

Genetic influences on cognitive function using The Cambridge Neuropsychological Test Automated Battery

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Abstract

The genetic relationship between intelligence and components of cognition remains controversial. Conflicting results may be a function of the limited number of methods used in experimental evaluation. The current study is the first to use CANTAB (The Cambridge Neuropsychological Test Automated Battery). This is a battery of validated computerised cognitive tests, which allows assessment across a number of domains. A sample of 278 female–female Caucasian twin pairs from the UK (aged 18–76) performed such tests to establish the importance of genetic factors on four composite cognitive measures: general memory ability, inspection time (IT), working memory, and reaction time (RT). Estimates of heritability (additive genetic variance) were found to be 57% (95% CI 44, 68) for general memory, 38% (23, 51) for IT and 31% (16, 45) for working memory. The National Adult Reading Test (NART), a measure of IQ, had a heritability of 76%. RT was explained by common environmental influences and nonshared environmental influences. Moderate phenotypic correlations between general memory and NART ($r=.32$) and general memory and working memory ($r=.42$) were also reported. Both relationships could be explained by shared genetic determinants. © 2005 Elsevier Inc. All rights reserved.

Keywords: Working memory; g factor; Computerised cognition battery; Intelligence assessment

1. Introduction

The genetics of general cognitive ability has progressed rapidly over the past decade from the out-dated debates as to whether IQ was genetic or not. There is now good evidence for a general factor (often called *g*) that accounts for much of the total variance of inter-individual performance on tests of general cognitive ability (Carroll, 1993). Twin studies (several including over 10,000 twin pairs in total) indicate that heritability estimates for *g* vary from 40% to 80%, with meta-analysis revealing that approximately half of the variance of *g* is accounted

for by genetic variation (Plomin et al., 2001) and showing that this influence increases with age: from 20% in infancy to 40% in childhood to 60% in adulthood (McClearn et al., 1997).

Specific cognitive abilities such as processing speed, working memory, spatial ability and verbal ability have shown heritabilities that range from 30% to 60% in both young and elderly subjects (Finkel & McGue, 1993; Finkel, Pedersen, & McGue, 1995; Luo, Thompson, & Determan, 2003; McClearn et al., 1997; McGue & Christensen, 2002; Nichols, 1978; Pedersen, Plomin, Nesselroade, & McClearn, 1992; Petrill, Thompson, & Determan, 1995).

Such studies have applied cognitive tests such as the 'pencil and paper' tests used in the Hawaii Family Study

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of Cognition (DeFries et al., 1979; Nichols, 1978) and 'Working Memory Span' tasks (Shah & Miyake, 1996). However, the mechanics of these tests may have had an additional influence that obscured the pure cognitive component (Schatz & Browndyke, 2002).

Computer based testing for cognitive variables is now common and has been used in genetic research. Vernon (1989) made use of computerised tests to measure speed of processing and other elementary cognitive tasks, as did Luciano et al., in a study involving 15–18 year old twins, who employed delayed response and choice reaction time tasks (Luciano et al., 2001).

The most recent research has moved away from studying the genetic–environmental nature of the variance of one trait and has tended to look at the covariance between multiple traits. Multivariate genetic analysis has looked at the relationship between general cognitive ability and specific cognitive abilities. It has demonstrated how the elementary tasks that form a cognitive test battery (such as spatial span tasks and pattern recognition tasks) have genes in common; that genes that affect one cognitive ability may also affect other cognitive abilities (Alarcon, Plumen, Fulker, Corley, & DeFries, 1998; Petrill, Luo, Thompson, & Detterman, 1996; Casto, DeFries, & Fulker, 1995).

Those that have looked at general cognitive ability in this manner report that almost entirely all the relationship between such ability and specific cognitive abilities are mediated by genetic factors (Petrill, 1997).

Several studies have examined the genetic relationship between IQ and speed of information processing. One of the first twin studies to look at such measures (which used only 100 twin pairs) found that heritability for reaction time ranged from .23 to an unusually high .98 (Vernon, 1989). This study was later manipulated to demonstrate that the same genes may influence IQ and speed of processing (Baker, Vernon, & Ho, 1991; Petrill et al., 1995). In a larger study using 288 twin pairs aged 6–13, it was found that individual differences in a choice reaction task could only be explained by environmental influences (Petrill et al., 1995). Other studies have found common genetic factors for processing speed and IQ (Luciano et al., 2001; Posthuma, de Geus, & Boomsma, 2001). Neubauer, Spinath, Riemann, & Angleitner (2000), for example, state that two thirds of this relationship is mediated by genetic factors. However, the most recent study (Luciano et al., 2004) found no evidence that a unitary speed factor influenced diverse processing speed measures and IQ.

