

## Genetic Covariance Between Processing Speed and IQ

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Behavioral genetic studies of cognition have turned increasingly to lower level cognitive processes, as measured by elementary cognitive tasks, to help understand the genetic structure of human mental ability (Baker, Vernon, & Ho, 1991; Ho, Baker, & Decker, 1988; Rijdsdijk, Vernon, & Boomsma, 1998; Wright, Smith, Geffen, Geffen, & Martin, 2000). Elementary cognitive tasks often require a speeded response, and as such they have been largely considered to reflect mental speed, or speed of information processing (Jensen, 1998). In general, reaction time (RT) measures (including variability of responding) demonstrate correlations of approximately  $-0.30$  with IQ, whereas measures without an RT component, such as inspection time, reach correlations of  $-0.50$  with IQ (Deary & Stough, 1996; Jensen, 1993b). More complex elementary cognitive tasks correlate more highly with IQ; for example, choice RT confers a greater correlation with IQ than does simple RT (Larson, Merritt, & Williams, 1988).

In this chapter, we present the multivariate analyses of two processing speed measures (inspection time and choice RT) with IQ. First, we explore the complexity effect by including choice RT from three choice conditions in an analysis with full-scale IQ. Next, we explore the genetic covariance between inspection time and IQ, including a comparison of verbal and performance scales. Finally, we examine whether inspection time and choice RT relate to IQ through the same genetic factor. As the genes for processing speed overlap with genes for IQ, processing speed measures may provide a tractable framework through which to search for quantitative trait loci (QTLs) influencing intelligence. Herein lies the true value of the behavioral genetic study of basic information processing in the post-genomic era.

The earliest direct genetic study of basic processing speed and IQ was

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conducted by Ho et al. (1988) in a sample of 60 twins ages 8 to 18 years. The processing speed factor was defined by tests of rapid automatic naming (colors, numbers, letters, and pictures) and symbol processing (Colorado Perceptual Speed Test; Decker, & DeFries, 1981). Ho et al. found that the relationship between processing speed and IQ was almost completely mediated by genetic factors. Symbol processing was more strongly genetically correlated with IQ (0.67) than was rapid automatic naming (0.46). Nonshared environmental effects showed some influence, whereas shared environment was not important. Baker et al. (1991) replicated this finding of genetic overlap in processing speed and IQ by using a battery of RT tasks (as described by Vernon, 1989). A latent factor determined by additive genes influenced the RT component, verbal IQ, and performance IQ. Specific genes additionally contributed to the variance in performance IQ, whereas a specific common environment factor influenced verbal IQ. RT was somewhat determined by common environment (17%) but more so by unique environment (37%). Its genetic correlation with verbal and performance IQ was 1.00 and 0.92, respectively, indicating that nearly all the genetic variance of RT overlapped with IQ.

In other studies, elementary cognitive tasks that have demonstrated a substantial genetic relationship with IQ (genetic covariance ranging from 81% to 100%) include Sternberg's Memory Scanning, Posner's Letter Matching, and choice RT (Neubauer, Spinath, Riemann, Angleitner, & Borkenau, 2000; Petrill, Luo, Thompson, & Detterman, 1996; Rijdsdijk et al., 1998). On the basis of their extensive use in intelligence research, choice RT and inspection time were investigated in our ongoing research on twins. Choice RT is a measure of the speed of response to the appearance of a single stimulus from an array of others. We sampled RT in three choice conditions (two-, four-, and eight-choice). The inspection time task differs fundamentally from choice RT in that it does not require a speeded response. Inspection time measures the minimum amount of time required by the participant to discriminate accurately between two lines of noticeably different length; thus, the stimulus duration is the time that is measured.

The genetic relationship between two-choice RT and IQ in adolescents has been established. Rijdsdijk et al. (1998) used simple and two-choice RT in their longitudinal study of processing speed and IQ in 213 pairs of twins. Heritabilities for choice RT were lower on the second than the first occasion (0.49 vs. 0.62), perhaps owing to a change in task parameters and administration that may have produced the faster RTs and increased error rate observed on second test. The correlation of  $-0.22$  between choice RT and Raven IQ was completely genetically mediated, demonstrating a genetic correlation of  $-0.36$ . In their analysis of choice RT and Wechsler Adult Intelligence Scale (WAIS) IQ subtest scores, phenotypic correlations ranged between  $-0.05$  and  $-0.23$ , whereas genetic correlations ranged from  $-0.18$  to  $-0.40$  (higher for verbal than performance subtests). Simple and choice RT loaded on a general genetic factor (17% simple RT; 11% choice RT), but they loaded more highly on their own genetic factor (26% simple RT; 20% choice RT), indicating that although simple and choice RT

overlap genetically with IQ, there is considerable unique genetic variance. Nonetheless, the relationship between choice RT and IQ in adolescents appears to be entirely mediated by genes.

