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The Genetic Basis of Academic Achievement on the Queensland Core Skills Test and its Shared Genetic Variance with IQ

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First, this study examined genetic and environmental sources of variation in performance on a standardised test of academic achievement, the Queensland Core Skills Test (QCST) (Queensland Studies Authority, 2003a). Second, it assessed the genetic correlation among the QCST score and Verbal and Performance IQ measures using the Multidimensional Aptitude Battery (MAB), [Jackson, D. N. (1984) *Multidimensional Aptitude Battery manual.* Port Huron, MI:Research Psychologist Press, Inc.]. Participants were 256 monozygotic twin pairs and 326 dizygotic twin pairs aged from 15 to 18 years (mean 17 years ± 0.4 [SD]) when achievement tested, and from 15 to 22 years (mean 16 years ± 0.4 [SD]) when IQ tested. Univariate analysis indicated a heritability for the QCST of 0.72. Adjustment to this estimate due to truncate selection (downward adjustment) and positive phenotypic assortative mating (upward adjustment) suggested a heritability of 0.76 The phenotypic (0.81) and genetic (0.91) correlations between the QCST and Verbal IQ (VIQ) were significantly stronger than the phenotypic (0.57) and genetic (0.64) correlations between the QCST and Performance IQ (PIQ). The findings suggest that individual variation in QCST performance is largely due to genetic factors and that common environmental effects may be substantially accounted for by phenotypic assortative mating. Covariance between academic achievement on the QCST and psychometric IQ (particularly VIQ) is to a large extent due to common genetic influences.

KEY WORDS: Academic; achievement; heritability; intelligence; twins.

INTRODUCTION

There is abundant evidence that academic achievement is correlated with IQ for both school grades and standardised achievement test scores (see review by Jensen, 1998). Despite a large number of studies demonstrating the significant heritability of IQ there has been limited research examining the heritability of academic achievement or the relative genetic and environmental contributions to the correlation between academic outcomes and IQ (see review by Petrill and Wilkerson, 2000).

The purpose of this paper is two-fold. First, to investigate the heritability of a standardised test of academic achievement known as the Queensland Core Skills Test (QCST) (Queensland Studies Authority, 2003a), which is sat by approximately 85% of Queensland year 12 (final year of schooling, typically aged 17) students, many of whom progress to tertiary studies; and second, to examine the extent to which shared genetic factors influence covariance between total score on the QCST and psychometric IQ (Verbal and Performance). While previous studies have examined the genetic correlations between academic achievement and IQ in

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children (typically ranging from 5 to 13 years of age) (e.g., Bartels *et al*., 2002; Thompson *et al*., 1991; Wadsworth *et al*., 1995) the sample for this study is of students in their final year of secondary school, with an average age of 17 years (average age of 16 years when IQ tested). Investigation of sources of covariance between academic achievement and IQ at this age is of particular interest as it captures students about to embark on higher education.

While the QCST bears many similarities to other academic achievement measures it also has particular strengths which differentiate it from other indices. First, the test was specifically designed to limit any differential advantage in performance due to the particular curriculum undertaken (Matters and Gray, 1994), notwithstanding any cognitive differences that may exist between students in different educational streams. Second, previous studies of academic achievement have used either grades for school subjects or scores on standardised tests within traditional domains such as mathematics, spelling and word recognition (reading). The QCST provides a global index of academic achievement across an uncommon breadth and variety of skills employing a diverse array of stimuli. Thus, the aim of the test is to assess general, scholastically acquired higher order skills applicable to a broad range of problems (Viviani, 1990). The test is also decomposable into five measures of achievement (factors) falling under the rubrics of Comprehend and Collect; Structure and Sequence; Analyse, Assess and Conclude; Create and Present; and Apply Techniques and Procedures (Queensland Studies Authority, 2003a).

Thus, there are three primary motivations for this study. First, there is a relatively limited body of research investigating the genetic and environmental bases of the correlation between academic achievement and IQ (with even fewer studies distinguishing between Verbal IQ [VIQ] and Performance IQ [PIQ]); second, the focus of this study is on an older age sample (late adolescence) than previously employed (childhood, early adolescence) in such investigations; and third, the distinctive aspects of the QCST, which attempts to be curriculum independent, as a measure of academic achievement.

In reviews of genetic studies, Jensen (1967, 1969) suggested that the heritability of academic achievement was quite low, (approximately 0.2–0.4) with the majority of variability arising from unique environmental effects. However, in some studies preceding (e.g., Nichols, 1965) Jensen's (1967, 1969) reviews and in a number of subsequent investigations (e.g., Bartels *et al*., 2002; Martin, 1975; Trimble and Mi, 1973) estimates in the range of approximately 0.6–0.8 have been obtained. Participants in these studies have typically ranged in age from 15 to 16 years old (Martin, 1975; Nichols, 1965), although Bartels *et al*. (2002) sample had an average age of 12 years. Plomin (1986a) reviewing large scale studies (Loehlin and Nichols, 1976; Nichols, 1965) of the National Merit Scholarship Qualifying Test (NMSQT) (age 16–17 years) suggested, that averaged across various domains, the heritability of academic achievement was approximately 0.4. Gill *et al*., (1985) provided an additional layer of analysis by adjusting for both truncate selection (systematic omission of less able students from the sample) and phenotypic assortative mating on heritability for the Australian Scholastic Aptitude Test (ASAT) (average age of 17 years), with the adjusted heritability estimated to range between 0.6 and 0.7. The overall consistency of estimates from these studies has emerged from research conducted in different countries including Australia, The Netherlands and the United States using a variety of achievement measures.