There is also evidence of a genetic factor contributing to the relationship between RT, working memory and IQ (Luciano et al., 2001) and it has further been established

that there are multiple genetic factors associated with working memory (Ando, Ono, & Wright, 2001).

The current study uses computerised tests of cognition, The Cambridge Neuropsychological Test Automated Battery (CANTAB) (Sahakian et al., 1988), to examine four areas of cognitive function: general memory and learning; working memory and executive function; inspection time (IT); and reaction time (RT). CANTAB is new to the field of quantitative genetic studies, using the accuracy and rigour of computerised psychological testing whilst also allowing for a wide range of ability avoiding ceiling and floor effects in the young (Coull, Middleton, Robbins, & Sahakian, 1995) and old (Sahakian et al., 1988), respectively. Direct feedback and appropriately graduated levels of challenge have been shown to increase interest in the tasks and so promote motivation to do well. This mitigates the problem in assessing elderly patients as not only the limits to their abilities but also their levels of motivation may be reduced by age or pathology. The tests are culture and language free (and can even be administered without verbal instruction). We used this test in a large group of female adult twins of wide age-range to assess the importance of genetic factors in the four cognitive measures. We also aimed to show the genetic and environmental relationships between a general memory factor, working memory, IT, RT and a measure of IQ, The National Adult Reading Test (NART; (Nelson, 1991)).

2. Methods

2.1. Participants

Two hundred and seventy-eight white Caucasian female–female twin pairs participated in the study; comprising 108 MZ and 170 DZ pairs. The subjects were recruited from the Twins UK (St Thomas' Adult UK Twin Registry) (Spector & MacGregor, 2002) and had a mean age of 56 with a range from 18 to 76. All are healthy volunteers who were originally recruited through a national media campaign and from twin registers, and were unaware of any hypothesis (Spector, Cicuttini, Baker, Loughlin, & Hart, 1996). The zygosity of the twins was assessed by questionnaire, which has an accuracy of over 95% (Martin & Martin, 1975) and validated by multiplex DNA fingerprinting using variable tandem repeats where necessary (i.e., when zygosity determination was unclear), thus giving 99.7% accuracy.

2.2. The CANTAB tests

The Cambridge Neuropsychological Test Automated Battery (CANTAB) is a series of computerised tests of

cognition that run on a personal computer fitted with a touch sensitive screen. It has been standardised on a large sample of 787 normal elderly volunteers (Robbins et al., 1994) and test–retest reliability studies demonstrate correlations for individual test items range between .56 and .86 (Lowe & Rabbitt, 1998). Subjects were screened with a preliminary motor task to ascertain whether or not they were capable of performing the task and all of the participants passed. A practice run was not administered.

The ten main cognitive functions included in the test are:

2.2.1. Pattern recognition memory (PRM)

Twelve patterns appear one after the other, none of which can be given a simple verbal label. Then, two choice boxes appear and the subject is instructed to choose which of the patterns they had already seen. Two variables: PRM and PRM mean latency (ml), an inspection time measure, were included in the analysis.

2.2.2. Paired associated learning (PAL)

Six boxes appear and each opens in sequence showing up to 6 patterns. Subjects were then shown a pattern in the middle of the screen and asked to choose the box the pattern previously appeared in.

2.2.3. Delayed matching to sample (DMS)

Subjects are presented with a pattern in a box and then — either simultaneously (with no delay) or a 12 s delay — shown four boxes and instructed to choose the pattern that had previously appeared. Two variables: DMS and DMS (ml), an inspection time measure, were used in the subsequent analysis.

2.2.4. Spatial span (SSP)

Many boxes appear and after presenting a sequence of opening boxes of different colours, the subject was asked to recall the order of the colours that appeared by pointing to the correct boxes in sequence.

2.2.5. Spatial working memory (SWM)

Blue squares are hidden inside a subset of boxes on the left side of the screen. The subject is required to try to locate all the blue squares and transfer them to the right side of the screen without reopening a box that has previously been selected. Two scores are calculated: SWM (be) Between errors — defined as times the subject revisits a box in which a token has previously been found. This is calculated for trials of four or more tokens only. SWM(t) Strategy — Owen, Sahakian, Semple, Polkey, & Robbins (1995) have suggested that an efficient strategy for

completing this task is to follow a predetermined sequence by beginning with specific box and then, once a blue token has been found, to return to that box to start the new search sequence. An estimate of the use of this strategy is obtained by counting the number of times the subject begins a new search with the same box. A high score represents poor use of this strategy and a low score equates to effective use.