We sought to replicate this genetic relationship using RT and variability indices in the largest sample of twins studied to date for RT measures. On the basis of findings that genetic effects increase proportionately with a test's *g* loading, it was expected further that this genetic relationship would be greatest for the more complex eight-choice condition and smallest for the two-choice condition, with the four-choice condition intermediate.

Ours was the first study of the genetic relationship between inspection time and full-scale IQ. We found that the phenotypic association between inspection time and IQ also was mediated entirely by genes (genetic correlation of  $-0.63$ ), and furthermore, that the genetic covariance with inspection time was greater for performance IQ than verbal IQ (Luciano, Wright, et al., 2001). An additional genetic model (common pathway) of the covariance among inspection time, performance IQ, and verbal IQ is presented later in this chapter. Posthuma, de Geus, and Boomsma (2001) replicated our findings on inspection time and IQ in an extended twin design that included 688 family members (twins and siblings) from 271 families. They showed that the common genetic factor explained more variance in performance (22%) than verbal (10%) IQ. This result mirrors phenotypic findings of a higher association between inspection time with performance IQ than with verbal IQ (Deary, 1993; Kranzler & Jensen, 1989).

As diverse elementary cognitive tasks are moderately intercorrelated (Barrett, Alexander, Doverspike, Cellar, & Thomas, 1982; Saccuzzo, Johnson, & Guertin, 1994; Vernon, 1983), it has been suggested that the relationship between different elementary tasks and IQ is due to the same factor, for instance, neural transmission speed (e.g., Jensen, 1993a). This notion of a unitary speed factor has been supported by multiple regression analyses, which show that inspection time and choice RT do not make independent contributions to the prediction of IQ (Larson & Saccuzzo, 1989; Vernon, 1983). However, evidence to the contrary also has been reported showing that inspection time and reaction time factors from a battery of elementary cognitive tasks do make independent contributions to the prediction of IQ (Kranzler & Jensen, 1991). Behavioral genetic studies (e.g., Vernon, 1989) have shown differing strengths and patterns of genetic and environmental contributions to variance across diverse elementary cognitive tasks, indicating that there may not be a single processing mechanism influencing intelligence but rather different component processes (e.g., speed of perceptual apprehension, speed of short-term memory retrieval). The genes influencing these component processes may constitute the genes for intelligence (see Plomin, chapter 11, this volume).

It is possible then that the genes affecting choice RT are different from those affecting inspection time, despite the fact that both tasks index processing speed of some kind. Different genes may correspond to the different cognitive processes that are tapped by each task rather than the pre-

dominance of a single genetic factor controlling some basic biological mechanism. By using choice RT and inspection time as individual task measures rather than as a less informative unitary processing speed factor, a multivariate genetic analysis with IQ will establish whether the relationship is mediated by the same or separate genetic factors.

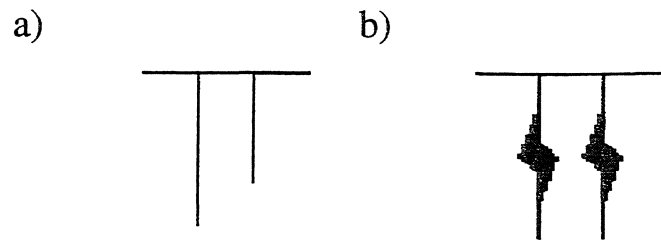
## Method

### *Sample and Measures*

Data were collected in the context of the ongoing Brisbane Memory, Attention, and Problem-Solving (MAPS) twin study (see Wright et al., 2001). Here we report data from the first 390 twin pairs: 97 monozygotic (MZ) females, 87 MZ males, 52 dizygotic (DZ) females, 48 DZ males, and 106 DZ opposite-sex pairs. Zygosity was determined by ABO, MN, and Rh blood groups and by nine independent polymorphic DNA markers. Twin pairs were excluded if either one had a history of significant head injury, neurological or psychiatric illness, or substance dependence or if they were currently taking long-term medications with central nervous system effects. Participants had normal or corrected-to-normal vision (better than 6/12 Snellen equivalent). The twins were mostly in their penultimate year of secondary school and were between ages 15 and 18 years ( $M = 16.17$  years,  $SD = 0.34$ ).