Martin (1975) has suggested that the low estimate discussed by Jensen (1967, 1969) was partly due to the poor reliability of some academic measures, particularly school grades, as well as data inadequacies in cited work by Burt (1966). Nevertheless, standardised tests have sometimes evidenced quite weak heritabilities for academic achievement (in the range of 0.2–0.3) (Petrill and Thompson, 1993; Thompson *et al*., 1991) (samples in these studies ranged between 6 and 13 years old, and 6 and 12 years old, respectively). However, these disparities are probably explained by age differences between studies with younger samples typically exhibiting stronger effects for common environment consistent with findings for general cognitive ability (*g*) (see review by Petrill and Wilkerson, 2000).

There is abundant evidence attesting to genetic effects on variation in *g* (extracted as a factor representing what is common among IQ subtests) (Plomin, 2003), with heritability increasing from early infancy (e.g., 0.15 [Plomin, 1986b]) through to adulthood (e.g., 0.81 [Finkel *et al*., 1995]). Across the totality of data obtained from a large number of studies the average estimate of the heritability of *g* is approximately 0.5 (Plomin, 2003), although this may be an underestimate since it takes no account of

assortative mating. The heritability of FSIQ in samples similarly aged to those participating in the present study is at least of this magnitude. For example Wilson's (1983) data suggested a heritability of approximately 0.70 at 15 years, while McGue *et al.*'s, (1993) study indicated a heritability close to 0.55 for 16–20 year olds. Likewise, there is evidence that variation in factors subsumed by *g* (e.g., VIQ and PIQ) are substantially influenced by genetic variation. For instance, Baker (1991) using the full version of Multidimensional Aptitude Battery (MAB) (shortened form used in the present study) reported heritabilities of 0.68 for VIQ and 0.85 for PIQ.

The evidence that genetic factors have a significant influence on the correlation between academic achievement and IQ mainly comes from studies in children. Thompson *et al.* (1991) using twins aged from 6 to 12 years old found genetic correlations ranging from 0.78 to 0.85 (full model) between achievement scores (Reading, Mathematics, Language) from the Metropolitan Achievement Test (MAT) and IQ measures (Verbal and Spatial). A similar although slightly larger genetic correlation of 0.92 between the MAT and IQ was reported by Petrill and Thompson (1993) for children aged from 6 to 13 years. Using an adoption design with 7 year old children Wadsworth *et al.* (1995) reported genetic correlations of 0.57 and 0.41 between mathematics achievement and the Verbal Comprehension (VC) and Perceptual Organisation (PO) indices, respectively of the Wechsler Intelligence Scale for Children-Revised (WISC-R) Wechsler (1981a), and of 0.80 and 0.72 between word recognition and the VC and PO scales. Chambers (2000) found genetic correlations of 0.89 and 0.86 between mathematics and reading achievement (both subjectively rated by teachers on a five point scale) and FSIQ for 7 year olds. Bartels *et al.* (2002) reported an increase in the genetic correlation between the CITO (Dutch national test of educational achievement) and IQ at ages 5, 7 and 10 (0.42, 0.74, 0.90, respectively) with a decline in the genetic correlation (0.47) at age 12. While trends are difficult to discern due to data from participants ranging from 6 to approximately 13 years old being analysed collectively in some studies, overall, previous findings suggest that the genetic correlation between IQ and academic achievement may increase during childhood (up to about 10 years of age).

For this paper analysis of QCST data is conducted first and the potential effects of truncate selection and phenotypic assortative mating on heritability of the QCST are examined. Multivariate analysis follows to assess the extent of overlap of genetic effects on QCST, VIQ, and PIQ.

METHODS

Participants

Data collection is proceeding as part of a continuing study of cognition, the Brisbane Memory, Attention and Problem Solving (MAPS) twin study (Wright *et al.*, 2001). Results are reported for a total sample of 582 twin pairs (256 MZ, 326 DZ) who had IQ scores available by December 2003. Each participant was IQ tested as close as possible to their sixteenth birthday (16.2 years ± 0.41 SD, range 15.4–18.4), most in their penultimate year of secondary education, with the exception of one twin pair who were 22 years old. Participants sat the QCST in their final year of education (17.3 years ± 0.39SD, range 15.3–18.6).

QCST data were unavailable for 164 twin pairs with an additional 75 twin pairs having one twin without QCST data. This was due to (a) some participants being not required to sit the test (see eligibility criteria in description of the QCST) and (b) some pairs sitting the test in late 2003 with their results being unavailable at the time of writing.

Approximately 70% of twin pairs were drawn from a study of naevi susceptibility (Zhu *et al.*, 1999) conducted through the Queensland Institute of Medical Research (QIMR), with the remaining 30% of twin pairs ascertained through mail-outs to high schools within south east Queensland (Wright *et al.*, 2001). For same sex twin pairs zygosity was determined using the commercial kit (AmpFISTR Profiler Plus Amplification kit, ABI) incorporating 10 independent DNA markers (nine short tandem repeat (STR) loci and one homologous region on the X and Y chromosomes, amelogenin, which confirms gender). Same sex twin pairs were checked for concordance across the nine STR loci. Results were checked against blood group results (typed by ABO, MNS and Rh systems) by the Australian Red Cross Blood Service, Brisbane and/or phenotypic data (hair, skin, eye colour). Probability of error in zygosity assignment is less than 10^{-4}.

