Multivariate Genetic Analysis of Academic Skills of the Queensland Core Skills Test and IQ Highlight the Importance of Genetic *g*

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This study examined the genetic and environmental relationships among 5 academic achievement skills of a standardized test of academic achievement, the Queensland Core Skills Test (QCST; Queensland Studies Authority, 2003a). QCST participants included 182 monozygotic pairs and 208 dizygotic pairs (mean 17 years ± 0.4 standard deviation). IQ data were included in the analysis to correct for ascertainment bias. A genetic general factor explained virtually all genetic variance in the component academic skills scores, and accounted for 32% to 73% of their phenotypic variances. It also explained 56% and 42% of variation in Verbal IQ and Performance IQ respectively, suggesting that this factor is genetic *g*. Modest specific genetic effects were evident for achievement in mathematical problem solving and written expression. A single common factor adequately explained common environmental effects, which were also modest, and possibly due to assortative mating. The results suggest that general academic ability, derived from genetic influences and to a lesser extent common environmental influences, is the primary source of variation in component skills of the QCST.

A range of studies suggests that between 40% to 80% of variation in academic achievement is genetic in origin (e.g., Bartels et al., 2002; Loehlin & Nichols, 1976; Martin, 1975; Plomin, 1986), similar to estimates for the heritability of psychometric IQ (Plomin, 2003). While a number of studies have explored the genetic structure of IQ (e.g., Luciano et al., 2003; Rijsdijk et al., 2002), there is less work on the genetic fabric of the related phenotype of academic achievement (Gill et al., 1985; Martin, 1975; Martin et al., 1984). The purpose of this article is to investigate the genetic structure of five academic achievement skills designated a priori, and assumed to underlie performance on the Queensland Core Skills Test (QCST), which assesses academic achievement in year 12 (final year of secondary schooling) students.

There is good evidence that general (*g*), group (e.g., verbal, nonverbal) and specific (subtest) genetic factors influence phenotypic variation in IQ (Luciano et al., 2004; Pedersen et al., 1994; Petrill et al., 1996; Rijsdijk et al., 1998), and that variation in *g* is largely due to genetic influences (Plomin, et al., 2001). Genetic *g* also accounts for substantial variation in educational outcomes (Bartels et al., 2002; Thompson et al., 1991; Wainwright et al., 2005), with Plomin (2003) asserting that virtually all genetic variation in cognitive abilities derives from this source. Nevertheless, there is some genetic variation in cognitive measures that is not accounted for by a genetic general influence (Luciano et al., 2004; Martin, 1975, Martin et al., 1984; Petrill et al., 1996; Rijsdijk et al., 1998).

For genetic variance unexplained by *g* it is unlikely that there are specific genes that influence school topics uniquely (e.g., genes only influencing history or geography performance) but rather there are sets of genes at a group level (analogous to Verbal IQ [VIQ] and Performance IQ [PIQ]) that influence clusters of topics with overlapping skill requirements (Martin, 1975). The view that sets of generic skills are requisites for successful scholastic performance is established in the cognitive and academic achievement literature (Anderson, 1983; Benton & Kiewra, 1987; Glaser et al., 1987; Maxwell, 1987) and informs the structure of the QCST with the test delineating five a priori academic achievement skills labeled Comprehend and Collect; Structure and Sequence; Analyze, Assess and Conclude; Create and Present; and Apply Techniques and Procedures (Queensland Studies Authority, 2003a).

Recently, we reported that genetic variation in total QCST score (a measure of general academic achievement — sum score of all five academic achievement skills) was wholly accounted for by genetically induced

variation in IQ (Wainwright et al., 2005). It is of interest to determine whether different genetic elements contribute to variation in the five academic achievement skills independent of genetic g.

Method

Participants

Participants were drawn from a continuing study of cognition, the Brisbane Memory, Attention and Problem Solving (MAPS) twin study (Wright et al., 2001; Wright & Martin, 2004). Details regarding methods of twin ascertainment and exclusion criteria are described in Wainwright et al. (2005). In order to correct for ascertainment bias, IQ data were included in the multivariate analysis as described in Wainwright et al. (2005).