The choice RT task, inspection time task, and IQ test were part of a psychometric battery about 1.5 hours in length and were either preceded or followed by a testing session of similar duration that involved the measurement of event-related potentials during a delayed response task. The choice RT task was presented to the participants in the pseudo-game form of dripping taps, in which the participant had to quickly press the appropriate computer key to stop a tap from dripping. Participants aligned and rested their fingers on a keyboard rather than a home key (as used by Jensen, 1987). Different colored taps corresponded to the same fingers on both hands to aid tap and finger alliance; for example, the taps matching the index fingers were both red. The amount of water saved was indicated on the bottom left of the screen. Ninety-six, 48, and 96 trials were presented in the respective two-, four-, and eight-choice conditions. Individual trials were excluded if RT was less than 150 ms or greater than 2,000 ms. Output measures for each of the choice conditions included the mean RT and standard deviation ( $SD$ ) of correct responses. For a more detailed description of this task, see Luciano, Smith, et al. (2001).

Inspection time was tested by a line discrimination task, which was presented as a pseudo-computer game of choosing the longer of two worms to go fishing. The two lines of comparison (see Figure 10.1) were described as worms that would quickly burrow into the ground (i.e., appearance of masking stimulus). The participant's task was to identify the longer worm in an effort to catch the most fish by pressing the corresponding left or



**Figure 10.1.** The pi figure stimulus (a) is presented briefly (duration ranges from 14.2 ms to 2,000 ms) in the center of the screen, and then (b) is hidden by a flash mask, consisting of two vertical lines shaped as lightning bolts, presented for a period of 300 ms.

right arrow key on the keyboard. Feedback in the form of a fish appeared at the lower left-hand side of the screen following every five correct judgments. The importance of accuracy and not reaction time was stressed verbally by the experimenter before beginning the task.

Inspection time was estimated post hoc by fitting a cumulative normal curve ( $M = 0$ ) to accuracy as a function of stimulus onset asynchrony (SOA). Inspection time is commonly estimated through curve extrapolation so that performance at any desired accuracy level can be attained (see Nettelbeck, 1987). The statistic of interest is the SD of the curve, which is the SOA at which 84% accuracy is achieved. Participants whose data provided a poor fit to the cumulative normal curve ( $R^2 < 0.95$ ) were excluded (i.e., 21 participants, or 2.7% of the sample).

A shortened version of the Multidimensional Aptitude Battery (Jackson, 1984, 1998) was used to measure IQ and included three verbal subtests (Information, Arithmetic, and Vocabulary) and two performance subtests (Spatial and Object Assembly). All subtests had a multiple-choice format and were limited to 7 minutes each. Administration and scoring were computerized. The Multidimensional Aptitude Battery was patterned after the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler, 1981) and possesses good psychometric properties (Jackson, 1984, 1998).

### *Statistical Procedure*

As speed (i.e., mean RT) and variability (i.e., SD) indices were both derived from the choice RT task, it was necessary to establish whether there would be any gain in information by including both indices in the multivariate analyses. Preliminary analyses involved deriving phenotypic correlations across RT and SD variables within each choice condition and inspecting them for excessive collinearity, an indication that the cognitive processes tapped by these measures were highly similar. If RT and SD were highly correlated, RT indices would be preferred over SD indices because of their higher test-retest reliability. Collinearity also was assessed across choice conditions to evaluate the similarity of these measures.

Multivariate genetic modeling progressed from the approach of a Cholesky (see Neale & Cardon, 1992) decomposition of the additive genetic

(A), common environmental (C), and unique environmental (E) variance contributing to RT in all choice conditions and full-scale IQ. More simplified models (independent pathways and common pathway) were compared with the best-fitting Cholesky model.

A trivariate analysis of inspection time, performance IQ, and verbal IQ (following from the phenotypic findings of a stronger relationship between inspection time with performance IQ than verbal IQ) was performed. In this analysis, a common pathway model was compared with the best-fitting Cholesky model.