Participants were excluded if parental report indicated either twin had a history of significant head injury, neurological or psychiatric illness, substance abuse or dependence, or current use of medication with known effects on the central nervous

system (not including previously concluded short-term treatment). Participants had normal or corrected-to-normal vision (>6/12 Snellen equivalent).

Procedure

The experimental procedures for IQ testing and other assessments (information processing, behavioural and physiological indices of working memory, reading) have been detailed in previous papers from this laboratory (e.g., Hansell *et al*., 2001; Luciano *et al*., 2001; Wainwright *et al*., 2004). Written permission for obtaining QCST results was provided by the participants, and their guardians (if <18 years) and forwarded to the Queensland Studies Authority (QSA) (formerly the Queensland Board of Senior Secondary School Studies [QBSSSS]). A database with each participant's full name, date of birth and year in which they sat the QCST was provided to the QSA with a match against their records being conducted. The database was returned to this laboratory with data for all participants that could be located on their records. All identifying information for the participants was removed upon receipt. The returned data included the total score for the QCST, scores for each subtest of the QCST (not reported here) and scores for each of the five factors identified by the QSA (not reported here). Annual statistics for the QCST including the means and standard deviations (SD) for the total number of candidates for total score, subtest scores and factor scores were also provided by the QSA. Data for 7 years (1996–2002) were obtained for analyses reported here.

Measures

Multidimensional Aptitude Battery

The MAB (Jackson, 1984) is a multiple-choice test of general intelligence and is well suited for projects using large numbers of participants (Vernon, 2000). The MAB was based on the WAIS-R (Wechsler, 1981b) and yields VIQ, PIQ and FSIQ scores. The scales correlate strongly with their WAIS-R counterparts, with Jackson (1984) reporting correlations between the MAB and the WAIS-R of 0.94 for VIQ, 0.79 for PIQ and 0.91 for FSIQ. The scales also have acceptable test-retest reliabilities being equal to or above 0.95 as reported by Jackson (1984). Similar test-retest reliabilities (VIQ, 0.89; PIQ, 0.87; FSIQ, 0.90) were reported by Luciano (2001) using test-retest data from for 50 twin pairs drawn from the same overall sample used here.

Three subtests (Vocabulary, Information, Arithmetic) were used to assess VIQ and two subtests (Spatial, Object Assembly) were used to assess PIQ. Further details regarding these subtests have been provided in previous papers from this laboratory (Luciano *et al*., 2001; Wainwright *et al*., 2004).

Queensland Core Skills Test

The QCST is a test of academic achievement that must be sat by all year 12 students who are eligible to receive an Overall Position (OP), but students ineligible for an OP may sit the test if they wish. Eligibility for an OP requires completing 20 semester units of study across years 11 and 12, with at least three subjects studied for all four semesters (12 units). The OP is used to select students competing for entry into tertiary education. Responsibility for test design, administration and scoring lies with the QSA. While the format remains consistent, different items are used each year. The test is used to assess individual achievement and as a means of weighting academic performance according to subjects studied and school attended. Due to the importance of QCST outcomes, schools in Queensland provide practice sessions on sitting the test and there is a variety of publications available to assist student preparation. The test is composed of four papers; the Writing Task (WT), two Multiple-Choice papers (MC 1 and MC 2), and Short Response questions (SR). The maximum score obtainable for the QCST varies slightly in some years due to fluctuations in the number and score value of items in the SR. The test is conducted over two consecutive days in the third last week of the third term of the student's final (year 12) school year, and takes 7 hours in total (Queensland Studies Authority, 2003b).

The test covers a very broad range of scholastically acquired skills such as mathematical problem solving, comprehending, interpreting and explaining passages of prose, interpreting visual stimuli such as cartoons, photographs and flow charts, reading graphs, grasp of scientific methodology, spelling and basic calculations, understanding spatial and mechanical relationships, and producing written prose. While there are some basic skills tested such as spelling, the test primarily aims to assess higher order scholastic achievement such as reasoning, and synthesis and integration of data (Queensland Stud-

ies Authority, 2003a). As the QCST is a relatively new test there do not, at present, appear to be any studies comparing the QCST with other measures of academic achievement.

The WT requires a 600 word piece of prose to be written in response to all, any one of, or combination of, a number of stimuli grouped around a common theme. For example the 1998 WT provided a range of stimuli relating to the concept of rituals and traditions. Two hours is allowed for the WT. The piece of writing may be in any form chosen by the candidate (e.g., discursive essay, story, report, theatre script) except poetry. Until 2000 marking criteria were divided into Proficiency (vocabulary, grammar, spelling, punctuation, conformance with length requirement) and Purpose (central idea, organisation, relevance). Each script was marked by four especially trained independent markers, two of whom marked for Proficiency and two for Purpose (Queensland Board of Senior Secondary School Studies, 2000). Following 2000, five substantive criteria were defined (central idea; vocabulary; responsiveness; grammar, spelling, punctuation; structuring and sequencing) plus conformance with word limit. Each script receives a minimum of three markings, with each marker grading either four substantive criteria or three substantive criteria plus a judgement of conformance with length requirements. Thus different mixes of the six criteria are provided across the three readings. Strict standardised marking criteria are applied. The QSA considers that the marking process is sufficiently rigorous and reliable that there is no opportunity for appeal against the score obtained (Queensland Studies Authority, 2003 a,b).