QCST data were available from 390 twin pairs (182 monozygotic [MZ], 208 dizygotic [DZ]), and for one twin from a further 81 pairs. This was primarily due to one of the twins from each of these 81 pairs not seeking a tertiary entrance ranking that necessitates sitting the QCST. These 81 single twins represented a less academically able subsample than those in the sample who had taken the QCST, with the single twins having lower mean VIQ, PIQ and Full Scale IQ (FSIQ) scores, the differences being 6.4 ($p < .01$), 6.1 (ns) and 6.9 ($p < .05$) respectively. More IQ than QCST data were available because at the time of writing not all participants had sat the QCST, and not all QCST data had been obtained from the Queensland Studies Authority (QSA). VIQ data were available for 611 twin pairs (and five individuals from a twin pair) and PIQ data for 615 twin pairs (and one individual from a twin pair). Participants sat the QCST in their final year of education (17.3 years ± 0.39 SD). Each participant was IQ tested as close as possible to their 16th birthday, most in their penultimate year of secondary education, with the exception of one pair of twins who were 22 years old. Details regarding determination of zygosity have been described previously (Wainwright et al., 2005).

Measures

Queensland Core Skills Test

The QCST is composed of five a priori component academic skills achievement scores. Comprehend and Collect entails comprehension of facts from a broad range of stimuli, and utilization of information to display meaning (e.g., interpretation of data presented in tables). Structure and Sequence incorporates the selection, sorting, sequencing and organization of information, and discernment of complex patterns and relationships (e.g., visualization and manipulation of spatial relationships). Analyze, Assess and Conclude involves deduction and induction among relationships, identifying the essential elements and merits of complex arguments, and the drawing of conclusions (e.g., inferring meaning from text). Create and Present captures use of written language which is effectively structured and clearly develops relevant ideas. Apply Techniques and Procedures represents skills in making calculations and mathematical problem-solving (e.g., applying principles of proportionality to solve practical problems). Further detail regarding the QCST was included in Wainwright et al. (2005) and additional information including copies of past assessment papers, annual reviews, and assignment of questions to academic achievement skills is available from the QSA website (Queensland Studies Authority, 2005).

The most recent evidence that the QCST is an appropriate measure of academic achievement is provided by reports published by the QSA showing that in 2003, total QCST score correlated .73 with a within-school measure (WSM), which is an estimate of a student's overall achievement based on teacher-decided rank order information in school-based assessment. A correlation of .73 between QCST total score and actual level of achievement based on school grades is also reported for 2003 (Queensland Studies Authority, 2003b). These correlations are consistent with reports from previous years.

Multidimensional Aptitude Battery

The Multidimensional Aptitude Battery (MAB; Jackson, 1984) is a multiple-choice test of general intelligence and is well suited for projects using large numbers of participants (Vernon, 2000). Three subtests (Vocabulary, Information, Arithmetic) were used to assess VIQ and two subtests (Spatial, Object Assembly) were used to assess PIQ. Further details about these subtests have been provided in previous papers from this laboratory (Luciano et al., 2001; Wainwright et al., 2004). The experimental procedures for IQ testing and other assessments (information processing, behavioral and physiological indices of working memory, reading) have also been previously detailed (e.g., Hansell et al., 2001; Luciano et al., 2001; Wainwright et al., 2004).

Procedure

Full details of how QCST data were obtained, including consent procedures for phenotypic data, may be found in Wainwright et al. (2005). Data for 8 years (1996–2003) were obtained for analyses reported here. For the QCST the maximum score obtainable varied according to year. For this reason, QCST component scores in each year were standardized using the means and standard deviations of the entire Queensland sample within each year (ranging from 28,225 individuals in 1996 to 31,099 individuals in 2000). This allowed data across 8 years to be pooled and analyzed together. Because there was a limited number of participants for each year between 1996 and 2003, and different items were used each year, we were unable to conduct our own factor analysis on the data and thus used the a priori designations provided by the QSA.

