbf{Wf}')\mathbf{c}'+(\mathbf{I}+\mathbf{RpD})\mathbf{T}'(.5\mathbf{a}')$
C_f, C_1; C_f, C_2	$(\mathbf{Rpf}'+\mathbf{Wm}')\mathbf{c}'+(\mathbf{I}+\mathbf{RpD}')\mathbf{T}'(.5\mathbf{a}')$
C_1, C_2	$.5\mathbf{a}(\mathbf{R}_A+.5(\mathbf{T}(\mathbf{D}'+\mathbf{D})\mathbf{T}'))$ $\mathbf{a}'+\mathbf{c}\mathbf{R}_C\mathbf{c}'+\mathbf{asc}'+\mathbf{csa}'$
Adoptive families	
A_m, A_f	**W**
A_m, A_1; A_m, A_2	$\mathbf{Rp}((\mathbf{m}'+\mathbf{DRpf}')\mathbf{c}')$
A_m, S_2	$(\mathbf{Rpm}'+\mathbf{Wf}')\mathbf{c}'+(\mathbf{I}+\mathbf{RpD})\mathbf{T}'(.5\mathbf{a}')$
A_f, A_1; A_f, A_2	$\mathbf{Rp}((\mathbf{f}'+\mathbf{DRpm}')\mathbf{c}')$
A_f, S_2	$(\mathbf{Rpf}'+\mathbf{Wm}')\mathbf{c}'+(\mathbf{I}+\mathbf{RpD})\mathbf{T}'(.5\mathbf{a}')$
A_1, A_2	$\mathbf{c}\mathbf{R}_C\mathbf{c}'$
A_1, S_2	$\mathbf{c}\mathbf{R}_C\mathbf{c}'+\mathbf{cs}'\mathbf{a}$

third set of constraints,

$$\mathbf{R}_C = \mathbf{m}\mathbf{R}_P\mathbf{m}' + \mathbf{f}\mathbf{R}_P\mathbf{f}' + \mathbf{m}\mathbf{W}\mathbf{f}' + \mathbf{f}\mathbf{W}'\mathbf{m}' + \mathbf{I} \quad (5)$$

where **W** represents the matrix of predicted covariances between mother and father ($\mathbf{R}_P\mathbf{D}\mathbf{R}_P$). Finally, the phenotypic variance is constrained to be

$$\mathbf{R}_P = \mathbf{a}\mathbf{R}_A\mathbf{a}' + \mathbf{c}\mathbf{R}_C\mathbf{c}' + \mathbf{e}\mathbf{e}' + \mathbf{a}\mathbf{s}\mathbf{c}' + \mathbf{c}\mathbf{s}'\mathbf{a}' \quad (6)$$

These contraints follow the methods of Phillips and Fulker (1989) and Neale *et al.* (1994).

Expectations for summary, derived, and fixed parameter matrices, as well as for familial covariances under the multivariate model, are provided in Tables IV and V, respectively. Standardization of parameter matrices is accomplished according to the methods of Phillips (1988), Phillips and Fulker (1989), and Neale *et al.* (1994).

Table VI. Phenotypic Correlations Among Measures of Cognitive Ability (VERB and PERCEP) and Academic Achievement (REC and ARITH) Pooled Across Parents and Offspring

	VERB	PERCEP	REC	ARITH
VERB	1.00			
PERCEP	.39	1.00		
REC	.44	.25	1.00	
ARITH	.39	.33	.32	1.00

The use of MX to model resemblance between parents and twins has been described by Neale *et al.* (1994), based on the method of Phillips and Fulker (1989). The current study employs this program, with the necessary adjustments for analysis of data from adoptive and nonadoptive control families.

RESULTS

Phenotypic Analyses

Phenotypic correlations among measures of cognitive ability and academic achievement pooled across parents and offspring are presented in Table VI and range from .25 for the correlation between PERCEP and REC to .44 for that between VERB and REC. It is of interest to note that the correlation between VERB and ARITH is highly similar to that between VERB and REC.

