Research Article

ASSOCIATIONS BETWEEN COGNITIVE ABILITIES AND SCHOLASTIC ACHIEVEMENT: Genetic Overlap but Environmental Differences

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Abstract—*Little is known about the genetic and environmental etiology of the association between specific cognitive abilities and scholastic achievement during the early school years. A multivariate genetic analysis of cognitive and achievement measures was conducted for 146 pairs of identical twins and 132 pairs of fraternal twins from 6 to 12 years of age. At the phenotypic level, measures of achievement were moderately correlated with specific cognitive abilities. A multivariate model including one general factor and specific factors in the genetic and environmental matrices indicated that the phenotypic relationship between achievement and cognition was mediated primarily by genetic influences. Genetic correlations among the cognitive and achievement tests ranged from .57 to .85, shared environment correlations were essentially zero, and specific environment correlations were low (.00 to .19). We conclude that there is substantial overlap between genetic effects on scholastic achievement and specific cognitive abilities. Performance on ability measures differs from that on achievement measures largely for environmental reasons.*

Although the first intelligence tests were designed to predict school performance (Brooks-Gunn & Weinraub, 1983), the relationship between achievement tests and IQ is far from unity (Sattler, 1982). How can the communalities and the discrepancies between IQ and achievement be explored? Previous approaches to this question have been phenotypic, examining associations between scores on achievement and ability tests in an attempt to identify processes that differ. It is now possible to address this issue etiologically, in terms of genetic and environmental influences. Although both cognition and achievement are affected by genetic influences, genetic factors may or may not influence the relationship between cognition and achievement. Surprisingly, multivariate genetic analyses have yet to be conducted for twin data including both cognitive abilities and measures of achievement (Cardon, DiLalla, Plomin, DeFries, & Fulker, 1990; Plomin, 1986). A twin study of IQ and reading ability indicated that both the phenotypic and genetic correlations between the measures were significant (Brooks, Fulker, & DeFries, 1990). Adoption data reported in Cardon et al. (1990) also provides support for genetic overlap between IQ and reading performance, with a larger correlation between Verbal IQ and reading than Performance IQ and reading. The present report will extend the findings of Brooks et al. (1990) and Cardon et al. (1990) to explore the extent to which phenotypic relationships among specific cognitive abilities and scholastic achievement are mediated by genetic and environmental factors.

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IQ

Numerous behavior genetic studies have been conducted in which cognition and achievement are examined separately. Intelligence is one of the most widely studied human traits (see Bouchard & McGue, 1981, and Loehlin, Willerman, & Horn, 1988, for reviews). In general, IQ is substantially affected by genetic influences, with an average estimate of heritability across studies hovering around .50. From birth to early childhood, heritability gradually increases; by seven years of age, heritability appears to reach an adult level of around .50 (Fulker, DeFries, & Plomin, 1988; Wilson, 1983).

Specific Cognitive Abilities

Behavior genetic studies of specific cognitive abilities in middle childhood do not yet permit firm conclusions in terms of the relative influence of genes and environment across different abilities. Most of the studies involved analyses of subtests from standardized IQ tests as opposed to separate assessments of specific abilities (Plomin, 1986). Summarizing across the few twin studies involving specific abilities (Foch & Plomin, 1980; Garfinkle & Vandenberg, 1981; Ho, Baker, & Decker, 1988) is difficult, given the relatively small number of subjects involved and the diversity of tests used; however, verbal measures appear to be the most genetically influenced, whereas memory shows little genetic influence. Results for spatial ability and perceptual speed are unclear. The one adoption study of specific cognitive abilities during middle childhood suggests that at seven years of age, both verbal and spatial abilities are genetically influenced, but memory and perceptual speed are not (Cyphers, Fulker, Plomin, & DeFries, 1989).

