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FURTHER EVIDENCE FOR GENETIC INFLUENCES ON EDUCATIONAL ACHIEVEMENT

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SUMMARY. A genetic analysis of Tertiary Admission Examination (TAE) and Australian Scholastic Aptitude Test (ASAT) results for 264 pairs of MZ and DZ twins is reported. Purely environmental models are rejected as inadequate explanations of variation in examination performance and genetic factors must be invoked to obtain a satisfactory fit to the data. Within the portion of the age cohort who are candidates for these examinations, genetic factors appear to account for about 70 per cent of variation while environmental experiences shared by siblings appear to have little or no influence. However, when corrections are made on the assumption that examination candidates represent the top 34 per cent from a normal distribution of ability in the population, much greater variation between families is inferred for the population. If we also take account of the high correlation in educational achievement between husbands and wives the putative population twin correlations are consistent with heritabilities between 0.6 and 0.7 and modest contributions of shared environment around 20 per cent of the total variance. The data suggest that a distinction between IQ tests and tests of scholastic achievement on the basis of their causes of variation is not justified. We also show that while a common genetic factor is responsible for much of the covariation of ASAT Arts and Science scores, there are also some differences in the genes responsible for variation in the two areas.

INTRODUCTION

IN the last decade there have been great strides forward in the development of efficient methods for the analysis of individual differences and in their application to cognitive abilities. There is now little doubt that genetic factors contribute significantly to individual differences in intelligence and educational achievement (Eaves, 1975; Rao *et al.*, 1977; Rice *et al.*, 1980; Horn *et al.*, 1982) although it has been suggested that the heritability for scholastic achievement is lower than that for IQ (Jensen, 1969). Of far greater moment than the precise value of the heritability, however, are issues frequently overlooked in the traditional literature on the genetics of cognition. Is there evidence for environmental influences shared by siblings which would support the supposed importance of home background and differences between schools? Are people with different genes for ability equally influenced by environmental factors such as teaching methods (genotypes × environments interaction)? Is all genetic variation additive so that children's abilities can, on average, be predicted from parents' abilities, or is there non-additive genetic variation which makes such a prediction less accurate? What is the effect on ability differences between families of the well-known tendency of people to marry spouses of ability similar to themselves?

The most powerful method for beginning to answer some of these questions is the classical twin study in which monozygotic (MZ) and dizygotic (DZ) twins are compared. Martin (1975), analysing the South Australian Intermediate Examination results of 149 pairs of twins aged 14-15 years, found heritabilities in the range 0.76-0.89 for performance in mathematics, the sciences, languages and geography. He concluded that educational achievements, at least as assessed in large scale testing programmes, have heritabilities in the same range as IQ. One puzzling feature of Martin's results, however, was the absence of any evidence for the between pairs component of variation which one would have expected if cultural transmission and assortative mating were making any contribution to variation in educational achievement, as they do for IQ (Fulker and Eysenck, 1979).

In most studies of educational achievement the less able portion of the cohort escapes ascertainment (Martin, 1975; Loehlin and Nichols, 1976). Martin and Wilson (1982) have shown that one-sided sample selection of this kind can cause considerable bias in the estimation of genetic and environmental components of variance which are applicable to the population as opposed to the truncate sample. When they applied a correction to Martin's (1975) results to allow for the fact that only the top 67 per cent of the cohort were examined, estimates of population variance were now consistent with the existence of between families variance attributable to assortative mating or cultural transmission.

In the present study we analyse examination results in a sample of 17-year-old twins in which only the most able 34 per cent of the age cohort are represented. We attempt to take account of this severe truncate selection of the twin sample and also of the well-known correlation between husbands and wives for educational attainment in our analysis of the causes of individual differences in examination performance. We show that once allowance is made for these two complications the breakdown of variance is very similar to that found for IQ.

A further issue is the cause of correlation between ability scores. Two views may be advanced which are related to the classic debate between Spearman and Guilford on the factor structure of IQ. At one extreme is the view that all correlations are caused by a common set of genes which determine general ability and that it is environmental influences which channel this ability towards excellence in one subject or another. At the other extreme are envisaged independent gene effects, each responsible for variation in a different ability while environmental circumstances cause correlation between them by moving all scores up or down in concert. In this paper we attempt to throw light on this issue by analysing the causes of covariation between scores on an Arts and a Science test.