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Multivariate Statistical Analysis

Data Screening

Methods for assumption testing of sample representativeness, equality of means and variances according to zygosity, sex, education and age, and equality of covariances between male and female MZ pairs and same- and opposite-sex DZ pairs are described in Wainwright et al. (2005). Because at the time of IQ testing there were some differences in the duration of formal education experienced between twin pairs (students may leave school at 15 years; most co-twins had received the same duration of schooling), the effect on IQ of time spent in formal education was assessed. For QCST, duration of formal education was not considered a factor because students within a given year sit the QCST at the same time, but there is considerable variability in age. For this reason the effect of age on QCST scores was tested. Data were screened for normality, and univariate and multivariate outliers, with data distributed satisfactorily and no outliers detected. The individual observations were analyzed directly using the raw data option in the Mx package (Neale, 1997) using maximum likelihood (ML) procedures.

Multivariate Analysis

A model with a genetic general factor and genetic specific influences, a general common environment factor, and unique environmental influences in a Cholesky decomposition was compared against an ACE Cholesky decomposition. For the QCST, specific influences act on higher-order group academic achievement skills as defined by the QCST, as there are only two hierarchical (general and component) levels. The single common environment factor was simultaneously fitted with the genetic model as it has been consistently demonstrated for cognitive data that a single general common environment model best describes the architecture of common environmental effects (Eaves et al., 1984), probably reflecting positive phenotypic assortative mating acting on a linear construct of cognitive variables.

Results

Representativeness of the Sample and Equality of Means, Variances and Covariances According to Zygosity, Sex and Education

Means for Comprehend and Collect (+ 0.13 *SD*); Analyze, Assess and Conclude (+ 0.24 *SD*); and Create and Present (+ 0.17 *SD*) could not be equated to zero indicating that our twin sample was more able in these regards than the full population of test candidates. The variances for each of the five QCST academic achievement skills could be equated to a value of 1 without a significant loss of fit. Table 1 reports the means and standard deviations for females and males for the five QCST academic achievement skills, and VIQ and PIQ. Variances according to birth order and zygosity could be equated for all variables. Only for Comprehend and Collect could means not be equated at the .05 level:

Twin 2 MZ male pairs (MZM) ≠ Twin 1 MZM, DZ male pairs (DZM) or DZ opposite-sex pairs, female born first (DZFM; *p* = .036), and DZMF (DZ opposite-sex pairs, male born first) ≠ MZ female pairs (MZF) or DZ female pairs (DZF; *p* = .018). However, application of a Bonferroni correction to correct for comparison of 12 means within each variable resulted in no means differing significantly.

Males obtained higher mean scores for Structure and Sequence (*p* < .001) and Apply Techniques and Procedures (*p* < .001), while females had a higher mean score for Create and Present (*p* < .001). For none of the QCST component scores was there an effect for age. Males obtained significantly higher scores for VIQ (*p* < .001) and PIQ (*p* < .001) and greater duration of formal education was associated with higher scores for VIQ (*p* < .001) and PIQ (*p* < .005). Thus for relevant variables regression effects for sex and duration of education were incorporated into the means modeling in the subsequent multivariate analysis. Sex limitation effects were not modeled for any variables due to equality of covariances between male and female MZ pairs (scalar sex limitation), and equality of covariances between same-sex and opposite-sex DZ pairs (nonscalar sex limitation; Neale & Cardon, 1992).

Multivariate Analysis

MZ and DZ correlations for females and males for the five QCST academic achievement skills, and VIQ and PIQ are shown in Table 1. ML phenotypic correlations (95% confidence intervals) are shown in Table 2, and range from .56 to .80, although confidence intervals show that there are few significant differences in the strengths of these intercorrelations. All component skills scores correlated more strongly with VIQ than PIQ.

There was no significant loss of fit for the stipulated model compared to the Cholesky ACE decomposition with a –2LL difference of 30.45 being observed for a change of 35 *df* (*p* = .69). The path diagram in Figure 1 provides parameter estimates with 95% confidence intervals (ML). The general genetic factor (A) significantly influenced each of the five QCST academic achievement skills accounting for all genetic variance for Comprehend and Collect; Structure and Sequence; and Analyze, Assess and Conclude; and the majority of genetic influences on Create and Present, and Apply Techniques and Procedures. Between 32% and 73% of variation in component scores was accounted for by the general genetic factor. Statistically significant, although modest genetic specific effects (acting on group level component scores) explaining 12% and 10% of phenotypic variation were found for Create and Present, and Apply Techniques and Procedures respectively.