Scholastic Achievement

There are fewer behavioral genetic studies of scholastic achievement during childhood than of cognitive abilities. Hildreth (1925) found sibling correlations of .65 and .58 for IQ and achievement, respectively, in one study, and .31 and .42 in another study. Sibling relationships, however, may be due to the combined effects of genetic and environmental influences. A study of 71 pairs of adopted siblings, unrelated children reared together, found similar correlations for achievement and ability (Willerman, Horn, & Loehlin, 1977). Results from the Colorado Reading Study have indicated that reading performance is genetically influenced during the early school years (LaBuda, DeFries, & Fulker, 1986).

Several large twin studies of scholastic achievement in adolescence have been conducted (see Plomin, 1986, for a review). One of the largest involved two cohorts of twins who received the National Merit Scholarship Qualifying Test (NMSQT; Nichols, 1965; Loehlin & Nichols, 1976). Summarizing the results across the two cohorts, it appears that about 40% of the variance is due to genetic influences. Genetic influences appear to affect the subtests uniformly. However, twins in the NMSQT studies were selected to be above average in ability and the results from these studies may not be generalizable to the full population. Furthermore, substantial changes in the interrelationship between cognition and achievement may occur between the elementary and high school years.

Phenotypic Relationships

Studies reporting the relationships between WAIS subtest scores and achievement for adults find moderate correlations ranging from .17 to .65, with the higher correlations found for verbal subtests, especially vocabulary (Matarazzo, 1980). Cattell (1987) reports correlations ranging from .20 to .60 for measures of primary mental abilities and achievement tests in a high-school sample. The highest relationships involved verbal ability. For younger children, achievement tests again correlate more highly with the WISC-R Verbal scale (.60 to .64) than with the Performance scale (.26 to .48; Sattler, 1982).

Western Reserve Twin Project

In this study, we investigate the relationship between achievement and measures of specific cognitive abilities in a behavior genetic framework. A model similar to that used by Martin, Jardine, and Eaves (1984) was used in the current study of twins during middle childhood, except that both achievement and cognitive tests were analyzed simultaneously. The approach allows genetic and environmental influences to be estimated for each measure separately and allows the covariation or overlap between any pair of tests to be broken down into genetic and environmental components. Based on previous research, we expected to find that genetic influences are important for both ability and achievement and that the etiology of the overlap between ability and achievement is structured by genetic influences.

METHODS

Subjects

Scholastic achievement and cognitive tests were administered to 132 like-sexed fraternal (DZ) and 146 identical (MZ) twin pairs as part of a larger battery of tests in the Western Reserve Twin Project (WRTP). Zygosity was determined by two raters who compared the physical similarity of the twins using items from the Nichols and Bilbro (1966) zygosity questionnaire, which has a reported accuracy of 95%. If diagnoses were uncertain, blood samples were drawn and sent to the Minneapolis Memorial Blood Bank for analysis. As is typical of twin studies that recruit on a voluntary basis, the sample is composed of more identical twins than fraternal. The twins ranged in age from 6 to 12 years (mean age, 9.8 years) and were recruited through elementary schools and birth record information provided by the Ohio State Bureau of Vital Statistics. All twins reside within a six-county area encompassing Greater Cleveland. The entire sample has a mean Wechsler intelligence score of 104.5 (SD = 15.8).

Measures

All subjects were individually administered a battery of specific cognitive ability tests (SCA). Eight subtests were selected from a larger battery developed in the Colorado Adoption Project (CAP; Cyphers, Fulker, & Plomin, 1989; DeFries & Plomin, 1985). Four composite scores were formed by summing age- and sex-corrected standardized scores. Table 1 presents the composites.

All subjects also received a group test of scholastic achievement, the Metropolitan Achievement Test (MAT; Prescott, Balow, Hogan, & Farr, 1986). The MAT provides standardized scores representing reading, mathematics, and language skills. The MAT was designed to yield comparable standard scores across grades. Item Response Theory was used in developing the MAT, providing an easy-to-difficult continuum across test levels, so that theoretically the same skills are tapped at different grade levels. The test levels used in the current study were: Primer (administered to low-functioning first graders), Primary 1 (grades 1 to mid-2), Primary 2 (grades 2 to mid-3), Elementary (grades 3 and 4), and Intermediate (grades 5 and 6).