Each MC paper is composed of 50 items (four possible responses per item) with 1.5 hours allowed for each paper. The items may be individual or presented in clusters based on a common stimulus material (e.g., a graph). Items are drawn from a wide range of disciplines including language, literature, philosophy, history, physical, life and social sciences, art, and mathematics. The tests are computer scored (Queensland Studies Authority, 2003 a, b).

SR requires short responses to items drawn from a variety of disciplines and may include performing arithmetic calculations and mathematical proofs, solving complex mathematical problems, locating spelling or grammatical errors in written passages, explaining a cartoon or piece of prose, and drawing inferences from maps, graphs, designs and diagrams. Two hours is allowed for the SR. Responses are marked by two especially trained independent markers, with a third marking by a referee in the case of a discrepancy. As with the WT there is no provision for appeal against the mark obtained (Queensland Studies Authority, 2003a).

For the QCST the maximum score obtainable varied according to year. For this reason QCST scores in each year were standardised using the means and SD of the entire Queensland sample within each year. This allowed data across 7 years to be pooled and analysed together. While the QCST provides subtest and factor scores this study focussed on the total QCST score.

Statistical Analyses

Data Screening

The individual observations were analysed directly using the raw data option in the MX package (Neale, 1997) using Maximum Likelihood (ML) estimation procedures. All data were screened for normality, univariate and multivariate outliers. No univariate or multivariate outliers were detected using a conservative significance level of $p < 0.001$ (Tabachnick and Fidell, 1996). For all other assumption testing a significance level of 0.05 was used.

Representativeness of the Sample

To determine whether our sample was representative of students who sit the QCST the mean and SD of our sample were constrained to zero and one, respectively (constrained model). These constraints were then relaxed (unconstrained model). A significant difference in fit (χ^2 statistic) between constrained and unconstrained models was interpreted as the constrained model being unlikely to be true.

Testing Equality of Means, Variances, and Covariances according to Zygosity, Sex and Education

To establish regularity in sampling and measurement, the equalities of means and variances according to birth order (first born, second born) and zygosity (MZ females (MZF), MZ males (MZM), DZ females (DZF), DZ males (DZM) and opposite sex pairs with the female born first (DZFM) or male born first (DZMF) were tested using MX. Successive nested models with increasingly restrictive equality constraints upon means and variances were assessed, with each model being compared to a preceding less restrictive model using

a χ^2 statistic. A significant change in fit was interpreted as a given constraint hypothesis being unlikely to be true.

Equality of means according to sex and duration of formal education for VIQ and PIQ scores, and sex and age for QCST were also assessed. A male mean was specified for each variable as a deviation from the female mean. A χ^2 statistic was then used to determine whether the deviation parameter could be dropped without a significant change in fit. 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) a weighted regression parameter for time spent in formal education was specified and the effect of dropping this parameter 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 a weighted regression parameter for age for the QCST was included and the effect of dropping this parameter was tested.

Equality of covariance between MZF and MZM and between DZF and DZM was tested to assess potential differences in the magnitude of genetic effects according to sex. Equality of covariance between same sex DZ twin pairs and opposite sex DZ twin pairs was also examined to determine whether different genes were being expressed according to sex (Neale and Cardon, 1992).

Univariate and Multivariate Analyses

ACE, AE, and CE decompositions were compared using a χ^2 statistic for the univariate and multivariate analyses. Univariate analysis was conducted first to ascertain the heritability of the QCST and to permit adjustment to estimated parameters due to truncate selection and phenotypic assortative mating. Adjustment for truncate selection was made as it has been noted that ascertainment bias may lead to inflated estimates of genetic influences particularly when investigating educational achievement, although Martin and Wilson (1982) and Neale *et al.*, (1989) have demonstrated that these effects are relatively small. Martin (1978) has provided a detailed explanation of the mechanism of potential overestimation (overrepresentation of MZ pairs with above threshold concordance relative to DZ pairs) as well as a means of revising estimates of heritability according to the level and type of selection truncation assumed to be in effect (selection may be according to a strict cut-off [hard] or of varying probability contingent on the value of the measure [soft]). Parameter estimation for genetic effects on academic achievement is further complicated as a consequence of positive phenotypic assortative mating. In contrast to truncate selection, phenotypic assortative mating inflates estimates of common environment to the detriment of genetic effects, and it is known that assortative mating occurs for educational attainment (Plomin *et al.*, 1977; Watkins and Meredith, 1981).

Adjustment for truncate selection may be made by interpolating values on Figure 1 from Martin and Wilson (1982). It was estimated that our sample, in terms of academic ability, was representative of the upper 75% of the birth cohort (based on school retention rates and QCST participation). The revised heritability estimate from the univariate analysis was based on an assumed hard selection (see Gill *et al.*, 1985) above the 25th percentile.