2.2.6. Reaction time (RT)

Reaction time is measured by asking the subject to touch the screen immediately after a spot appears in the centre of the screen. The five choice reaction time test, RT (5), showed the subject five circles and the response time to a spot appearing in one of the five circles was measured.

2.3. NART

The National Adult Reading Test (NART; (Nelson, 1991)) is a 50 word oral reading test that measures vocabulary and reading ability. The words are ordered in increasing difficulty. It tests for premorbid intellectual ability; testing ability to read out aloud a series of phonemically irregular spelled words. It is highly correlated with overall intelligence, with WAIS-R, $r = .85$ (Mockler, Riordan, & Sharma, 1996; Willshire, Kinsella, & Prior, 1991).

2.4. Analysis

2.4.1. Descriptive statistics

Characteristics of the twin sample were calculated. Data on the individual test items were transformed to assure each of the ten items was normally distributed. Item correlations were also calculated. Composite scores were computed for the four factors, three of which were derived from a factor analysis of the individual items based on a study of a large sample of normal volunteers (Robbins et al., 1994). From a sample of 787 individuals, it was found that the most parsimonious interpretation of a factor analysis was that

Table 1
Summary of loadings for CANTAB tests on factors 1–3 following factor analysis performed by Robbins et al. (1994)

	Factor 1	Factor 2	Factor 3
PRM	0.73		
DMS	0.63		
PAL	0.82		
SSP	0.54		
PRM (ml) ^a		0.72	
DMS (ml)		0.76	
SWM (be)			0.88
SWM (st)			0.77

^a A similar measure of mean latency is given in Robbins et al.

Table 2
Descriptive statistics

	MZ (<i>n</i> =108 pairs)		DZ (<i>n</i> =170 pairs)		<i>T</i> -test (<i>p</i> -value)
	Mean	S.D.	Mean	S.D.	
Age	56.0 (20–75)	11.2	55.7 (18–76)	11.4	0.77
Ave. NART	114.1	10.4	113.0	10.2	0.05
<i>CANTAB Individual Tests</i>					
PRM [GM]	.44	.70	.32	.74	0.05
DMS [GM]	.19	.97	.13	.96	0.41
PAL [GM]	–.25	.94	–.35	1.07	0.24
SSP [GM]	.19	.93	.23	.95	0.68
PRM (ml) [IT]	.07	.72	.01	.74	0.42
DMS (ml) [IT]	–.34	1.40	–.37	1.32	0.81
SWM (be) [WM]	.40	.78	.40	.79	0.92
SWM (st) [WM]	.03	.82	.06	.85	0.70
RT [RT]	–1.08	1.89	–1.15	1.99	0.70
RT (5) [RT]	–.19	1.08	–.22	1.32	0.79
<i>Composite scores</i>					
GM	.05	.55	–.03	.62	0.14
IT	.03	.90	–.02	.84	0.56
WM	.00	.68	.00	.67	0.99
RT	.04	1.35	–.02	1.49	0.65

S.D.: standard deviation from the mean.

Key: NART — National Adult Reading Test; PRM — Pattern recognition memory; DMS — Delayed matching to sample; PAL — Paired associated learning; SSP — Spatial span; PRM (ml) — Pattern recognition memory (mean latency); DMS (ml) Delayed matching to sample (mean latency); SWM (be) — Spatial working memory (between errors); SWM (st) — Spatial working memory (strategy); RT — Reaction time; RT (5) — 5 choice reaction time; GM — General memory; IT — Inspection time; WM — Working memory; RT — Reaction time.

the first factor represented general learning, the second factor represented speed of responding to a task (or inspection time) and the third factor represented executive processes including working memory. A summary of loadings for CANTAB tests is displayed in Table 1.