Analyses

There were three primary goals for the analyses. First, the pattern of phenotypic relationships between the achievement and cognitive measures was examined. For this analysis each member of the twin pair was treated as an individual, and correlations were computed for each of the achievement and cognitive variables.

Second, estimates of heritability, common environment, and within-pair environment were computed for each of the cognitive and achievement variables separately. The twin design hinges upon the fact that identical (MZ) twins are 100% genetically alike and fraternal (DZ) twins are, on average, only 50% genetically alike. MZ and DZ twins raised together share the same common family environment; therefore, any differences

Table 1. *Composite scores representing specific cognitive abilities*

Verbal	Spatial	Perceptual Speed	Memory
WISC-R Vocabulary	PMA Spatial relations	Colorado Perceptual speed	Names and faces (immediate and delayed)
ETS Things (verbal fluency)	ETS Hidden patterns	ETS Finding A's	Picture Memory* (immediate and delayed)

*Originally developed for use in the Hawaii Family Study of Cognition (DeFries et al., 1979).

within a pair of MZ twins must be due to within-pair, or specific, environmental influences. If MZ twins are more similar to each other than are DZ twins, genetic influences are implicated. The extent to which MZ twin similarity is greater than the estimate of genetic influence estimates the influence of common family environment. The simplest way to estimate heritability is to subtract the DZ twin intraclass correlation from the MZ twin intraclass correlation and double the difference. Common family environment can then be estimated by subtracting the estimate of heritability from the MZ twin correlation. Within-pair environmental influences are calculated by subtracting the MZ twin correlation from 1.0. Although this simple method is commonly used, the univariate estimates presented in the present report were obtained in a similar fashion through a multivariate model-fitting approach that involves between- and within-pair mean squares.

The third major objective was to assess the genetic and environmental factors influencing phenotypic covariation. Multivariate quantitative genetics is a straightforward extension of the traditional univariate approach described above. Instead of analyzing the correlation for the same trait for members of twin pairs, the unit of analysis is the "cross-correlation" between one trait for one twin and a different trait for the co-twin. For example, just as univariate analyses indicate that genetic factors contribute to the variance of a trait when the MZ twin correlation exceeds the DZ twin correlation, genetic covariance between two traits is implicated if the MZ twin cross-correlation between the two traits exceeds that cross-correlation for DZ twins. The primary source of genetic covariance is pleiotropy, multiple effects of a gene.

The proportion of shared variance between ability and achievement due to common genetic influences is called a genetic correlation. For a genetic correlation to exist, achievement and cognitive abilities must be correlated phenotypically and both must be heritable. It should also be noted that the genetic correlation represents the extent to which the same genetic influences determine individual differences on achievement and ability measures regardless of their contribution to the phenotypic relationship. In other words, even if heritabilities are relatively low, the genetic correlation may be quite large. The same holds true for correlations among common family environmental influences and among specific environmental influences.

Although the analytic approach outlined above will allow genetic and environmental correlations to be estimated for each pair of variables, simultaneous analysis of all of the data is more efficient and powerful. Model-fitting procedures allow all of the measures to be analyzed simultaneously, provide goodness-of-fit indices, and allow alternative models to be tested. In the present analysis, a biometrical genetic analysis of twin data proposed by Fulker, Baker, and Bock (1983; see also Boomsma & Molenaar, 1986) was used. The approach involves fitting parameters to between- and within-pair cross-products that can be easily transformed into the equivalent cross-correlations. (See the special issue of *Behavior Genetics*, *19*, 1989, on structural equation modeling for details.) The initial model tested allowed one general factor each for genetic, common environment, and within-pair environment influences. Specific genetic and environmental factors were also allowed for each measure. The program LISREL VI (Joreskog & Sorbom, 1987) was used to fit the model to the data and obtain maximum-likelihood estimates of the genetic and environmental parameters.