SAMPLE AND MEASUREMENTS

Each year approximately 8700 final year high school students (average age 17 years), or 34 per cent of the age cohort, attempt the Tertiary Admissions Examination (TAE) in Western Australia. There is a choice of 35 subjects in which a candidate may be examined although many of these are attempted by very few people. Candidates attempting the TAE normally enter for six subjects, with a small number attempting seven or more. Since 1976, most candidates have also completed the Australian Scholastic Aptitude Test (ASAT), developed by the Australian Council for Educational Research, which yields scores for performance in Mathematics/Science (ASAT Science) and Humanities/Social Science (ASAT Arts). To ensure comparability between examination results in different subjects, TAE scores are scaled by an anchor variable method, whereby the raw scores of a group taking a particular subject are scaled according to their performance on the ASAT test.

Through the Tertiary Institutions Services Centre, which administers the TAE, the magnetic tapes containing the TAE and ASAT results of all candidates in the period from 1975 to 1981 were used to extract candidates with the same surname and birthdate who had been enrolled in a particular year. This generated 517 pairs of whom 267 pairs shared the same address, 8 pairs repeated the examination and were listed twice, and the remaining 242 pairs were at different addresses. Each of the 509 prospective twin pairs was contracted to see if they were twins, and whether they were willing to cooperate in the study. No contact could be established with five pairs. Of the 242 pairs at different addresses only two pairs were found to be twins. Our final sample for which TAE and ASAT results were available thus consisted of 264 pairs of twins (41 MZ males, 55 MZ females, 52 DZ males, 38 DZ females, 78 DZ opposite- sex). Because many subjects were only attempted by a small number of candidates, we have analysed only those subjects where at least 90 twin pairs were concordant for subject choice, (English, Geography, Mathematics I and Biology), which is probably the lower limit for the useful application of the statistical methods employed below (Martin *et al.*, 1978).

Diagnosis of the zygosity of same-sex pairs was based on their response to the following questions:

1. As children were you and your twin mistaken by people who knew you?

(*a*) Frequently
(*b*) Sometimes
(*c*) Rarely

2. "Non-identical twins are no more alike than ordinary brothers and sisters. Identical twins on the other hand have such a strong resemblance to each other in stature, colouring, features of the face, etc. that people often mistake one for the other" Having read the above statement, do you think you are?

(*a*) Identical
(*b*) Non-identical

This method of zygosity diagnosis has been found by other workers (Cederlöf *et al.*, 1961; Nichols and Bilbro, 1966; Martin and Martin, 1975; Kasriel and Eaves, 1976) to be about 95 per cent correct, approximately the same reliability as obtained by typing for the most common six or seven blood group polymorphisms.

RESULTS

Sampling

Ideally one would like to analyse the data separately for each year but the numbers are too small to make this practicable. It is necessary, therefore, to pool the results of twins over years, first checking that their means and variances are homogeneous. To assess any overall significant differences over years in the means of the TAE and ASAT results for twins (Table 1), separate one-way analyses of variance were performed. Multiple comparisons were made using Scheffe's test. With the exception of Mathematics I, where there is a significant difference between the 1976 and 1977 values, there is no significant difference between the subject means for the different years. Homogeneity of the twin total variances across years (Table 1) was tested using the Bartlett-Box F test and no significant differences were found.

Since the purpose of a genetical analysis of twin data is to make inferences about the causes of variation in the population, it is important that twins are comparable with non-twin subjects. Table 2 presents the means and variances for the total population of candidates attempting the TAE and ASAT in the years 1976 to 1981. Although in the majority of cases the twin sample had a higher mean than that of the total population, the differences were not great. Differences in variances were similarly small. We are thus justified in generalising the results from the twin sample to the population of TAE and ASAT candidates.