To address the question of whether a single factor explained the relationship among choice RT, inspection time, and IQ, we performed a multivariate analysis of these variables. As inspection time has been shown to have different strengths of association with verbal and performance IQ, the subscales were investigated rather than the full-scale score. To arrive at a simpler model solution with equally weighted contributions from inspection time and choice RT, we chose only one choice RT measure to include with inspection time, performance IQ, and verbal IQ.

## Results

### *Choice Reaction Time and IQ*

Using the criterion of exceeding  $\pm 3.5$  SDs from the mean, we excluded eight outliers from the two-choice condition, seven outliers from the four-choice condition, and five outliers from the eight-choice condition. In a contrasts analysis of mean and variances across birth order and zygosity, a multivariate outlier (twin pair) and three individual outliers in the eight-choice condition were removed. Following a  $\log_{10}$  transformation, the number of outliers for SD in the two-choice, four-choice, and eight-choice conditions were eight, one, and two, respectively. All analyses using choice RT included a regression coefficient for accuracy in the means model to account for significant speed–accuracy trade-off effects. Computer or experimenter error resulted in the loss of five unrelated participants' verbal IQ scores (0.64%). IQ data were normally distributed with no outliers. As twins were tested as close as possible to their 16th birthdays, months of schooling differed across individual twin pairs, and so mean IQ was adjusted for months of schooling completed since the beginning of Grade 10.

The correlations between RT and SD within each choice condition were very high (see Table 10.1). The four- and eight-choice conditions showed excessive collinearity between RT and SD, which suggests that they are largely measuring the same process. This was further indicated by the comparison of the MZ and DZ cross-variable cotwin correlations in which genetic identity between RT and SD was apparent. Hence, SD variables from the four- and eight-choice conditions were not used in further analyses as RT measures were more reliable (data not shown.)

In the two-choice condition, the correlation between RT and SD was

**Table 10.1.** Phenotypic Correlations Between RT and SD Within Each Choice Condition and Cotwin Cross Variable (RT and SD) Correlations Within Each Choice Condition (95% Confidence Intervals in Parentheses)

Condition	Phenotypic $r$ ( $N = 780$ individuals)	MZ $r$ ( $N = 184$ twin pairs)	DZ $r^a$ ( $N = 206$ twin pairs)
2 choice	0.73 (0.69–0.76)	0.34 (0.23–0.43)	0.19 (0.08–0.30)
4 choice	0.80 (0.77–0.83)	0.50 (0.41–0.58)	0.37 (0.26–0.46)
8 choice	0.87 (0.85–0.89)	0.60 (0.53–0.67)	0.39 (0.27–0.49)

*Note.* RT = reaction time; SD = standard deviation; MZ = monozygotic twins; DZ = dizygotic twins.

<sup>a</sup>Includes opposite-sex twins.

lower than those correlations from the four- and eight-choice conditions. A bivariate genetic analysis therefore was performed on two-choice RT and SD to assess whether the measures were tapping the same or separate genetic factors. There was insufficient power to differentiate between additive genetic and unique environmental (AE) and common environmental and unique environmental (CE) models in this analysis. For a gain of 3 degrees of freedom, increases in the  $-2$  log-likelihood (LL) ratio from the additive genetic, common environmental, and unique environmental (ACE) model were 7.55 and 4.07 for respective AE and CE models. Importantly, the ACE model showed that a single genetic factor accounting for 26% of variance in SD and 29% of variance in RT explained the total genetic variation in the measures. Because RT and SD were influenced by the same genetic factor and to the same degree, we decided to only use RT, the more stable measure of the two, in subsequent multivariate analyses.

Phenotypic correlations between the RTs in the differing choice conditions were expected to be high as a result of the linear relationship between the variables (known as Hick's Law; Hick, 1952). The phenotypic and cotwin correlations across variables are displayed in Table 10.2. The correlation between two- and four-choice RT was slightly lower than either two- or four-choice correlations with eight-choice RT. Across all variable pairings, MZ cotwin correlations were higher than DZ cotwin correlations.