Application of the full phenotypic Cholesky to the pooled parent–offspring and sibling data yielded a log-likelihood of -7513.61 for the 10 parameters estimated. Results of fitting this phenotypic model are presented in Fig. 4. As indicated by the phenotypic correlations, the relationship between VERB and ARITH in this sample approximates that between VERB and REC. In addition, nearly 60% of the observed covariation between the achievement variables is due to influences shared with cognitive ability, primarily VERB. However, none of the factors could be dropped without significant loss of model fit (Table VII), suggesting significant covariation between the achievement measures independent of cognitive ability.

Genetic Analysis

The Cholesky decomposition employed in the phenotypic analysis was also used for the genetic analysis. The full model includes genetic, shared environmental, and nonshared environmental influences on each of the measures, as well as on the covariances among the measures. In addition, cultural transmission from the phenotype of the parent to be shared environment of the offspring and phenotypic assortative mating are also included, both of which may induce correlations between genetic and shared environmental factors. This full model yielded a log-likelihood of -7412.95 for a total of 78 estimated parameters. The full model was compared to a saturated model to determine the fit of the model. Model comparisons are given in Table VIII, along with the log-likelihood and number of parameters estimated for each. In addition, the corresponding χ^2, degrees of freedom for each comparison, p- value, and Akaike's Information Criterion (AIC) are also given. Comparison of the full model to the saturated model indicates an acceptable fit ($\chi^2_{296} = 321.41, p \geq .15$). Further model comparisons were conducted to determine the significance of the cultural transmission parameters. It can be seen from these comparisons that the maternal and paternal cultural transmission parametters can be equated (Model 3). Moreover, the entire cultural transmission component of the model, including genotype–environment covariance, can be dropped without significant deterioration of fit (Model 4).

Given the nonsignificance of the cultural transmission component of the model, estimates were obtained for a model excluding cultural transmission, against which subsequent models are compared. This model yielded a log-likelihood of -7427.55 for 46 estimated parameters, providing an acceptable fit compared with the saturated model ($\chi^2_{328} = 350.15, p \geq .19$). The genetic and environmental factor structures obtained from fitting this model are depicted in Fig. 5. Genetic influences are moderate, with much of the genetic covariance among the measures being due to influences shared with VERB. Indeed, nearly half (48%) of the genetic covariance between REC and ARITH is due to such influences. However, genetic influences independent of those shared with measures of cognitive ability are responsible for 45% of their genetic covariance. Contrary to the phenotypic results, the genetic covariance between VERB and REC is nearly twice as large as that between VERB and ARITH. PERCEP has virtually no effect on REC independent of VERB, but its rela-