Before fitting models to explain trait variation it is important to test whether the individuals in the MZ and DZ groups have been drawn at random from the same population by testing whether the subgroup means and variances are equal. Table 3

TABLE 1

EXAMINATION RESULTS FOR TWIN INDIVIDUALS BY SUBJECT AND YEAR

Subject		Year							All years combined
		1975	1976	1977	1978	1979	1980	1981	
ASAT Arts	Mean		26·27	25·80	33·24	28·01	30·91	29·20	28·40
	SD	N/A	8·61	7·85	8·65	7·35	7·10	7·80	8·55
	N		93	76	74	69	97	61	470
ASAT Science	Mean		31·50	28·95	25·84	29·36	36·55	31·67	30·95
	SD	N/A	7·07	7·82	8·18	9·65	7·63	9·02	8·81
	N		93	76	74	69	97	61	470
ASAT Total	Mean		57·76	51·75	59·08	57·38	67·45	60·87	59·35
	SD	N/A	14·38	13·82	15·96	15·89	13·80	15·01	11·48
	N		93	76	74	69	97	61	470
English	Mean	60·99	55·77	57·15	56·13	55·30	56·26	60·18	57·03
	SD	16·00	14·93	14·10	13·05	15·71	15·33	13·59	14·73
	N	44	94	73	69	69	91	59	499
Geography	Mean	53·62	53·87	51·40	55·50	51·52	53·44	55·00	53·44
	SD	15·17	15·80	14·50	13·00	15·47	15·75	11·12	14·56
	N	20	58	44	40	35	43	29	269
Mathematics I	Mean	57·24	61·81	51·44	56·35	59·85	57·79	60·32	57·82
	SD	12·35	11·39	12·68	13·25	13·93	15·84	13·20	13·78
	N	22	45	43	39	35	63	39	286
Biology	Mean	51·11	54·58	51·49	54·73	54·08	55·34	55·66	54·09
	SD	12·45	11·63	15·09	10·91	16·35	12·72	12·28	13·16
	N	14	47	46	47	40	45	34	273

lists the means and variances of the TAE and ASAT scores for the five twin groups. Two-tailed tests and variance ratio tests were performed between MZ and DZ means and total variances, separately for males and females. No significant differences in means or total variances in either sex were found.

It is of interest to know whether there is a difference between MZ and DZ twins in their concordance for subject choice. Table 4 shows that MZ twins choose more subjects in common than same-sex DZ twins which suggests that genetic differences influence the choice of subject taken. In his smaller sample of twin pairs Martin (1975) found no significant differences in concordance for subject choice between MZ and DZ same-sex pairs.

Testing hypotheses about the causes of trait variation

Traditional analyses of twin data have done little more than compare the correlations of MZ and DZ twins calculate a "heritability" based on some crude formula which is both inefficient, in that it uses only part of the information available, and often inaccurate in that its calculation is based upon a number of untested assumptions. For these reasons Jinks and Fulker (1970) urged the abandonment of such practices and the rigorous application of the hypothesis testing approach of biometrical genetics. Alternative models of trait variation are fitted to between-and within-pairs mean squares by the method of iterative weighted least squares (Eaves and Eysenck, 1975; Martin, 1975, Eaves *et al.*, 1978). A chi-square test of goodness-of-fit, based on expected mean squares calculated from the least squares parameter estimates, then provides a test of the adequacy of each model.

A large difference in the means of males and females will inflate the within pairs

TABLE 2

EXAMINATION RESULTS BY SUBJECT AND YEAR FOR ALL CANDIDATES

Subject	1977			1978			1979			1980			1981		
	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
ASAT Arts	8786	23·5	8·5	8612	26·3	8·0	8714	27·7	8·8	8768	35·0	8·7	8678	28·8	10·1
ASAT Science	8786	29·5	7·1	8612	34·7	7·7	8714	27·8	7·0	8768	31·0	6·8	8678	28·1	7·4
ASAT Total	8786	53·0	13·9	8612	61·0	14·3	8714	55·5	14·1	8768	65·9	14·0	8678	56·9	15·5
English	8786	54·9	15·2	8703	57·7	13·8	8803	56·4	15·0	8882	56·7	15·0	8765	56·3	14·9
Geography	3853	52·4	14·5	3810	54·3	13·5	3823	53·3	14·3	3730	52·9	14·6	3525	53·1	14·5
Mathematics I	3849	54·6	14·2	4072	55·6	14·8	4134	55·7	14·5	4128	57·1	14·1	4136	56·8	13·7
Biology	4490	52·3	13·8	4626	53·8	13·3	4579	52·9	14·0	4509	53·6	14·0	3917	53·1	14·0