For phenotypic assortative mating Martin (1978) has provided a formula for adjustment of common environmental influence as follows:

$$c^2_{\text{adj}} = c^2_{\text{R}} - h^2_{\text{R}} A/(1 - A),$$

where c^2_{R} and h^2_{R} are estimates of common environment and genetic effects derived from the twin model (in which random mating is assumed) and A is the correlation of the additive genetic values of mates. A is required to be estimated using observable mate correlation (μ) and h^2_{R}, and is derived from the following formula:

$$A = 0.5(1 - \sqrt{(1 - 4\mu h^2_{\text{R}})}).$$

RESULTS

Representativeness of the Sample

While the variance of our sample was not significantly different from that of the QCST population for the years 1996–2002 the mean of our sample could not be equated to zero ($p = 0.025$). However, our sample mean was only 0.13 of a SD above the QCST population mean which was considered of little substantive import.

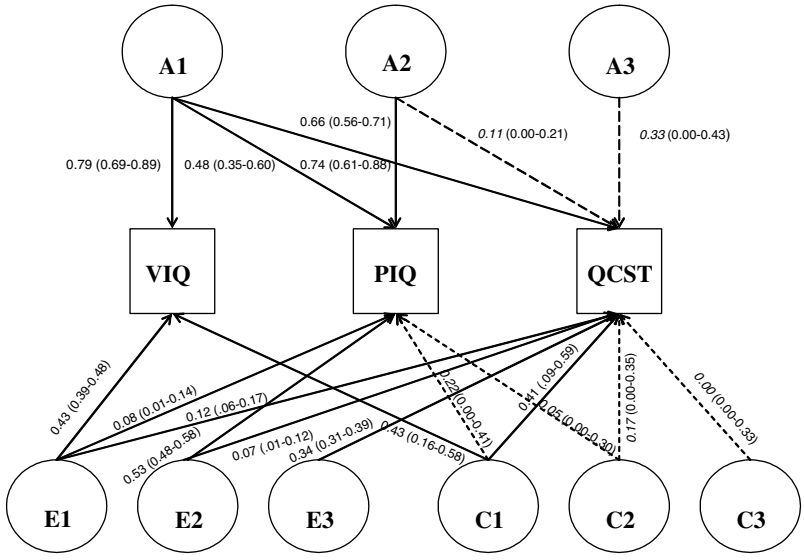

Fig. 1. Path diagram for trivariate ACE Cholesky decomposition showing additive genetic (A), common environmental (C), and unique environmental (E) factor loadings with 95% confidence intervals (ML). Non-significant parameters are shown in italics and with dashed paths. VIQ = Verbal IQ, PIQ = Performance IQ, QCST = Queensland Core Skills Test.

Testing Equality of Means, Variances, and Covariances according to Zygosity, Sex and Education

Table I reports the means and SDs for females and males for the QCST, VIQ and PIQ. For the QCST and PIQ there were no significant differences in means or variances according to birth order or zygosity, as was the case with variances for VIQ. A small number of means (MZM twin1 $\neq$ MZM twin2 [$p = 0.008$], MZM twin1 $\neq$ males from DZM, DZFM, DZMF pairs [$p = 0.0009$], MZM twin2 $\neq$ males from DZM, DZFM, DZMF pairs [$p = 0.002$], females from DZMF pairs $\neq$ females from MZF, DZF and DZFM pairs [$p = 0.03$]) for VIQ could not be equated. However, there was no pattern to these inequalities and given the large number of means tested (means for twin1 and twin2 for six zygosity groups yielding 66 comparisons of means for each variable) these differences were consistent with chance fluctuation. Consequently, means and variances for each of QCST, VIQ and PIQ were equated according to birth order and zygosity in subsequent modelling of residual genetic and environmental effects.

For QCST there was no effect for either sex or age. Males obtained significantly higher scores for VIQ ($p < 0.001$) and PIQ ($p < 0.001$), and greater duration of formal education was associated with higher scores for VIQ ($p<0.001$) and PIQ ($p<0.005$). Thus, for VIQ and PIQ regression effects for sex and duration of education were incorporated into the means modelling in subsequent analyses.

For each of QCST, VIQ and PIQ, covariances of female and male MZ twin pairs could be equated, as could covariances for female and male DZ twin pairs, indicating an equal magnitude of genetic effects for females and males for each measure. As such scalar sex limitation effects were not modelled for any of the variables. Likewise, there were no significant differences for any of the variables between same sex DZ twin pairs and opposite sex DZ twin pairs indicating that for each measure the same genes were acting on females and males (i.e., no evidence for non-scalar sex limitation).

Univariate and Multivariate Genetic Analyses

MZ and DZ correlations for females and males for QCST, VIQ and PIQ are shown in Table I. The greater magnitude of MZ correlations suggests genetic influences for each measure, and as DZ correlations are more than half the respective MZ correlations it suggests the influence of common environment outweighs any genetic dominance effects. ML Phenotypic correlations (95% confidence intervals) were 0.81 (0.78–0.84) between QCST and VIQ, 0.57 (0.52–0.61) between QCST and PIQ, and 0.51 (0.46–0.55) between VIQ and

Table I. Means and Standard Deviations (SD) for Females and Males and Correlations According to Zygosity for the Queensland Core Skills Test (QCST), Verbal IQ (VIQ), and Performance IQ (PIQ) with range of N pairs

	Means (SD)				Correlations				
					MZF	MZM	DZF	DZM	DZO
	N	Females	*N*	Males	(95–136)	(73–119)	(58–81)	(41–77)	(100–167)
QCST	424	126.4 (29.7)	337	127.9 (30.7)	0.83	0.89	0.47	0.48	0.52
VIQ	599	108.5 (10.9)	556	111.0 (12.1)	0.84	0.80	0.54	0.42	0.54
PIQ	600	109.0 (16.6)	559	114.4 (15.8)	0.73	0.70	0.41	0.44	0.27

Note: Maximum total QCST score varied according to year (231, [1996, 1997]) to 236 [2000]. All analyses were conducted using standardised scores derived from means and SDs of total Queensland student population sitting the QCST within each year. 1996, Mean = 125.3 (28.6); 1997, Mean = 123.8 (29.2); 1998, Mean = 122.9 (28.7); 1999, Mean = 114.8 (29.8), 2000, Mean = 119.0 (28.4); 2001, Mean = 132.4 (29.1); 2002, Mean = 126.0 (30.9).