**Table 10.2.** Maximum Likelihood Estimates of Correlations Between RTs Obtained in the Different Choice Conditions and Their Respective Cross-Variable Cotwin Correlations

Relationship	Phenotypic $r$ ( $N = 780$ individuals)	MZ $r$ ( $N = 184$ twin pairs)	DZ $r^a$ ( $N = 206$ twin pairs)
2 choice–4 choice	0.55 (0.50–0.60)	0.45 (0.36–0.52)	0.33 (0.23–0.42)
2 choice–8 choice	0.66 (0.61–0.70)	0.46 (0.38–0.54)	0.34 (0.24–0.44)
4 choice–8 choice	0.66 (0.62–0.71)	0.57 (0.49–0.63)	0.39 (0.29–0.48)

*Note.* RT = reaction time; MZ = monozygotic twins; DZ = dizygotic twins.

<sup>a</sup>Includes opposite-sex twins.



The phenotypic correlations between the RT measures and full-scale IQ are presented in Table 10.3, separately for female and male participants (although these estimates did not differ as indicated by the overlapping confidence intervals). The highest correlations with IQ were in the four-choice condition, followed by the eight-choice, then two-choice conditions.

The cotwin correlations across RT and IQ pairings were higher for MZs ( $-0.30$ ,  $-0.54$ ,  $-0.45$ ) than DZs ( $-0.16$ ,  $-0.26$ ,  $-0.23$ ) for the respective two-, four-, and eight-choice conditions. A multivariate analysis including the differing choice RT conditions and full-scale IQ was performed to determine whether a single genetic RT (or speed) factor could explain the shared variance. Three multivariate outliers (twin pairs) were removed from the analysis, as these observations were not consistent with the base model (ACE Cholesky). Goodness-of-fit statistics for the various models are reported in Table 10.4. The model of best fit was an AE Cholesky model in which nonsignificant parameters were dropped (Figure 10.2). In this reduced AE model, only two parameters could be dropped from the model: a genetic path coefficient from the third factor to full-scale IQ and a unique environment path coefficient from the third factor to full-scale IQ. The first genetic factor explained between 14% and 53% of variance in each of the measures. The second genetic factor explained 23%, 17%, and 30% of variance in four-choice RT, eight-choice RT, and full-scale IQ, respectively. Individual genetic factors accounted for 15% of the variance in eight-choice RT and 38% of variance in full-scale IQ.

Genetic factors almost completely accounted for the phenotypic correlations between each of the RT measures and IQ. Genetic and unique environment correlations among the choice RT variables and full-scale IQ are displayed in Table 10.5. These are derived from the full AE model.

**Table 10.3.** Maximum Likelihood Estimates (95% Confidence Intervals) of Phenotypic Correlations Among Choice Reaction Time (CRT) Variables and Full Scale IQ (FIQ) for Female (Below Diagonal) and Male (Above Diagonal) Participants

Variable	1	2	3	4
1. 2 CRT	—	0.54 (0.46–0.61)	0.66 (0.59–0.71)	–0.32 (–0.22––0.41)
2. 4 CRT	0.51 (0.43–0.58)	—	0.68 (0.62–0.73)	–0.56 (–0.49––0.63)
3. 8 CRT	0.62 (0.56–0.68)	0.65 (0.58–0.70)	—	–0.50 (–0.42––0.58)
4. FIQ	–0.31 (–0.22––0.40)	–0.53 (–0.45––0.60)	–0.46 (–0.38––0.53)	—

*Note.* Female participants,  $N = 396$ – $399$ ; male participants,  $N = 366$ – $370$ .



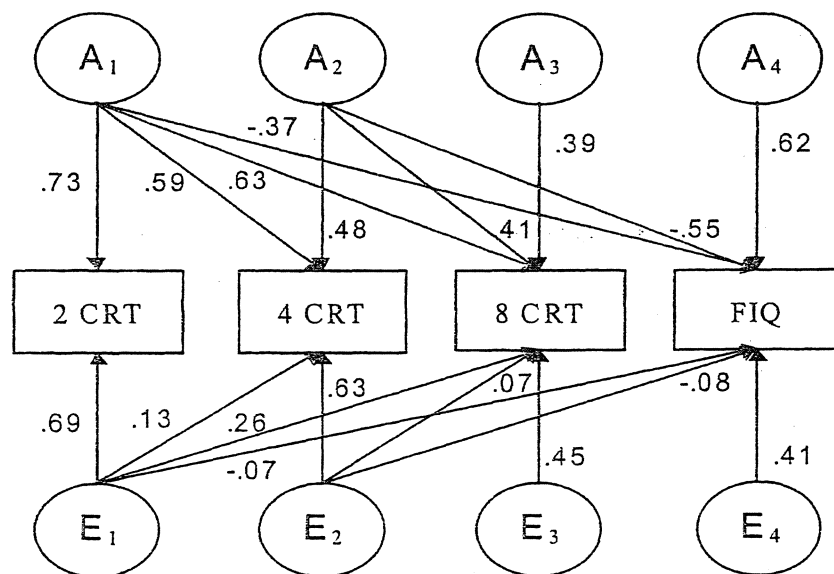
**Table 10.4.** Goodness-of-Fit Statistics for the Multivariate Model of Two-Choice RT, Four-Choice RT, Eight-Choice RT, and Full Scale IQ: Fit ( $-2$  LL) of the Cholesky Model and Change in Fit ( $\chi^2$ ) of the Independent Pathways and Common Pathway Models