For the general common environment factor (C) there were significant influences on Comprehend and Collect; Analyze, Assess and Conclude; and Create and Present. There was also a significant effect on VIQ. Unique environment effects were primarily specific to each of the variables, and for clarity only these

Table 1

Means and Standard Deviations for Females and Males, and Correlations According to Zygosity for Queensland Core Skills Test Academic Achievement Skills and Verbal IQ and Performance IQ, with Range of *n* Individuals for Means and Pairs for Correlations

| | Means (standard deviations) | | | | Correlations | | | | |
| | Female | | Male | | MZF | MZM | DZF | DZM | DZO |
	n	*M (SD)*	*n*	*M (SD)*	105–138	77–123	61–89	48–85	99–180
CC	477	23.44 (7.31)	384	24.07 (7.77)	.75	.73	.31	.49	.48
SS	477	21.32 (7.09)	384	22.61 (7.18)	.74	.82	.42	.33	.46
AAC	477	24.86 (7.86)	384	24.95 (8.10)	.73	.73	.41	.49	.46
CP	477	43.10 (9.14)	384	40.82 (9.99)	.58	.70	.37	.30	.26
ATP	477	14.36 (5.98)	384	16.48 (6.25)	.78	.74	.37	.45	.48
VIQ	634	108.51 (10.81)	594	111.11 (11.98)	.81	.80	.55	.39	.51
PIQ	635	109.29 (16.61)	597	114.28 (15.75)	.73	.71	.40	.43	.26

Note: MZF = monozygotic female pairs; MZM = monozygotic male pairs; DZF = dizygotic female pairs; DZM = dizygotic male pairs; DZO = dizygotic opposite-sex pairs; CC = Comprehend & Collect; SS = Structure & Sequence; AAC = Analyze, Assess & Conclude; CP = Create & Present; ATP = Apply Techniques & Procedures; VIQ = Verbal IQ; PIQ = Performance IQ.

specific influences are shown in Figure 1. However, there was some evidence of minor generalized unique environmental effects influencing multiple test performances (maximally accounting for approximately 2% of phenotypic variation for QCST variables and 1% for IQ variables).

Genetic correlations (beneath diagonal) and the proportions of covariation accounted for by genetic influences (above diagonal) with 95% confidence intervals (ML) are shown in Table 3. Heritabilities appear along the diagonal. The genetic correlations show that the overwhelming majority of genetic variance for all measures arises from common genetic influences. Also, the majority of phenotypic covariation is clearly attributable to genetic factors. Moderate to strong heritabilities for component scores were evident, accounting for between 44% and 73% of phenotypic variation.

QCST data were also analyzed without correction for ascertainment bias (IQ data not included). Results from this analysis showed that correction for ascertainment bias had a minimal effect on heritability estimates of the academic skills components, reducing estimates of total genetic influences by no more than 5% for any of the component skills.

Discussion

For the genetic structure, a model incorporating a general factor and specific influences on the five QCST academic achievement skills fit the data satisfactorily. The general genetic factor accounted for all genetic variation for Comprehend and Collect; Structure and Sequence; and Analyze, Assess and Conclude, and contributed a substantial majority of genetic influence for Create and Present, and Apply Techniques and Procedures. Additionally, for the IQ measures (included to adjust for truncate selection for the QCST) genetic variability was also principally due to the general factor. Thus the model is consistent with previous research in affirming the importance of genetic *g* for academic achievement and psychometric IQ (Jensen, 1998; Plomin, 2003), although the strength of this influence varies considerably, ranging from accounting for 32% to 74% of variation in academic achievement skills and 42% and 56% of variation in PIQ and VIQ respectively.

Table 2

Phenotypic Correlations With 95% Confidence Intervals (ML) Among Queensland Core Skills Test Academic Achievement Skills and Verbal IQ and Performance IQ

	CC	SS	AAC	CP	ATP	VIQ
SS	.76 (.73–.79)					
AAC	.80 (.77–.82)	.78 (.75–.81)				
CP	.64 (.60–.68)	.58 (.53–.63)	.63 (.59–.67)			
ATP	.72 (.68–.75)	.78 (.75–.80)	.73 (.70–.76)	.56 (.51–.61)		
VIQ	.73 (.70–.76)	.73 (.70–.76)	.75 (.72–.78)	.61 (.56–.65)	.73 (.69–.76)	
PIQ	.48 (.42–.53)	.58 (.53–.62)	.49 (.43–.54)	.34 (.28–.40)	.56 (.52–.61)	.50 (.45–.54)