RESULTS

Phenotypic Correlations

Although cognitive abilities and school achievement are assumed to be highly correlated, different aspects of intelligence—specific cognitive abilities—may be more or less important for school performance. Table 2 presents the phenotypic correlations for the measures of achievement and cognition for the total sample of 556 individuals. The correlations were in general only moderate in magnitude, ranging from .22 to .40. Memory was not as strongly related to scholastic achievement as were the other three ability scales.

Table 2. *Phenotypic correlations between specific cognitive abilities and school achievement*

	Verbal	Spatial	Speed	Memory
Reading	.40	.40	.33	.26
Math	.32	.32	.32	.22
Language	.34	.33	.36	.22

Note: $n = 556$. All correlations are significant (two-tailed $p < .001$).

Table 3. *Twin correlations and cross-correlations*

	Verbal	Spatial	Speed	Memory	Read	Math	Language
Identical Twins (146 pairs)							
Verbal	.60						
Spatial	.43	.75					
Speed	.24	.39	.69				
Memory	.34	.39	.29	.43			
Read	.39	.40	.29	.28	.94		
Math	.31	.34	.30	.22	.85	.91	
Language	.34	.35	.34	.22	.86	.85	.87
Fraternal Twins (132 pairs)							
Verbal	.41						
Spatial	.34	.44					
Speed	.19	.21	.39				
Memory	.21	.18	.24	.31			
Read	.23	.23	.22	.18	.79		
Math	.21	.18	.18	.17	.74	.81	
Language	.18	.19	.19	.20	.72	.73	.71

Genetic and Environmental Correlations

Twin correlations and cross-correlations for the cognitive abilities and achievement tests are listed in Table 3. Simply scanning the table reveals that for every entry, the MZ twins are more similar than the DZ twins, thus implicating genetic influence. The MZ–DZ comparisons on the diagonal indicate that heritabilities for specific cognitive abilities and achievement measures are generally substantial. For example, doubling the differences between MZ and DZ correlations yields heritability estimates of .38 for the verbal test and .30 for the reading test. Comparisons between the MZ and DZ cross-correlations in the lower left portion of the matrix indicate that genetic factors to some extent mediate the associations between specific cognitive abilities and achievement measures. That is, the MZ cross-correlation between specific cognitive abilities and achievement measures are as high as the phenotypic correlations for the same individual shown in Table 2, but the DZ cross-correlations are consistently lower. For example, doubling the difference between the MZ and DZ cross-correlations for verbal and reading (.39 vs. .23) yields .32, which is an estimate of the extent to which the phenotypic correlation between the verbal and reading tests is mediated by genetic factors. (The error of estimation in such analyses is substantial.) The remainder of the phenotypic correlation, .40 (from Table 2), is due to common family environmental influences, which can be estimated by subtracting the heritability estimate from the MZ cross-correlation ($E_c = .39 - .32 = .07$).

The genetic contribution to the phenotypic correlation represents the genetic correlation weighted by the product of the square roots of the heritabilities of the two traits, as explained by Plomin and DeFries (1979). When we divide the estimate of .32 by the product of the square roots of the heritabilities, we obtain an estimate of .94 for the genetic correlation between the two traits, thus indicating that there is substantial overlap in the genes that affect verbal ability and reading achievement.

As indicated earlier, multivariate model fitting analyzes all of the measures simultaneously, yields goodness-of-fit estimates,

Table 4. *Univariate estimates of genetic and environmental influences*

	Full Model			Reduced Model		
	h^2	c^2	w^2	h^2	c^2	w^2
Cognitive Abilities						
Verbal	.54	.08	.38	.63	—	.37
Spatial	.74	.02	.24	.76	—	.24
Speed	.70	.01	.29	.70	—	.30
Memory	.37	.07	.56	.45	—	.55
Achievement						
Reading	.27	.66	.07	.29	.64	.07
Math	.17	.73	.10	.19	.71	.10
Language	.19	.65	.16	.21	.62	.17