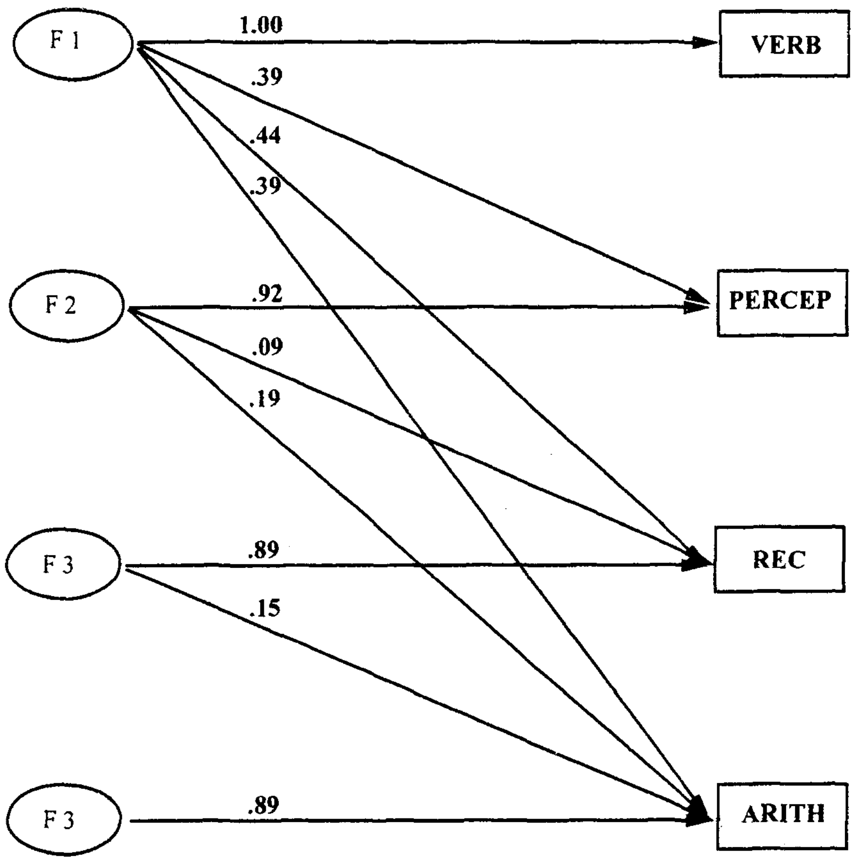

Fig. 4. Results of phenotypic analysis of cognitive ability and achievement data pooled across parents and offspring.

Table VII. Model Comparisons for Phenotypic Cholesky Based on Pooled Parent–Offspring and Sibling Data

Model	log-likelihood	NPAR	vs.	χ^2	df	p
1. Full	−7513.61	10				
2. Single common factor	−7570.31	7	1	113.40	3	≤.001
3. Two common factors (F_1 & F_2)	−7531.97	9	1	36.71	1	≤.001
4. Two common factors (F_1 & F_3)	−7547.88	8	1	68.54	2	≤.001

Table VIII. Model Comparisons for Cultural Transmission Analysis

Model	log-likelihood	NPAR	vs.	χ^2	df	p	AIC
1. Saturated	−7252.25[a]	374					
2. Full	−7412.95	78	1	321.41	296	≥.15	−270.59
3. Equate m and f	−7421.22	62	2	16.53	16	≥.30	−286.06
4. No cultural transmission	−7427.55	46	2	29.20	32	≥.50	−305.40

[a] Data from adoptive families did not meet all convergence criteria; therefore, the most consistent log-likelihood obtained for the saturated model is presented here.