Note: CC = Comprehend & Collect; SS = Structure & Sequence; AAC = Analyze, Assess & Conclude; CP = Create & Present; ATP = Apply Techniques & Procedures; VIQ = Verbal IQ; PIQ = Performance IQ.
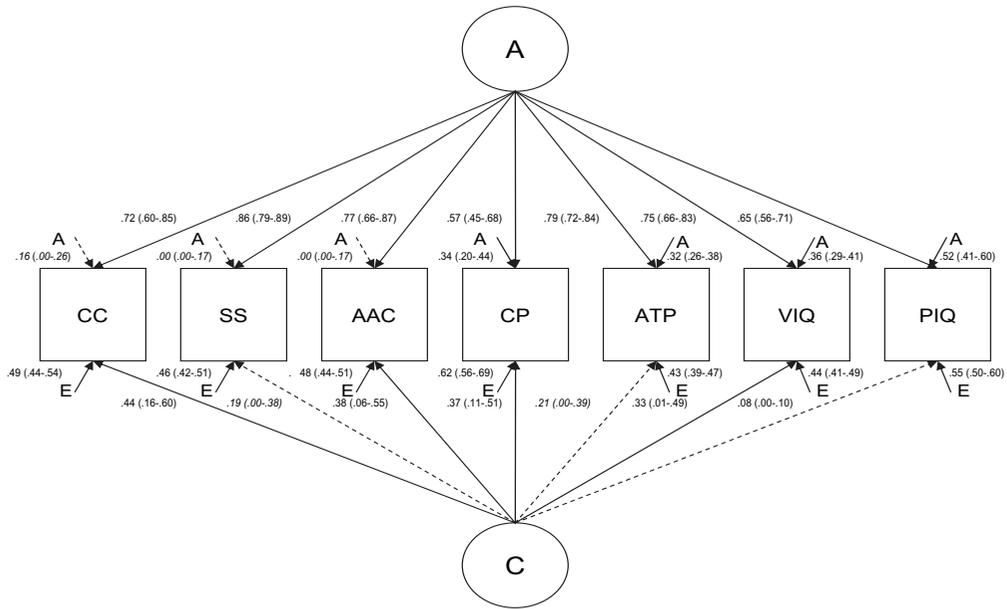
Figure 1

Path diagram showing additive genetic (A) and common environmental (C) general factor loadings, and specific additive genetic and unique environmental (E) loadings with 95% confidence intervals (ML).

A general E factor is omitted for clarity: see text. Nonsignificant parameters are shown in italics and with dashed paths. CC = Comprehend & Collect; SS = Structure & Sequence; AAC = Analyze, Assess & Conclude; CP = Create & Present; ATP = Apply Techniques & Procedures; VIQ = Verbal IQ; PIQ = Performance IQ.

Notably, adjustment for truncate selection was minuscule, consistent with ascertainment bias for the sample being relatively mild, although as previously suggested (Wainwright et al., 2005), IQ measures act as imperfect screening variables for QCST analyses. Interestingly, adjustment for ascertainment bias for total QCST score (Wainwright et al., 2005) was a little larger, presumably due to the stronger correlations between IQ measures and total QCST score than between IQ measures and component skills scores.

The two most homogenous academic achievement skills of the QCST, being Create and Present, and Apply Techniques and Procedures, were the only skill measures to evidence significant specific genetic effects, capturing distinctive achievements in written expression and mathematical problem solving. These somewhat minor genetic influences on specific skills

Table 3

Genetic Correlations, Heritabilities, and Proportions of Phenotypic Correlations Accounted for by Genetic Factors With 95% Confidence Intervals (ML) Among Queensland Core Skills Test Academic Achievement Skills and Verbal IQ and Performance IQ