PIQ. The strong QCST–VIQ correlation differed significantly from the other phenotypic correlations (all inferences regarding significant differences in parameter estimates are based non-overlapping 95% confidence intervals).

Values for full and nested sub-model decompositions for univariate and multivariate analyses are shown in Table II. For both univariate and multivariate analyses an AE model provided a satisfactory fit when compared to an ACE model, while a CE model yielded a poor fit in comparison with an ACE model. However, due to known power limitations in jointly discerning A and C influences (Martin *et al*., 1978) results of the full ACE models with 95% confidence intervals (ML) are reported for univariate and multivariate analyses.

For the univariate analysis of QCST the A factor had a significant loading of 0.85 (0.73–0.94), with C having a non-significant loading of 0.37 (0.00–0.57) and E having a significant loading 0.38 (0.33–0.43). Genetic influences were significantly stronger than either common environment or unique environment effects and it is clear that genetic sources had the largest influence on variability for total QCST score accounting for 72% of the variance. The effects of C and E were relatively small, although E had tighter confidence intervals due to greater power to detect E effects. Adjustments due to truncate selection and phenotypic assortative mating to the heritability derived from the univariate analysis of the QCST are shown in Table III which also shows QCST heritability derived from the multivariate analysis. While truncate selection diminished the estimated heritability of the QCST, even a modest putative value for parental phenotypic correlation of 0.3 resulted in a substantial reduction of common environment effects.

For the multivariate analysis the path diagram in Figure 1 provides parameter estimates with 95% confidence intervals (ML). The first genetic factor (A1) significantly influenced QCST, VIQ and PIQ

Table II. Univariate and Multivariate ACE Decompositions

Model	−2LL	df	Δ −2LL	Δdf	*p* value
Univariate Analysis					
ACE	1914.58	757			
AE	1916.14	758	1.56	1	0.21
CE	1979.22	758	64.64	1	0.00
Multivariate Analysis					
ACE	18953.97	3050			
AE	18960.14	3056	6.17	6	0.40
CE	19100.09	3056	146.12	6	0.00

Note: A value below 0.05 represents a significant change in χ^2 and thus a significant loss of fit.

Table III. Proportions of Variability of the QCST Accounted for by Genetic (A), Common Environmental (C) and Unique Environmental (E) Factors Derived from; Univariate Analysis with Adjustment for Truncate Selection and Assortative Mating; and Multivariate Analysis

Analysis	A	C	E
Univariate	0.72	0.14	0.14
Truncate selection	0.64	0.28	0.08
Assortative mating (0.1)	0.68	0.24	0.08
Assortative mating (0.2)	0.72	0.20	0.08
Assortative mating (0.3)	0.76	0.16	0.08
Multivariate	0.67	0.19	0.14

Note: Parenthetic values for assortative mating are putative parental phenotypic correlations. Heritability from multivariate analysis of VIQ = 0.62, PIQ = 0.66.

accounting for 55%, 62%, and 23% of the variances, respectively. Effects from A1 on QCST and VIQ did not differ significantly from each other, with both effects being significantly stronger than the influence of A1 on PIQ. The only significant effect from the second genetic factor (A2) was on PIQ accounting for 44% of its variance. There was no significant effect from the third genetic factor (A3) on QCST meaning that all the genetic variance for the QCST could be accounted for by genetic influences on VIQ and PIQ.

Of the common environment factors only the first factor (C1) had significant effect on the measures, accounting for 17% and 18% of the variance of QCST and VIQ, respectively with these values not differing significantly from each other. There was no significant effect from C1 on PIQ. Unique environment effects were primarily specific to each of the variables with these specific influences accounting for 12%, 18% and 28% of the variance for QCST, VIQ and PIQ, respectively.

Genetic correlations from the full ACE Cholesky model with 95% confidence intervals (ML) were 0.91 (0.83–1.00) between QCST and VIQ, 0.64 (0.52–0.77) between QCST and PIQ, and 0.59 (0.47–0.72) between VIQ and PIQ. It is clear that the overwhelming proportion of genetic variance for QCST and VIQ arose from common genetic influences and this correlation was significantly greater than that between QCST and PIQ.

Proportions of the phenotypic correlations among the tests that were accounted for by genetic, common environment and unique environment factors were derived from the full ACE Cholesky model. Genetic influences accounted for 72% of the covariance between QCST and VIQ, 75% of the covariance between QCST and PIQ, and 75% of the covariance between VIQ and PIQ. Common environment accounted for 22%, 17% and 19% of the covariance between QCST and VIQ, QCST and PIQ and VIQ and PIQ, respectively. Unique environment accounted for between 6% and 8% of the covariance between each of the measures.