Table 3
Correlations of individual items

	PRM	DMS	PAL	SSP	PRM (ml)	DMS (ml)	SWM (be)	SWM (st)	RT	RT(5)
PRM	1.0									
DMS	0.29	1.0								
PAL	0.40	0.33	1.0							
SSP	0.33	0.32	0.38	1.0						
PRM (ml)	0.29	0.08	0.22	0.15	1.0					
DMS (ml)	0.08 (ns)	0.12	0.15	0.10	0.39	1.0				
SWM (be)	0.27	0.33	0.44	0.48	0.16	0.07 (ns)	1.0			
SWM (st)	0.20	0.25	0.33	0.40	0.08	0.04 (ns)	0.72	1.0		
RT	0.07 (ns)	0.18	0.18	0.18	0.12	0.05 (ns)	0.22	0.17	1.0	
RT (5)	0.14	0.21	0.16	0.16	0.20	0.09	0.18	0.13	0.67	1.0

Key: (ns) not significant at 5%.

Reaction time measures were not included in this factor analysis and so a fourth factor, a composite score of reaction time to contrast with inspection time was constructed (the contrast is reflected in the low correlations between the reaction time measures and the ‘speed to respond to task’ measures, DMS and PRM (ml)).

General learning and memory ability (GM) consisted of PRM, DMS, PAL and SSP; inspection time (IT) comprised PRM and DMS mean latencies; working memory (WM) is a measure of SWM (strategy score) and SWM (between errors score); and reaction time (RT) consisted of RTI, RTI (five choice).

All preliminary analyses were conducted using STATA.

2.4.2. Genetic modelling

The details of fitting models to data on twins have been described elsewhere (Neale & Cardon, 1992). In summary, an individual person’s phenotype is the sum of the effects of both genotype and environment. To study the sources of individual differences (i.e., the variance) in a phenotype, genetically related subjects such as twins or sib-pairs are required.

MZ twins are genetically identical. DZ twins share on average half their genetic material. Both groups can be assumed to share their cultural and family environment to an equal extent. Hence demonstrating greater phenotypic correlation in MZ compared with DZ pairs provides an indication that genetic factors are involved in determining a trait.

The relative contribution of genetic and environmental variation to a trait can be assessed quantitatively by variance components analysis based on the pattern of correlation among the twins. The analysis considered five measure traits. The genetic contribution to variation has a potential contribution from additive (A) and non-additive or dominance (D) variation. Environmental variation has a potential contribution from variation in the

Table 4

MZ and DZ correlations and estimated variance components from best-fitting AE/CE model with 95% lower and upper confidence intervals (*df*=4)

	<i>r</i> MZ	<i>r</i> DZ	Model	Additive genetic variance C % (95% CI)	A %/Shared environmental variance	Non-shared environmental variance E % (95% CI)	χ^2	AIC
NART	0.71	0.37	AE	76(70, 81)		24(19, 30)	19.40	11.4
GM	0.53	0.43	AE	57(44, 68)		43(32, 56)	4.01	-3.99
IT	0.43	0.12	AE	38(23, 50)		62(50, 77)	8.89	0.89
WM	0.29	0.21	AE	31(16, 45)		69(55, 84)	10.56	2.56
RT	0.14	0.13	CE	13(1, 25)		87(75, 99)	6.16	-1.84

common family environment of the twins (C) and variation that is unique to individual twins (E). The twin model stipulates that the phenotypic covariance (Cov) among twins can be expressed in terms of these variance components such that:

$$\text{Cov(MZ)} = A + D + C$$

$$\text{Cov(DZ)} = 0.5A + 0.25D + C$$

The extent to which the observed pattern of variation and covariation among traits measured in MZ and DZ twin pairs can be accounted for by contributions from A, D, C and E can be assessed by comparing the fit of a set of nested models from which variance components are sequentially removed as follows: ACE, ADE, AE, CE and E (C and D cannot be included in the same behavioural genetic model). The significance of the contribution of individual variance components is assessed by the change in model χ^2 statistics.

Age influences cognitive functioning and thus the similarity in age within pairs has the potential to inflate correlations for cognitive traits in both monozygotic and dizygotic twins. If unaccounted for in modelling, this might lead to an overestimate of the contribution of the common environment (Snyder, 1999). In this analysis we eliminated the effect of age by conducting modelling on the residuals of the regression analysis in which age was included.

Cognitive factors are known to be correlated in individual subjects. The extent to which shared genetic and environmental factors might explain this correlation was investigated here by considering a set of bivariate models, constructed as a Cholesky factorization for all 10 possible pairs of variables. This factorisation includes

Table 5
Bivariate model fitting

Model (AE Cholesky)	Genetic correlation	Environmental correlation	χ^2	<i>df</i>	AIC	<i>p</i>
GM, NART	0.41	0.13	18.81	14	-9.19	0.17
IT, GM	0.32	0.00	24.97	14	-3.03	0.04
WM, NART	0.33	0.01	32.78	14	4.78	<0.01
WM, GM	0.80	0.20	30.86	14	2.86	0.01

genetic and environmental variance components that were both unique to each of the pair variables and shared between them. Parameter estimates from the most appropriate bivariate models provide an estimate of the extent to which genetic and environmental factors contribute to the phenotypic correlation between pairs of variables and through providing a measure of the genetic and environmental correlation.