TABLE 3

SUBJECT MEANS, VARIANCES AND NUMBER OF INDIVIDUALS BY TWIN TYPE, SUMMED OVER YEARS

Subject	MZ Males			MZ Females			DZ Males			DZ Females			DZ Opposite-Sex		
	N	Mean	Variance	N	Mean	Variance	N	Mean	Variance	N	Mean	Variance	N	Mean	Variance
ASAT Arts	66	28·06	72·93	100	29·06	77·44	98	27·84	81·54	66	26·76	59·29	140	29·26	69·89
ASAT Science	66	29·88	80·10	100	31·77	73·27	98	30·41	93·51	66	29·99	67·24	140	31·69	73·10
English	80	52·11	189·61	103	61·37	161·54	95	53·90	238·39	72	59·25	188·79	149	57·58	240·25
Geography	45	50·92	186·05	53	54·71	201·64	52	51·74	243·67	42	53·84	244·30	77	54·96	197·40
Mathematics I	36	55·70	165·64	61	58·87	254·40	50	58·10	243·36	45	55·06	103·84	94	59·14	169·78
Biology	24	51·70	137·59	63	54·96	138·30	43	51·48	199·37	54	54·48	196·00	89	55·15	182·25

TABLE 4

CONCORDANCE OF SUBJECT CHOICE FOR DIFFERENT TYPES OF TWINS

Twin type		Number of subjects in common 0	1	2	3	4	5	6	7	8	N	Mean
MZM	Frequency	0	0	4	7	7	6	14	2	1	41	4·71
MZF		2	2	2	5	9	14	19	2	0	55	4·64
DZM		5	2	4	7	15	11	8	0	0	52	3·73
DZF		0	8	5	6	8	9	2	0	0	38	3·29
DZOS		5	10	9	28	15	7	3	1	0	78	2·97

mean squares (WMS) of DZ opposite-sex pairs. In every case except ASAT Science, female twins have a higher mean score than males and so the DZ opposite-sex within pairs mean squares have been corrected for these sex differences (Clark *et al.*, 1980). The mean squares and their degrees of freedom for each variable are shown in Table 5.

A model for variation in MZ and DZ mean squares is shown in Table 6. E_1 is the environmental variance within families, specific to the individual and shared with no one else, not even members of the same family; it also includes measurement error. E_2,

TABLE 5

OBSERVED MEAN SQUARES BETWEEN (b) AND WITHIN (w) PAIRS USED IN MODEL FITTING

Statistic	df	ASAT Arts	df	ASAT Science	df	English	df	Geography	df	Mathematics I	df	Biology
MZM_b	32	129·93	32	139·78	39	324·46	17	290·46	13	302·77	5	165·39
MZM_w	33	17·70	33	22·36	40	58·36	18	48·81	14	60·22	6	53·70
MZF_b	48	137·00	48	124·57	49	247·64	24	308·01	24	289·77	27	232·50
MZF_w	49	17·86	49	18·48	50	65·70	25	92·59	25	204·49	28	58·60
DZM_b	48	131·51	48	154·85	45	354·49	19	471·75	16	316·92	13	218·53
DZM_w	49	32·55	49	33·49	46	127·33	20	69·59	17	135·26	14	62·34
DZF_b	31	84·27	31	94·09	34	228·86	14	250·73	14	183·76	19	329·75
DZF_w	32	36·00	32	37·42	35	155·98	15	210·97	15	57·34	20	75·61
DZO_b	67	89·88	67	101·29	70	274·58	21	242·18	26	270·73	25	221·34
DZO_w^a	67	48·06	67	46·61	70	177·21	21	156·42	26	95·59	25	127·09

[a] Corrected for mean differences between males and females

TABLE 6

SIMPLE MODEL FOR TWIN MEAN SQUARES

Mean squares		E_1	E_2	V_A
MZ female	Between	1	2	2
	Within	1	0	0
MZ male	Between	1	2	2
	Within	1	0	0
DZ female	Between	1	2	$\frac{3}{2}$
	Within	1	0	$\frac{1}{2}$
DZ male	Between	1	2	$\frac{3}{2}$
	Within	1	0	$\frac{1}{2}$
DZ opposite-sex	Between	1	2	$\frac{3}{2}$
	Within	1	0	$\frac{1}{2}$

the between families environmental component, estimates sources of environmental variance shared by both members of a twin pair but differing between pairs, including such factors as cultural differences and parental rearing practices. Since the great majority of our twin pairs attended the same school E_2 would also include the effect of any differences between school environments.