Note: h^2 = heritability, c^2 = common environment, w^2 = specific environment

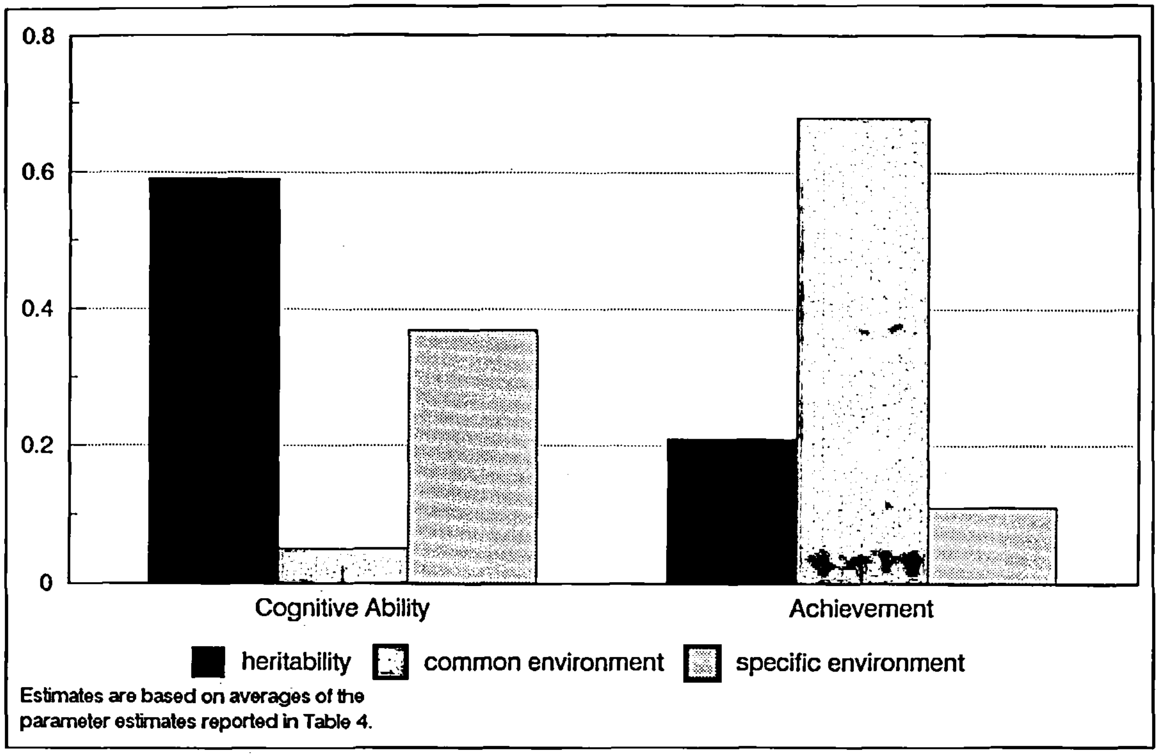

Fig. 1. Estimates of genetic and environmental influence on cognitive ability and scholastic achievement.

and makes it possible to test alternative models. The full model with one general factor and specific factors provided a chi-square value of 92.48, which significantly exceeds its 70 degrees of freedom (p = .04). The chi-square statistic is highly sensitive to large sample sizes and may not be the best indicator of fit with large samples (Marsh, Balla, & McDonald, 1988). However, the Goodness of Fit Index (GFI) provided by LISREL indicates that the model fits the data well (GFI = .95). To test the significance of common environmental and genetic contributions, two reduced models were used. In the first model, the common environment matrix was set to zero, and in the second, the genetic matrix was set to zero. Both models produced highly significant chi-squares, indicating a very poor fit, chi-square = 312.04 (df = 84, $p < .001$) and chi-square = 296.01 (df = 84, $p < .001$), respectively, for the two reduced models. Both models also provided significant changes in chi-square when compared to the full model: change in chi-square = 219.56 (df = 14, $p < .001$) and change in chi-square = 203.53 (df = 14, $p < .001$), respectively, thus indicating a significant deterioration in fit. These analyses confirm the significance of