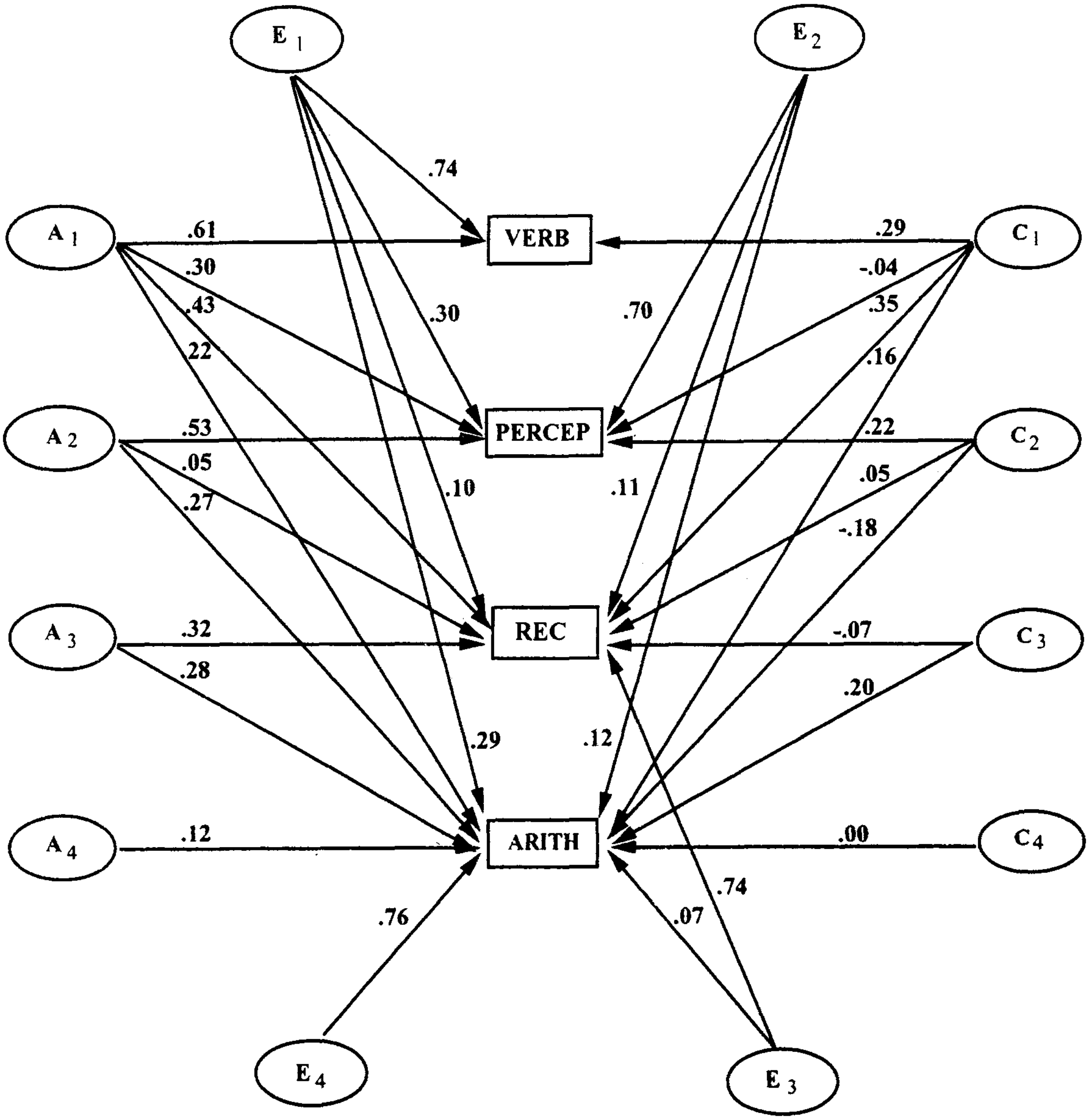

Fig. 5. Genetic factor structure among measures of cognitive ability and academic achievement estimated from the full model.

tionship with ARITH is somewhat stronger. Therefore, there does not appear to be a single factor which can account for the preponderance of the genetic covariance among the measures.

Shared sibling environmental influences are weak. With the exception of the shared environmental covariance between VERB and REC, these influences account for very little of the observed covariance among the measures. In contrast, nonshared environmental influences are relatively large and contribute somewhat to the phenotypic relationships between VERB and the other measures. The nonshared environmental path between VERB and ARITH is higher that that between VERB and REC. In addition, there is a large amount of nonshared environmental variance specific to each of the measures. It would appear, therefore, that one nonshared environmental factor may be sufficient to account for the nonshared environmental covariance among the measures.

Table IX provides the assortative mating parameter estimates from the model excluding cul-

Table IX. Assortative Mating Parameter Estimates

	Father			
Mother	VERB	PERCEP	REC	ARITH
VERB	.34	−.10	.00	−.01
PERCEP	−.07	.12	.03	−.04
REC	.10	.01	.17	.03
ARITH	−.12	.06	−.09	.04

Table X. Genetic Factor Covariance Matrix Arising from Phenotypic Assortative Mating

	Genetic factors			
	VERB	PERCEP	REC	ARITH
VERB	1.18			
PERCEP	−.01	1.04		
REC	.03	.01	1.02	
ARITH	−.01	.00	.00	1.00

Table XI. Genetic and Environmental Contributions to the Variance in Each of the Measures

Measure	a^2	c^2	e^2
VERB	.37	.08	.55
PERCEP	.37	.05	.58
REC	.29	.13	.57
ARITH	.21	.10	.68

tural transmission. Phenotypic assortment occurs primarily for VERB, with some weak assortment for the other variables. However, there is little or no cross-variable assortment, with the exception of a weak correlation between father's VERB and mother's REC. Genetic covariances among the genetic cognitive ability and achievement factors which are induced by assortative mating are presented in Table X. It can be seen from these estimates that assortment in this sample induces virtually no covariance among the genetic factors.

Moderate genetic influences were observed for all measures, with heritability estimates of .21 for ARITH, .29 for REC, and .37 for both VERB and PERCEP (Table XI). Nonshared environmental influences (including unreliability) are important for all of the measures, accounting for 57–68% of the variance in each. In contrast, shared environmental influences are negligible, accounting for no more than 13% of the variance in any measure.