Model	vs.	$-2$ LL	$df$	$\Delta\chi^2$	$\Delta df$	$p$
i. ACE Cholesky decomposition		30,315.67	3025			
ii. AE Cholesky decomposition	i	30,325.36	3035	9.69	10	.47
<b>iii. Reduced AE Cholesky decomposition</b>	<b>ii</b>	<b>30,326.79</b>	<b>3037</b>	<b>1.43</b>	<b>2</b>	<b>.49</b>
iv. CE Cholesky decomposition	i	30,393.16	3035	77.49	10	<.01
v. AE independent pathways (32 parameters)	ii	30,376.97	3039	61.3	4	<.01
vi. AE common pathway (30 parameters)	ii	30,704.07	3041	388.4	6	<.01

*Note.* LL = log likelihood; A = additive genetic; C = common environmental; E = unique environmental. Boldface indicates the most parsimonious model.

### Inspection Time and IQ

This next analysis was directed to the genetic association among inspection time, performance IQ, and verbal IQ. SD of the inspection time curve was positively skewed so a logarithmic transformation was applied to the data. Eleven outliers were removed. The phenotypic correlation between inspection time and performance IQ ( $-0.35$ ) was of similar magnitude to that of verbal IQ ( $-0.26$ ). Results of model fitting, in which a common pathway model was compared with the best-fitting Cholesky model, are displayed in Table 10.6. Because the common pathway model explained



**Figure 10.2.** Path diagram depicting standardized path coefficients for the reduced additive genetic (A) and unique environment (E) Cholesky factorization of two-choice reaction time (2 CRT), four-choice reaction time (4 CRT), eight-choice reaction time (8 CRT), and full scale IQ (FIQ).

**Table 10.5.** Genetic (Below Diagonal) and Unique Environment (Above Diagonal) Correlations Between Choice Reaction Time (CRT) Variables and Full Scale IQ (FIQ) Estimated From the Full Additive Genetic and Unique Environment Model

Variable	1	2	3	4
1. 2 CRT	—	0.19	0.50	-0.16
2. 4 CRT	0.79	—	0.22	-0.21
3. 8 CRT	0.74	0.90	—	-0.16
4. FIQ	-0.41	-0.71	-0.58	—

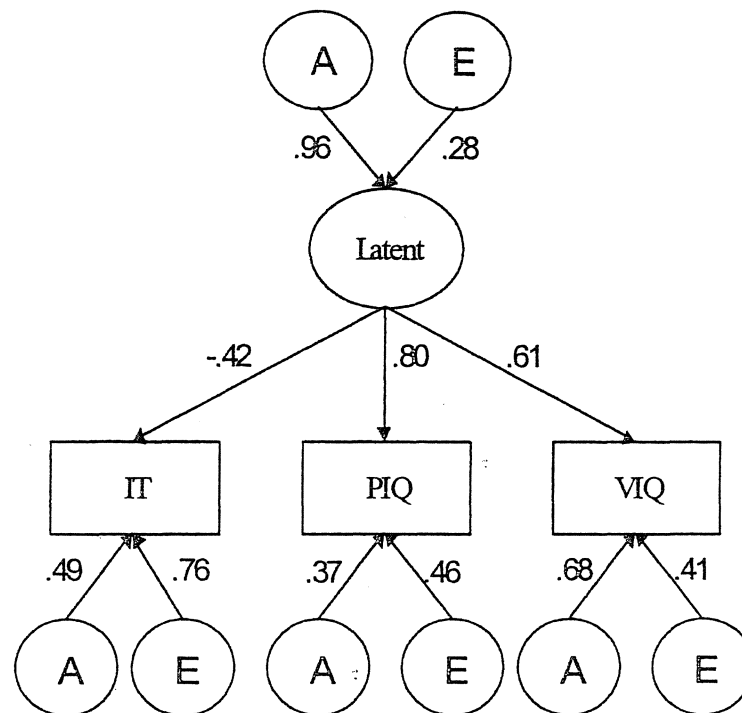
the data most parsimoniously, it is presented as a path diagram in Figure 10.3. The relationships among inspection time, performance IQ, and verbal IQ were mediated by a latent factor that was primarily influenced by genes (92%). This latent factor explained the most variance in performance IQ (64%), then verbal IQ (37%), then inspection time (18%). The specific genetic variance contributing to each measure also was substantial, accounting for 14%, 46%, and 24% of variance in performance IQ, verbal IQ, and inspection time, respectively. To test whether the latent factor explained more variance in performance IQ than verbal IQ, we equated the proportions of variance explained by the latent factor on performance IQ and verbal IQ. This led to a significant change in the  $-2$  LL ratio of 252.07 for one degree of freedom, confirming that the latent factor influenced performance IQ more than verbal IQ.