Table 5. *Estimates for genetic and environmental correlations for the specific cognitive abilities*

	Full Model			Reduced Model		
	Spatial	Speed	Memory	Spatial	Speed	Memory
Genetic						
Verbal	.68	.61	.71	.62	.49	.59
Spatial		.60	.66		.48	.58
Speed			.48			.46
Common Environment						
Verbal	.03	.16	.00			
Spatial		.18	.00			
Speed			.00			
Within-Pair Environment						
Verbal	.01	.07	.00	.01	.07	.00
Spatial		.02	.00		.02	.00
Speed			.00			.00

Table 6. *Estimates for genetic and environmental correlations for scholastic achievement*

	Full Model		Reduced Model	
	Math	Language	Math	Language
Genetic				
Reading	.98	1.00	1.00	1.00
Math		.98		1.00
Common Environment				
Reading	.92	.96	.90	.95
Math		.95		.95
Within-Pair Environment				
Reading	.28	.52	.26	.50
Math		.54		.53

both genes and common environment in the variance of ability and achievement measures and the covariance between them.

One goal of latent variable modeling is to construct the simplest model possible that can account for the data. Inspection of the factor structure for the full model indicated that specific factors in the genetic matrix for the MAT scores were very small (see Appendix for the LISREL estimates). Although common environment was important overall, the factor structure also suggested that the general factor loadings for the SCA measures for common environment could be dropped. This reduced model produced an acceptable fit ($\chi^2 = 95.26$, df $= 81, p > .13$; change in $\chi^2 = 2.78$, df $= 11$, $p > .99$). Although the final reduced model did not produce a significant change in fit from the full model, the last model was the most parsimonious and can be considered the best-fitting model. The results for the full model and reduced model are similar.

Univariate estimates of heritability, common, and within-pair environmental influences were calculated from the LISREL estimates for the full and reduced models (Table 4). Heritabilities are higher on average for ability measures than for achievement measures. Common family environment is more influential for achievement on average, than for ability (Fig. 1).

The estimates of genetic and environmental correlations from the full and reduced models are presented in Tables 5, 6, and 7. Table 5 contains the estimates for the four specific cognitive abilities. The interrelationships among the cognitive abilities appeared to be mediated by some overlap in genetic influences. In the full model, shared family environment did not contribute a great deal to the correlations (.00 to .18).

Table 6 presents estimates for the achievement tests. The genetic correlations of .98 and 1.0 indicate that the same genetic influences structured individual differences for all three measures. A similar picture emerged for the shared environment correlations; the correlations were very high, suggesting that

Table 7. *Estimates for genetic and environmental correlations between scholastic achievement and specific cognitive abilities*

	Full Model			Reduced Model		
	Reading	Math	Language	Reading	Math	Language
Genetic						
Verbal	.84	.85	.85	.80	.80	.80
Spatial	.78	.80	.80	.78	.78	.78
Speed	.57	.58	.58	.61	.61	.61
Memory	.82	.83	.83	.74	.74	.74
Common Environment						
Verbal	.16	.16	.16			
Spatial	.17	.17	.18			
Speed	.96	.95	1.00			
Memory	−.01	−.01	−.01			
Within-Pair Environment						
Verbal	.10	.10	.18	.10	.10	.19
Spatial	.03	.03	.05	.03	.03	.06
Speed	.19	.19	−.01	.19	.20	.38
Memory	−.01	−.01	−.01	.00	.00	.00

virtually the same shared environmental influences affect all three achievement measures.

Table 7 presents the genetic and environmental intercorrelations between the achievement and ability measures. The major finding is that substantial genetic overlap occurred between the two domains. Although the common environment correlations between perceptual speed and the achievement measures are quite high, these results are artifacts of the near-zero effect of common environment on perceptual speed (see Table 4). In the reduced model, genetic correlations ranged from .61 to .80. The within-pair environment correlations were low.