Table XII. Genetic and Environmental Correlations, with Phenotypically Standardized Genetic and Environmental Correlations Above the Diagonal

	Genetic			
	VERB	PERCEP	REC	ARITH
VERB	**1.00**	.18	.26	.13
PERCEP	.50	**1.00**	.15	.21
REC	.80	.49	**1.00**	.20
ARITH	.48	.75	.80	**1.00**
	Shared environmental			
	VERB	PERCEP	REC	ARITH
VERB	**1.00**	−.01	.10	.05
PERCEP	−.18	**1.00**	.00	−.05
REC	.99	−.04	**1.00**	.03
ARITH	.52	−.65	.29	**1.00**
	Nonshared environmental			
	VERB	PERCEP	REC	ARITH
VERB	**1.00**	.22	.07	.21
PERCEP	.39	**1.00**	.10	.17
REC	.13	.19	**1.00**	.09
ARITH	.35	.27	.15	**1.00**

Estimates of the genetic and environmental correlations among the measures estimated from this model are presented in Table XII, with the phenotypically standardized genetic and environmental correlations provided above the diagonal. Genetic correlations are substantial, ranging from .48 between VERB and ARITH to .80 between both REC and ARITH and VERB and REC. The phenotypically standardized genetic correlation of .26 between VERB and REC accounts for approximately 60% of their observed covariation, while that of .13 between VERB and ARITH accounts for about one-third of their phenotypic relationship. Phenotypically standardized genetic correlations of .15 between PERCEP and REC and .21 between PERCEP and ARITH account for 60 and 64% of their observed correlations, respectively. Finally, common genetic influences account for 63% of the relationship between REC and ARITH.

Although some of the shared environmental correlations appear substantial, the only noteworthy correlation is that of .99 between VERB and REC. The phenotypically standardized shared environmental correlation of .10 between these two variables accounts for 23% of their observed covariation.

The model excluding cultural transmission was subjected to a series of model comparisons. Table XIII lists the models compared, along with the corresponding fit statistics. As can be seen from the table, all shared environmental influences may be dropped from the model without significant deterioration of fit (Model 3). As expected, however, genetic influences cannot be omitted (Model 4). Moreover, a single genetic factor is not sufficient to account for the genetic covariances among the measures (Model 5). In contrast, although a reduced fit was obtained when all nonshared environmental common factors were excluded (Model 6), one factor was sufficient to account for the nonshared environmental covariances among the measures (Model 7). Assortative mating was significant only for isomorphic measures (Models 8–10).

DISCUSSION

The purpose of the current study was to assess the etiology of the covariation among measures of cognitive ability (arithmetic and reading recognition) and academic achievement (verbal comprehension and perceptual organization) by applying the methods of multivariate behavioral genetic analysis simultaneously to both sibling and parent–offspring data from the CAP.

Results of the phenotypic analysis confirmed previous findings of moderate correlations among measures of ability and achievement. The highest correlations involved VERB, with the correlation between VERB and ARITH being highly similar to that between VERB and REC. This may be due to the verbal nature of the mathematics test used in this study or to the mutual loadings of all the measures on general cognitive ability.

When the Cholesky model was fitted to the data, results indicated that over half of the covariation between REC and ARITH was due to influences shared with VERB. Although this was due, in part, to the order of entry of the variables, when PERCEP was entered first, VERB continued to mediate more of the relationship between the achievement measures than did PERCEP. However, there was a large amount of variance specific to each measure, and substantial covariation between the achievement measures independent of those influences shared with cognitive ability—a finding that is consistent with results of previous studies (Brooks *et al.*, 1990; Wadsworth *et al.*, in press). Thus, although measures of achievement are correlated with measures of general cognitive ability, there are, nonetheless, significant and substantial influences on measures of academic achievement that are independent of those influences shared with cognitive ability.

To examine the genetic and environmental relationships among these measures, the phenotypic Cholesky was partitioned to include genetic, shared environmental, and nonshared environmental contributions to the variance in each of the measures, as well as to the covariance among the measures. Results indicated that genetic influences on individual differences in performance on each of the measures were moderate, with heritabilities ranging from .21 for ARITH to .37 for both VERB and PERCEP. The remaining variance was due primarily to nonshared environmental influences, with shared environmental influences accounting for only 5 to 13% of the variance in the achievement measures. Although the estimates of genetic and environmental influences are in the same range as those obtained by other studies (Brooks *et al.*, 1990; Cardon *et al.*, 1990; Thompson *et al.*, 1991; Gillis, 1993; Wadsworth *et al.*, in press), the individual estimates vary considerably among studies. Such variation may be due to differences in the ages of the subjects, the measures used, sample size, and/or sample composition (twins/siblings versus parent–offspring, etc.).