V_A is that part of genetic variation due to the additive effect of genes in the absence of assortative mating. If assortative mating (the tendency of like to marry like, as measured by the correlation between husbands and wives) occurs for a given character it will increase the additive genetic variance between pairs but in proportions such that it is completely confounded with estimates of E_2 in twin data. Any variation attributed to this source must therefore be interpreted with caution since it could arise from assortative mating, shared environment or both.

In the interests of parsimony the simplest model should be fitted first and more complicated models considered only if simpler ones fail or a significant improvement in fit is obtained by addition of extra parameters. Accordingly we first fit a simple environmental model containing E_1 alone. Failure of this model indicates that there is significant variation between families. A model incorporating E_1 and E_2 tests whether the between-families variation is entirely environmental in origin, whilst an alternative incorporating E_1 and V_A tests whether it is entirely genetic. If both two parameter models fail, a model including E_1, E_2 and V_A must be considered.

Results of fitting models to explain trait variation

The results of fitting models of variation to the TAE and ASAT results are summarised in Table 7. With the exception of Mathematics I, a model (E_1) postulating

TABLE 7

SUMMARY OF RESULTS OF MODEL-FITTING. HERITABILITY ESTIMATES GIVEN WHERE APPROPRIATE

Subject	Data Set†	$\hat{E}_1$	$\hat{E}_2$	$\hat{V}_A$	df	χ^2	$\hat{h}^2$
	10	32·29***	40·67***	—	8	20·91**	
ASAT Arts		17·03***	—	54·68***	8	6·01	0·76±0·04
		17·67***	9·04	45·99***	7	5·26	
	10	33·06***	44·50***	—	8	16·26*	
ASAT Science		18·73***	—	57·23***	8	9·31	0·75±0·04
		20·14***	17·81*	39·82***	7	5·99	0·51±0·14
	10	121·70***	82·04***	—	8	22·23**	
English		68·29***	—	140·70***	8	7·97	0·67±0·05
		64·73***	−27·41	170·10***	7	7·04	
	10	111·50***	101·60***	—	8	15·57*	
Geography		74.06***	—	140·30***	8	11·12	0·65±0·08
		76·66***	23·42	115·40*	7	11·08	
	F	198·70***	—	—	3	6·37	
		149·30***	50·70	—	2	5·34	
		158·80***	—	39·70	2	5·23	
Mathematics I		179·80***	266·70**	−235·10	1	2·41	
	M	202·50***	—	—	3	8·54*	
		101·40***	104·60**	—	2	2·11	
		60·86**	—	147·40***	2	0·28	0·71±0·12
		61·72**	11·19	136·20	1	0·24	0·65±0·45
	10	80·92***	81·70***	—	8	7·52	
Biology		54·32***	—	107·40***	8	5·94	0·66±0·08
		59·90***	41·17	62·94	7	5·12	0·38±0·26

† Results are shown for females (F), males (M) and females, males and opposite-sex (10) where appropriate.
* P<0·05 ** P<0·01 *** P<0·001

that all variation was due to individual environmental experiences failed badly and is omitted from the table. For all subjects (except Mathematics I) the same model was appropriate for both sexes, so models were fitted to all ten mean squares. For Mathematics I, models have been fitted separately to the four mean squares for females and the four mean squares for males.

For ASAT Arts, English and Geography, a purely environmental (E_1E_2) model fails to account for the data while the simple genetic model (E_1V_A) gives a good fit. For these three variables no further reductions in chi-square are obtained with the addition of an E_2 parameter to the model.

Although the E_1V_A model provides an adequate description of the ASAT Science data, addition of the E_2 parameter results in significant estimates of all three sources of variation indicating that the $E_1E_2V_A$ model is most appropriate. This is despite the fact that the improvement in chi-square over the E_1V_A model is only of marginal significance ($\chi_1^2 = 3.32$, $0.05 < P < 0.10$).