DISCUSSION

There were two primary purposes of this paper. First to examine the heritability of the QCST; and second to assess the influence of genetic factors on the observable correlation between the QCST and IQ. The initial univariate analysis of the QCST revealed a substantial heritability of approximately 0.7, which despite the retention of a non-significant common environment factor is among the upper range of previous estimates of heritability for academic achievement. Even following adjustment for truncate selection a heritability of 0.64 for the QCST is commensurate with estimates from other studies (using similarly aged samples) and is comparable with estimates of genetic effects on general cognitive ability found in previous research (see review by Petrill and Wilkerson, 2000) including studies from this laboratory drawing on a slightly smaller sub-sample from the same sample pool (Luciano *et al*., 2001). In line with findings for general cognitive ability, the heritability calculated here is markedly larger than that found in studies using younger samples (e.g., Petrill and Thompson, 1993; Wadsworth *et al*., 1995) due to the larger effects of common environment on younger children, the importance of which is known to diminish throughout adolescence (see review by Petrill and Wilkerson, 2000).

Based on calculations using Martin's (1978) formula results showed that a substantial component of the effect of common environment may be explicable by extra additive genetic variance due to assortative mating. While it is clear that mates do not select each other based on assumed level of achievement on the QCST it is likely that a component of mate selection derives from observable characteristics such as occupational status or level of education which correlate with academic ability (Jensen, 1998). Given that spouse correlations for IQ typically range between 0.20 and 0.45 (see Mascie-Taylor, 1989) an adjusted heritability for the QCST at the upper end of the range of 0.68–0.76 appears reasonable. This is comparable with, albeit slightly larger than Gill *et al*.'s (1985) estimate of the range of heritability for academic achievement (0.6–0.7), whose methods of adjustment for truncate selection and assortative mating were reproduced in this study.

The QCST was explicitly designed to limit any differential advantage arising from having undertaken a particular curriculum (Matters and Gray, 1994). If the QCST does restrict such advantage it has the potential to provide a less biased estimate of the heritability of academic achievement than other standardised tests, assuming that other standardised achievement tests are in fact curriculum biased (the ASAT which the QCST superseded was considered to differentially advantage students from mathematics/science backgrounds). This would be

so if MZ twins were more concordant than DZ twins for either subject selection or magnitude of advantage derived from particular subject selection (potentially via the mechanism of general cognitive ability). Each of these processes would result in greater increases in MZ correlations relative to DZ correlations (giving increased heritability estimates) on achievement tests that were curriculum biased. However, it is worth noting that Martin (1975) investigating a sample of twins who sat public examinations in 1967 and 1968 in South Australia found no evidence of difference between MZ and DZ twins in concordance for subject selection.

The trivariate analysis supported previous research indicating that common genetic influences are primarily responsible for covariation between academic achievement and IQ measures (e.g., Bartels *et al*., 2002; Thompson *et al*., 1991). In fact the genetic correlation between the QCST and VIQ is among the strongest that has been reported between academic measures and IQ and suggests almost complete overlap of genetic influences on QCST score and VIQ. This very strong genetic correlation may be due to the nature of the QCST which assesses acquired higher order scholastic skills, using a diverse array of items (although these items, while varied, are essentially verbal [including quantitative items]), which are not curriculum bound and thus assesses academic outcomes influenced by broad, higher level cognitive skills as typically assessed by IQ tests.

Additionally, it is notable that there was a significantly stronger genetic correlation between QCST and VIQ than between QCST and PIQ. This is presumably due to QCST items being weighted towards verbal (rather than performance) skills with genetic influences for both general cognitive ability and verbal ability exerting concomitant effects on QCST and VIQ. The lower genetic correlation between QCST and PIQ was due to their genetic overlap being solely via genetic influences for general cognitive ability. This is apparent through the multiplicitous significant influence of the first factor (capturing both genetic general and genetic specific [verbal] influences) with the second genetic factor exclusively influencing PIQ (its influence on QCST is non-significant).

Interestingly, the estimated heritability of the QCST from the trivariate analysis shifted downward from the unadjusted univariate estimate and closely approximated the revised heritability derived from Martin and Wilson's (1982) method of adjustment for truncate selection. If VIQ (which was available for virtually all participants including those who had not sat the QCST) is conceptualised as a proxy screen for sitting the QCST then the trivariate analysis inherently adjusts for the truncate selection of the QCST providing unbiased ML estimates (Neale, 1997) based on the QCST data being missing at random (MAR) according to the nomenclature of Little and Rubin (1987) (see Felsenfeld *et al*., 2000) for application of this approach to stuttering data). However, it should be noted that VIQ does not act as a precise screen for the QCST with other factors also likely to be implicated in whether the QCST is undertaken. Given the potential error associated with the univariate adjustment (graphic interpolation) and the limitations of considering VIQ as a screen for sitting the QCST (additionally our sample may not be representative of VIQ within the birth cohort) the results are in good agreement and provide reciprocal support for each method as means of adjustment for truncate selection.