Based on results of previous studies, we predicted that the covariation between cognitive ability and achievement in this sample would be due at least in part to genetic influences. Genetic influences were found to account for approximately 60% of the phenotypic relationship between VERB and REC and for one-third of that between VERB and ARITH. These findings are consistent with earlier studies which suggested that a large proportion of the phenotypic covariance among measures of IQ and academic achievement is due to shared genetic influences. The remainder of the phenotypic covariance among the measures is due primarily to the influence of nonshared environment, including measurement error. Given that one factor was sufficient to account for the nonshared environmental covariances among the measures, nonshared environmental covariation may be due to the verbal nature of both the achievement and ability measures.

Table XIII. Model Comparisons for Analyses of Parent–Offspring and Sibling Data

Model	log-likelihood	NPAR	vs.	χ^2	df	p	AIC
1. Saturated	−7252.25[a]	374					
2. Full, excl. cult. trans.	−7427.55	46	1	350.16	328	≥.19	−305.40
3. No shared env.	−7435.51	36	2	15.92	10	≥.09	−309.48
4. No genes	−7460.24	36	2	65.39	10	≤.001	−260.02
5. One genetic factor	−7441.03	40	2	26.96	6	≤.001	−290.44
6. Nonshared env. specs. only	−7436.93	40	2	18.77	6	≤.01	−298.64
7. One NS env. factor plus specs	−7429.61	43	2	4.12	3	≥.20	−307.28
8. No assortment	−7466.76	30	2	78.41	16	≤.001	−258.98
9. Assort. on VERB only	−7443.84	31	2	32.58	15	≤.01	−302.82
10. Assort. within trait	−7434.69	34	2	14.29	12	≥.30	−315.12

[a] Data from adoptive families did not meet all convergence criteria; therefore, the most consistent log-likelihood obtained for the saturated model is presented here.

Although much of the genetic covariation between the achievement measures was due to influences shared with verbal ability, there was substantial genetic covariance between REC and ARITH that was independent of the genetic influences shared with cognitive ability. This suggests that there may be genetic influences on achievement which are not directly related to intellectual performance.

One of the advantages of utilizing parent–offspring data in genetic analyses is the opportunity to assess assortative mating and cultural transmission. The contributions of these factors cannot be determined from analysis of twin or sibling data, without data from the parents. In the current study, assortative mating parameter estimates were significant only within trait, and substantial only for VERB and REC. Similarly, cultural transmission was nonsignificant for these data. However, this does not imply that there are no environmental influences provided by the parents. Results of the present study suggest that if cultural transmission is present, it is not operating as an effect of the parent phenotype on the shared environment of the offspring. Future analyses of CAP parent–offspring and sibling data should explore alternative models of cultural transmission, such as transmission of environmental influences from the parents to either the shared or the nonshared environment of the offspring.

In summary, results of the current study provide further evidence of genetic influences on the variance in each of the measures of IQ and academic achievement, as well as to the covariation among the measures. Although the strongest relationships, both phenotypically and genetically, occurred between verbal ability and the achievement measures, there was substantial phenotypic and genetic covariation between the achievement measures independent of cognitive ability. In addition, nonshared environmental covariation was also significant. In contrast, shared environmental influences contributed little to either the variance or the covariance of the measures.

Finally, it is noteworthy that the results of earlier sibling analyses (Wadsworth, 1994; Wadsworth *et al.*, in press) and those of the current analyses were similar, despite differences in tests of mathematics, as well as the possibility that the same tests may not measure the same characteristics in children and adults. The similar results obtained from these two methods provide evidence for the isomorphism of the measures, as well as for genetic and environmental continuity from middle childhood to adulthood. With separate estimates of heritability and environmentality for children and adults, it would be possible to determine the extent to which these influences are correlated during development. Although this is not possible with the currently available data, as the sibling pairs in the CAP approach adulthood, it will be possible to test such hypotheses more rigorously, through longitudinal models of continuity and change.

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