For Mathematics I, the E_1 model is able to describe adequately the data in females, indicating that there is no significant between families variation to be accounted for and that all variance is due to individual environment experiences. Although in males the data are consistent with both an E_1E_2 or E_1V_A model, the genetical model gives a better fit. When all three parameters are fitted, non-significant estimates are obtained for both $\hat{E}_2$ and $\hat{V}_A$, and $\hat{E}_2$ accounts for a trivial proportion of the variance (about 5 per cent).

For Biology, as with Mathematics 1 in males, there is little to choose between the E_1E_2 and E_1V_A models, although the latter gives a slightly better fit. Again, where all three parameters are fitted, non-significant estimates are obtained for $\hat{E}_2$ and $\hat{V}_A$, although $\hat{E}_2$ accounts for about 25 per cent of the variation.

The causes of covariation between ASAT Arts and Science scores

We have detected genetic variation for performance in all subjects (with the possible exception of Mathematics in females) and we may ask whether each subject is probing the same variation in a different way or whether some gene action is specific to certain subjects. Since not all twins have sat examinations in the same subjects we cannot employ the most elegant methods to answer this question (Martin and Eaves, 1977; Martin *et al.*, 1984). However, all twins since 1976 have taken the ASAT Arts and Science tests. The correlation between scores for these two tests is 0.58 and we wish to know the basis of this covariation. The procedure is described in detail in Eaves *et al.*, (1978, pp. 301-304). The first step is to calculate the 4 × 4 covariance matrices between the Arts and Science scores for Twin 1 and Twin 2, one matrix for each of the five twin types. Models are then fitted to the covariance matrices in which the variation and covariation between Arts and Science scores is attributed to various combinations of the three major sources, E_1, E_2 and V_A. For an E_1E_2 model of variation and covariation a fit of $\chi_{44}^2 = 42.7$ was obtained while the corresponding E_1V_A model yielded $\chi_{44}^2 = 23.1$. When covariation and variation from all three sources was specified in the model, a fit of $\chi_{41}^2 = 18.2$ resulted. Although none of the models is formally rejected by the chi-square criterion we note that the three source model represents a large and significant improvement over the E_1E_2 model ($\chi_3^2 = 24.5$, $P < 0.001$) but not over the E_1V_A model ($\chi_3^2 = 4.9$, $0.10 < P < 0.20$). We conclude that genetic factors are an important cause of covariation between Arts and Science performance but that E_2 is not. Estimates for the variance components for Arts and Science are similar to those from the univariate model fitting in Table 7 and the components of covariance for the three source model are $V_A = 31.0 \pm 8.5$, $E_1 = 6.9 \pm 2.2$, $E_2 = 5.7 \pm 7.9$. These translate into genetic, E_1 and E_2 correlations of 0.73, 0.37 and 0.43 respectively.

DISCUSSION

Twins taking the Tertiary Admission Examination in Western Australia from 1975 to 1981 appear typical of the other candidates in their cohorts. There is no indication of substantial heterogeneity in the twin samples between years nor between zygosity groups after pooling over years. Greater concordance between MZ than between DZ twins in the choice of examination subjects suggests that there is a genetic component in this choice.

Our analysis of the causes of variation in examination performance demonstrates that a significant proportion of this variation in each subject (except perhaps Mathematics in females and Biology) must be due to genetic factors. A model in which we sought to explain all variation in terms of environmental influences unique to the individual (E_1) or shared with co-twins (E_2) was firmly rejected. A model invoking additive genetic variation, however, gave a good fit in each case and no further significant improvement in fit could be obtained by allowing for shared environmental variation as well. Our results are very similar to those of other studies of examination performance on younger twin samples in South Australia (Martin, 1975) and Brazil (Salzano and Rao, 1976).

None of the above is to suggest that the *only* source of variation between pairs is due to the segregation of additive genes, but simply that our study, although bigger than most, does not have the statistical power to detect any other source. It has been shown that very much larger samples of twins than those available here are needed to reliably detect V_A and E_2 when both sources are making substantial contributions to trait variation (Martin *et al.*, 1978). The inability to resolve the causes of variation in Mathematics and Biology is largely due to the very small numbers of twins who were candidates for examination in those subjects.