Model fitting to twin data is based on either variance–covariance matrices or raw data. In this case variance–covariance matrices of MZ and DZ twins were used with the maximum likelihood approach implemented. Structural equation model fitting of this kind is performed using the statistical package Mx (Neale, Boker, Xie, & Maes, 1999).

3. Results

3.1. Descriptive statistics

The mean ages were not significantly different (Table 2). MZ twins had a mean age of 56 years (S.D. = 11 yr, range 25–75 yr) and DZ twins 55 years (S.D. = 11 yr, range 18–76). NART IQ scores for DZ twins are one point lower on average than for MZ twins, which was of borderline significance (*p* = 0.05).

As expected, most of the individual tests were correlated (Table 3). Apart from non-significant results, individual test items are correlated between 0.09 and 0.72 in keeping with previous studies (Robbins et al., 1994). Analysis proceeded using composite scores.

Correlations between the four composite score ranged from none (*r* = .00, *p* = .95) for working memory and inspection time) to moderate (*r* = .42, *p* < .001) for GM and WM. The correlations between NART and three of the four composite scores of cognition were positive and ranged from .12 for RT to .32 for GM. There was no significant correlation between NART and IT. There was however, as expected, a strong, negative correlation with age for all four composite scores: -.42 (GM), -.27 (IT), -.43 (WM) and -.20 (RT).

Table 6
Phenotypic, genetic and environmental correlations

	NART	General memory	Inspection time	Working memory
General memory (phen)	0.31			
G	0.27			
E	0.04			
Inspection time (phen)	0.02 (ns)	0.13		
G	–	0.13		
E	–	0.00		
Working memory (phen)	0.16	0.42	0.00 (ns)	
G	0.16	0.32	–	
E	0.00	0.10	–	
Reaction time (phen)	0.12	0.19	0.08	0.14
G/C	–	–	–	–
E	0.12	0.19	0.08	0.14

Key: (phen) — phenotypic correlation.

3.2. Heritability

Heritability estimates for the individual CANTAB tests range from moderate to high (34–64%), with NART score displaying a heritability of 76% (95% CI 70–81).

Twin pairs showed varying degrees of similarity in their composite scores although MZ correlations (0.14–0.71) were always greater than DZ correlations (0.12–0.43) (Table 4). Univariate model-fitting analysis of the covariance matrices of the composite scores confirmed that a model containing parameters for additive genetic effect and unique environment provided the best explanation of the data for three composites with no significant loss of fit when the effect of common environment was removed from the model. A model fitting common environment and unique environment best described the RT composite. The parameter for the common shared environment was estimated at 13% (95% CI 1, 35) with the remaining variance attributed to the unique environment and a measurement of error. Estimates of heritability ranged from 31% (95% CI 16, 45) for WM to 57% (95% CI 44, 68) for GM. Details of the remaining parameter estimates and 95% confidence intervals for the composite scores are given in Table 4.

3.3. Genetic and environmental correlations

Bivariate genetic analysis (Tables 5 and 6) demonstrated that the phenotypic relationships between NART, general memory and working memory are largely mediated by genetic factors. The correlation between NART and WM ($r=.16$) can be explained entirely by genetic factors and similarly, almost 90% of the correlation between NART and general memory ($r=.31$) could be explained by shared genes, the remaining 10% due to nonshared environmental

influences. Approximately 75% of the relationship between WM and GM ($r=.42$) was found to be influenced by shared genes. Again, the remainder was accounted for by nonshared environmental influences.

The relationship between IT and GM was entirely mediated by genetic factors and the phenotypic correlations that included reaction time (.12, .19 .08 and .14 for NART, GM, IT and WM, respectively) were entirely explained by nonshared environmental influences (and includes error).

Only the relationship between GM and NART was found to be statistically significant though the relationship between IT and GM was approaching significance. Since RT was not found to be influenced by genetic factors, it was not included in the bivariate analysis.