DISCUSSION

The results support our hypothesis that genetic influences are important contributors to individual differences in verbal, spatial, perceptual speed, and memory abilities. Common family environment does not appear to influence specific cognitive abilities. In contrast, measures of scholastic achievement are substantially affected by common family environment. Genetic factors are relevant for achievement, although to a lesser degree than for cognitive abilities.

The most novel feature of this study is its analysis of the associations between specific cognitive abilities and achievement measures. The results are quite surprising: Ability–achievement associations are almost exclusively genetic in origin. The genetic correlations in Table 7 indicate that genetic influences on specific cognitive abilities overlap substantially with genetic influences on achievement measures. As mentioned earlier, genetic correlations can be high even if genetic factors are only modestly involved in the phenotypic correlation—this can occur, for example, if heritabilities are low. In the case of ability–achievement associations, however, the phenotypic correlations are almost entirely due to genetic mediation.

Given the preceding findings, additional insight into ability/achievement discrepancies can be obtained. Genetic and environmental correlations describe the etiology of the covariance between ability and achievement. Subtracting each of the genetic and environmental correlations from 1.0 describes the etiology of the unique variance of each measure. In other words, we can estimate the extent to which genetic and environmental differences contribute to differences in performance on ability and achievement measures.

Averaging the genetic and environmental correlations presented in Table 7 for the reduced model yields estimates of .73, .00, and .11 for the average genetic, common environment, and within-pair environment correlations, respectively. Subtracting each of these from 1.0 yields estimates of .27, 1.0, and .89 for genetic, common environment, and within-pair environment differences. These estimates suggest that both common and within-pair environmental differences are primarily responsible for ability–achievement discrepancies. Future environmental research should identify those aspects of the child's environment that contribute to ability–achievement discrepancies.

The results presented in this report are important from three different perspectives. First, they add to the literature on the nature of specific cognitive abilities by finding significant genetic influences and no effect of common family environment. Second, the results are the first published twin analyses of a scholastic achievement test battery during the early school years. The results indicate that, unlike cognitive abilities, achievement is substantially affected by common family environment as well as genetic influences. And third, the results represent the first attempt to explore the etiology of the overlap between specific cognitive abilities and achievement in terms of genetic and environmental factors. The results indicate that the covariance between ability and achievement is primarily genetically determined and that ability–achievement discrepancies are due to environmental differences.

Acknowledgments—This work was supported by NICHD Grant HD-21947. We are grateful to the twins and their families in the Western Reserve Twin Project for their time and effort. We also thank the undergraduate and graduate students who have worked on the project, and Linda Gilmore, the project coordinator.

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(RECEIVED 5/17/90; REVISION ACCEPTED 11/15/90)

Appendix. *LISREL estimates for the full and reduced models*

	General Factor	Specific Factor Loadings						
Full Model								
Genetic								
Verbal	.62	.38						
Spatial	.66		.51					
Speed	.51			.66				
Memory	.50				.33			
Reading	.50					−.10		
Math	.41						.00	
Language	.43							.09
Common Environment								
Verbal	.05	.28						
Spatial	.03		.15					
Speed	.07			.00				
Memory	.00				−.25			
Reading	.78					.22		
Math	.81						.26	
Language	.80							.00
Within Family Environment								
Verbal	.11	.60						
Spatial	.02		.48					
Speed	.19			.50				
Memory	−.01				.74			
Reading	.14					.23		
Math	.17						.27	
Language	.28							.29
Reduced Model								
Genetic								
Verbal	.63	.48						
Spatial	.66		.53					
Speed	.51			.66				
Memory	.49				.44			
Reading	.53					—		
Math	.43						—	
Language	.45							—
Shared Family Environment								
Reading	.75	−.24						
Math	.79		−.26					
Language	.77			−.06				
Within Family Environment								
Verbal	.12	.59						
Spatial	.03		.48					
Speed	.20			.50				
Memory	.00				.73			
Reading	.13					.23		
Math	.17						−.27	
Language	.28							−.29