A further complication in the interpretation of our results is that our twin sample is not typical of the population cohort as a whole but only of that portion of the cohort who were candidates for the TAE. This portion is only 34 per cent of the age cohort and we assume, in the absence of evidence to the contrary, that they represent the top 34 per cent from an underlying normal distribution of ability. Martin and Wilson (1982) have considered the bias that such truncate selection of twin samples will introduce to the calculation of genetic and environmental components of variation. Correlation coefficients estimated from such truncate samples will be biased downwards from their true population values, but if the trait has a genetic component then this bias will not be in the same proportion in MZ and DZ twins. In the present case let us take rough median values from our data of $r_{mz}=0.70$ and $r_{dz}=0.35$ which are consistent with a heritability of 0.70 and no E_2 variance. If we now interpolate in Figure 1 of Martin and Wilson (1982) using 66 per cent (100-34) sample truncation, we would obtain approximate estimates for the underlying ability trait in the population of $R_{mz}=0.87$ and $R_{dz}=0.65$. These putative population correlations would now be consistent with a random mating heritability of 0.44 and an E_2 component of 0.43.

Before assuming that this correction for truncate sampling has reinstated shared family environment to an important place in the aetiology of individual differences in educational achievement, we must remember that what we have estimated above as "E_2" also contains any additional genetic variance arising from assortative mating. There is certainly detectable covariation between spouses for educational achievement, estimates of the marital correlation ranging from about 0.3 to 0.7 (Jencks, 1972; Heath *et al.*, 1984). Even under moderate levels of assortative mating the extra additive genetic variation generated by assortative mating is considerable (Eaves *et al.*, 1978). Taking a median correlation between husbands and wives for educational attainment of 0.4, it can be calculated (see Martin, 1978) that more than half the variance attributed to "E_2" is genetic variance arising from assortative mating.

Taking all the above considerations into account, we would conclude that the total proportion of variance due to genetic factors is in the range of 60-70 per cent and that shared environmental influences (home background, shared schooling etc.) account for no more than 20 per cent of the total variance in examination performance. These proportions are very similar to the best estimates for the causes of variation in IQ (Fulker and Eysenck, 1979) and suggest that a distinction between IQ tests and tests of scholastic achievement on the basis of their heritabilities (e.g. Husén, 1960; Jensen, 1969) is not justified (cf. Willerman *et al.*, 1977).

We have been able to show that much of the covariation between ASAT Arts and Science scores is genetic in origin and that environmental factors contribute little to their correlation. The fact that the genetic correlation is only 0.73 indicates that, in addition to the common genetic factor underlying covariation, there are some differences in the genetic effects on the two traits. There is thus some support for the view that it is principally genetic factors which determine general ability and mainly (but not exclusively) environmental factors which channel it into proficiency in a particular subject area such as arts or science.

The finding of both common and specific genetic variation for performance in different tests is in line with the results from multivariate analyses of other twin studies of multiple abilities (Martin, 1975; Martin and Eaves, 1977; Martin *et al.*, 1984). A feature of the latter two studies, however, was that the "E_2" correlations between variables were all near unity. Eaves *et al.*, (1984) have argued that this is a consequence of assortative mating and/or cultural transmission operating on a latent variable which is a linear combination of the measured ability variables. In the present study we suggest that the low value of the "E_2" correlation is due to the combined effects of truncate sampling and the low power available to distinguish between additive genetic variation and other sources of variation between families.

The individual environmental correlation of 0.37 is small but the fact that it is greater than zero suggests that not all E_1 variance can be written off as "error". Heritabilities corrected for unreliable "error" variance will, of course, be higher than those quoted above but it is not clear what is gained by this practice, especially since it has been shown that "unreliability" itself may have a genetic component (Eaves and Eysenck, 1976). To the extent that an individual's career prospects are determined by his performance in a single examination, one is interested only in the causes of variation in that single measurement. However, to the extent that examination performance is an imperfect measure of an underlying trait on which, for instance, mate selection is based, heritability of the latent variable may be of more interest.

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