While this study examined the genetic correlation between academic achievement and IQ in a sample of students with an average age of 17 years (achievement tested)/16 years (IQ tested), previous studies have focussed on children up to about 12 years old (e.g., Bartels *et al*., 2002; Thompson *et al*., 1991; Wadsworth *et al*., 1995). Overall, despite some anomalies (possibly due to heterogeneously aged samples in some studies), previous work suggested an increase in genetic correlation between academic achievement and IQ up to about age 10. This increase may reflect the staggered initiation of genetic effects with general influences on cognition (perhaps reflecting development of higher executive processes), or more simply, may suggest that academic achievement for children under 10 years is less dependent on genes that influence higher level cognitive ability than, for example, rote learning. Results here when compared with previous studies (e.g., Bartels *et al*., 2002; Petrill and Thompson, 1993; Thompson *et al*., 1991) suggest that there may be relatively little increase in the genetic correlation between academic achievement and IQ after the age of approximately 10–12 years (bearing in mind that this is a cross-sectional inference only and based on different tests in different countries). Of course, it is important to note that the genetic correlation does not appear to diminish from age 10 (however, see Bartels *et al*., 2002) which would suggest a fractionation of genetic influences on academic achievement and IQ.

The strong phenotypic and genetic correlations between QCST and IQ (particularly VIQ) do not diminish the utility of the QCST as a test of academic achievement. It should not be surprising that there is a strong relationship between a test of learning outcome (achievement) and learning potential (IQ). Indeed VIQ subtests from the MAB (Jackson, 1984) and Wechsler Adult Intelligence Scale-III (WAIS-III) (Wechsler, 1997) such as Vocabulary and Information index VIQ by assessing what has been learned through general cultural exposure.

The absence of a statistically significant specific genetic influence on QCST score may appear puzzling. It seems reasonable to consider that influences with a genetic basis distinct from IQ (e.g., extent of scholastic effort) would influence academic outcomes. A possible explanation may lie with a personality factor that Ackerman (1996) has described as Typical Intellectual Engagement (TIE) (reflecting consistent involvement in intellectual pursuits such as thinking, pursuing a wide range of interests in depth, and undertaking cognitively challenging tasks, and characterised by typicality of optimal cognitive effort) which correlates between 0.3 and 0.4 with VIQ and also influences academic achievement. It may be that the first genetic factor captured aspects of TIE which are pertinent to both academic achievement and VIQ (prorated VIQ as measured by the MAB in this study is heavily weighted towards acquired knowledge). Of course for this to be the case there would have to be genetic correlations underpinning the phenotypic correlations among academic achievement, VIQ and TIE (evidence of genetic correlations among measures of temperament, IQ and academic achievement have been reported by Petrill and Thompson, 1993). It would be of considerable interest to assess whether there was specific genetic variance for achievement on the QCST in a bivariate analysis with a more fluid test of verbal intelligence such as Similarities (Horn, 1989) (verbal tests such as Vocabulary and Information typically assess crystallised abilities, while performance tests typically measure fluid abilities) from the WAIS-III (Wechsler, 1997). Future investigation of genetic correlation between academic achievement, IQ measures and TIE would also be worthwhile.

Behaviour genetic studies also provide insights into the effects of the environment on academic performance. The effect of common environment on variation in QCST score was relatively weak even following adjustment for truncate selection. If the potential effects of assortative mating are considered then the influence of common environment was minimal. The relevance of phenotypic assortative mating when estimating the heritability of educational outcomes is well recognised (Bartels *et al*., 2002; Eaves *et al*., 1984; Plomin *et al*., 1977) with deflated estimates of genetic influences arising because correlation between DZ twins greater than half that of MZ twins is attributed to the common environment when it is assumed that DZ twins, on average, share only half their genes. However, when positive assortative mating occurs DZ twins, on average share more than 50% of their genes because the phenotypic similarity between parents partly arises from genetic similarity, resulting in DZ twins having a greater probability of inheriting the same genes than would occur in a random mating population.

The trivariate analysis showed the first common environment factor significantly influencing both QCST and VIQ accounting for approximately 22% of their covariance. This could potentially reflect effects within the home such as parental influences on childrens' reading habits or drive towards achievement, as well as scholastic experiences. The somewhat minor effects of common environment suggest that variation in QCST scores is influenced to a limited extent by variation in scholastic experiences. In an affluent country such as Australia with a strong universal education system it appears that there may be limited variability in the nature of educational experiences (either at home or at school) that impact on QCST performance. Consistency in the quality of school based experiences pertinent to QCST results is suggested by the apparently uniform thorough pre-test preparation undertaken by schools in south east Queensland. The limited effect of unique environment indicates that there is relatively little influence from idiosyncratic environmental sources on QCST achievement. Additionally, because unique environmental influences were essentially specific to each of the measures it suggests that individual variation in environmental experiences does not have an appreciable general influence on the abilities measured here. The specificity of unique environmental influences suggests that the majority of variation from this source is due to measurement error. This component of variance in the QCST was quite small which was unsurprising given the rigour applied to the test's construction and its marking regime.

This study has found that variation in QCST performance is primarily due to genetic influences. The magnitude of genetic effects is comparable with the previous largest published estimates of genetic effects on academic achievement. The relatively small effect of common environment may be largely attributable to the effects of assortative mating. Unique environmental influences were small indicating high reliability for the test and minimal effects due to idiosyncratic environmental experiences. Genetic correlation between QCST and VIQ indicated almost complete overlap of genetic effects on QCST and VIQ indicating that genetic effects that influence general and verbal cognitive ability are largely responsible for academic outcomes measured in this way. Subsequent research will entail genome-wide linkage analyses to identify chromosomal regions that may harbour genes that influence academic achievement.

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