4. Discussion

The CANTAB Battery (Robbins et al., 1994) applies computerised testing for concise, accurate measurement of a range of cognitive domains. The battery is a useful addition to the field: it delivers effects and it has a wide application from neuropsychology to psychopharmacology to neurotoxicology (Fray & Robbins, 1996). The current study is the first genetic study to use CANTAB and to our knowledge, the first to test a female subgroup with a wide age range.

NART, a measure of IQ that correlates .85 with WAIS-R, demonstrated a high heritability (76%), consistent with other measures of IQ (Bouchard, 1998). Model fitting results suggest this estimate ought to be treated with caution but the confidence intervals (70–81 and 19–30) are close enough to suggest that the result is genuine. Though NART, by testing familiarity with irregular words, is an indicator rather than a direct measure of intelligence (Crawford, Deary, Starr, & Whalley, 2001).

The composite factor of ‘general memory ability’, derived from the first principle component of Robbins et al. (1994), is akin to a measure of g ; tapping the cognitive resources of the elementary cognitive tasks. A high heritability (57%) was demonstrated in the current study, slightly above estimated values that takes into account all family, adoption and twin data (Chipuer, Rovine, & Plomin, 1990; Loehlin, 1989). The phenotypic correlation between NART and ‘general memory ability’ was found to be moderate ($r=.32$, $p<.001$) and this is also consistent with the literature (Wright et al., 2002).

Working memory, as a composite score of measures on tasks that assesses executive functions, span length and visual memory, demonstrated a moderate heritability (31%) which is lower than that previously reported

(Ando et al., 2001; Finkel & McGue, 1993; Finkel & McGue, 1998; Nichols, 1978; Pedersen et al., 1992). It should be noted that the model fit for WM was bordering significance (AIC — 2.56) but as with NART, the confidence intervals suggest the result is plausible. A moderate correlation between WM and GM is evident (.42). Some commentators argue that working memory and g are closely related (Deary, 2001) and this may account for the strong relationship here.

IT heritabilities have been reported at 45% (Luciano et al., 2001; Petrill et al., 1995) and 46% (Posthuma, de Geus et al., 2001) so the estimate reported here, 38%, is reasonably consistent with these. IT has a weak and positive relationship with GM ($r = .13$) in our study. This is surprising as from previous studies one might expect a negative correlation and a relationship that is moderate in size ($-.19$ to $-.56$) (Luciano et al., 2001; Posthuma, de Geus et al., 2001). RT displays a similar weak, positive relationship with both NART and general memory. Evidence does exist in the literature to suggest that faster brains do not necessarily mean smarter brains (Posthuma, Neale, Boomsma, & de Geus, 2001) but this used EEG peak frequencies as an index of speed of CNS processing. The bulk of literature that use similar measures to the current study (Luciano et al., 2001; Vernon, 1987) points to a negative relationship between speed of information processing and intelligence. This may be a reflection on the reliability of the reaction time measures that demonstrated low twin correlations. RT, in particular, was shown to have a large proportion of variance (83%) due to unique environmental effects and error.

Importantly, bivariate genetic analysis revealed that genetic factors explain a large proportion of the phenotypic correlations between NART, WM and GM: approximately 75% between GM and WM, almost 90% between GM and NART and almost all of the relationship between WM and NART (though it should be noted that GM and NART provided the only significant result in the analyses). Many studies have shown similar findings (Petrill, 1997). For example, Ando et al. (2001) looked at the relationship between working memory and two composite scores of IQ — a spatial cognitive (SC) ability score and a verbal cognitive (VC) ability score. Like the current paper, a common genetic factor explained a substantial amount of the overlap. It appears to be the case that genetic influences rather than environmental influences contribute to the relationship between working memory and higher order cognitive abilities.

However, unlike previous studies that have looked at the relationship between processing speed and IQ (Luciano et al., 2001; Neubauer et al., 2000; Posthuma,

de Geus et al., 2001), it was found that the phenotypic correlation between IT and GM was explained by genetic factors.

In conclusion we have shown the application of computerised cognitive testing for genetic studies and demonstrated a range of heritabilities for the composite scores. Whilst various measures, including speed of processing measures, have not performed as would be expected, we have demonstrated the use of such a battery to evaluate general cognitive functioning and its relationship with specific cognitive abilities.

A further application of the CANTAB system would be to look prospectively at genetic influences on cognitive decline. There is also potential, through the use of functional neuro-imaging, to extend our understanding of the neuro-anatomical basis of the CANTAB tests and, crucially, the genetic structure of cognitive function.

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