	CC	SS	AAC	CP	ATP	VIQ	PIQ
CC	**.55 (.38–.73)**	.81 (.63–.96)	.70 (.50–.92)	.64 (.43–.89)	.79 (.61–.96)	.75 (.55–.96)	.98 (.79–1.00)
SS	*.98 (.93–1.00)*	**.73 (.62–.80)**	.85 (.67–.98)	.83 (.62–1.00)	.87 (.73–.94)	.89 (.71–1.00)	.97 (.86–1.00)
AAC	*.98 (.93–1.00)*	*1.00 (.97–1.00)*	**.60 (.43–.76)**	.70 (.48–.93)	.83 (.65–.97)	.77 (.58–.96)	1.00 (.84–1.00)
CP	*.84 (.74–.93)*	*.86 (.76–.94)*	*.86 (.76–.94)*	**.44 (.29–.59)**	.80 (.59–.99)	.70 (.50–.92)	1.00 (.83–1.00)
ATP	*.90 (.85–.95)*	*.93 (.89–.95)*	*.93 (.89–.95)*	*.79 (.70–.88)*	**.73 (.62–.80)**	.82 (.66–.94)	.91 (.80–.98)
VIQ	*.88 (.82–.93)*	*.90 (.86–.94)*	*.90 (.86–.94)*	*.77 (.68–.86)*	*.84 (.79–.88)*	**.70 (.56–.82)**	.99 (.83–1.00)
PIQ	*.76 (.69–.84)*	*.78 (.71–.86)*	*.78 (.71–.86)*	*.67 (.58–.76)*	*.72 (.65–.80)*	*.71 (.64–.78)*	**.70 (.57–.75)**

Note: Genetic correlations appear in italics beneath the diagonal, heritabilities appear in bold on the diagonal and proportions of phenotypic correlations accounted for by genetic influences appear above the diagonal.

CC = Comprehend & Collect; SS = Structure & Sequence; AAC = Analyze, Assess & Conclude; CP = Create & Present; ATP = Apply Techniques & Procedures; VIQ = Verbal IQ; PIQ = Performance IQ.

Heritability of total QCST score for this sample was .68.

are consistent with findings from IQ studies that have shown that specific genetic effects on particular abilities (subtest level) tend to be weak (Luciano et al., 2003; Pedersen et al., 1994).

In contrast to Create and Present, and Apply Techniques and Procedures, the academic achievement skills of Comprehend and Collect, Structure and Sequence, and Analyze, Assess and Conclude incorporate more heterogeneous content. These categories while reflecting nominally distinct cognitive abilities represent higher-order abstract reasoning and information processing skills applied to problems from a range of domains. Given that g captures intellectual processes that are in common among cognitive tests and are particularly evinced in tests of reasoning and the eduction of relations and correlates (Jensen, 1998), it is not surprising that genetic variation in these three higher order skills is wholly accounted for by a general factor. Thus, while from heuristic and pedagogical perspectives distinctions among these three academic achievement skills may be useful, processes involved in solving problems within these domains are essentially derived from a single set of genetic influences.

Heritabilities for the five academic achievement skills were moderate to strong, and comparable with findings for academic achievement in previous studies (Bartels et al., 2002; Loehlin & Nichols, 1976; Martin, 1975; Plomin, 1986). The effects of common environment were somewhat limited. In fact, the reported influence of common environment is likely to be less, given that positive phenotypic assortative mating, which inflates estimates of 'common environment' parameters although it is actually extra additive genetic variance, is known to occur for education and IQ measures (Mascie-Taylor, 1989). A shared factor for common environmental effects is consistent with positive phenotypic assortative mating, because it appears to occur for a linear construct (sum) rather than for individual abilities (Eaves et al., 1984).

Effects of the unique environment were largely specific to each component, suggesting that test unreliability is the major component of unique environmental variation. However, it is noteworthy that there were more general effects of the unique environment on QCST component scores, suggesting that individual variation in educational experiences (and/or correlated test error) yields a small amount of variation (accounting for 1% to 2%) across academic achievement skills.

In summary, a general genetic factor explained the majority of genetic variation in academic skills defined by the QCST. Specific genetic effects were limited to skills in mathematical problem-solving and written expression. A single shared factor satisfactorily explained common environmental variation, and unique environmental effects were largely specific to each variable, suggesting that test error was a major component of these effects. The results indicate that general cognitive ability, and specific skills in mathematical reasoning and verbal expression, each substantively influenced by genetic factors, sufficiently explain variation in QCST performance.

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