The genetic correlation between inspection time and performance IQ was  $-0.59$ , whereas for inspection time and verbal IQ it was  $-0.42$ ; performance IQ and verbal IQ showed a genetic correlation of  $0.61$ . The genetic correlations between inspection time and the IQ measures were fairly strong, substantiating our hypothesis that variation in genes that produce faster inspection times are strongly related to the variation in genes that promote higher IQs.

**Table 10.6.** Goodness-of-Fit Statistics for the Multivariate Model of Inspection Time, Performance IQ, and Verbal IQ: Fit ( $-2$  LL) of the Cholesky Models and Change in Fit ( $\chi^2$ ) of the Common Pathway Model

Model	vs.	$-2$ LL	$df$	$\Delta\chi^2$	$\Delta df$	$p$
i. ACE Cholesky decomposition		11,570.13	2262			
ii. AE Cholesky decomposition	i	11,581.78	2268	11.65	6	.07
iii. CE Cholesky decomposition	i	11,639.48	2268	69.35	6	<.01
<b>iv. AE Common pathway model</b>	<b>ii</b>	<b>11,585.40</b>	<b>2269</b>	<b>3.62</b>	<b>1</b>	<b>.06</b>

*Note.* LL = log likelihood; A = additive genetic; C = common environmental; E = unique environmental. Boldface indicates the most parsimonious model.



**Figure 10.3.** Common pathway model depicting the additive genetic (A) and unique environmental (E) relationship among inspection time (IT), performance IQ (PIQ), and verbal IQ (VIQ).

### *Choice Reaction Time, Inspection Time, and IQ*

The maximum likelihood estimates of the phenotypic correlations among inspection time, choice RT measures, and verbal and performance IQ are displayed in Table 10.7, separately for female and male participants, although confidence intervals overlapped indicating that estimates did not differ across sex.

Two-choice RT was selected for use in the multivariate analysis with inspection time and IQ for several reasons. First, its correlation with IQ was more aligned with previous findings, suggesting that it was most likely tapping the same process as that measured in other choice RT studies (especially home-key paradigms). Second, it was the least complex of the choice conditions and as such could be argued to be a purer measure of processing speed (tapped fewer information processes).

Table 10.8 displays the goodness-of-fit statistics for the multivariate analysis of inspection time, choice RT, performance IQ, and verbal IQ. Common environment could be dropped from the Cholesky model with no significant change in fit of the model. The model of best fit was an AE common pathway model, and it is depicted in Figure 10.4. Additive genes accounted for 92% of the variance in the latent factor. The latent factor explained the most variance in performance IQ (53%), then verbal IQ (44%), then inspection time (21%), and then choice RT (15%). Specific additive genetic effects were of the same magnitude for verbal IQ and choice RT (40% of the variance) and were roughly the same for inspection time (21%) and performance IQ (25%). The genetic correlation between inspec-

**Table 10.7.** Maximum Likelihood Estimates (and 95% Confidence Intervals) of Phenotypic Correlations Among Inspection Time (IT), Choice Reaction Time (CRT) Variables, Verbal IQ (VIQ), and Performance IQ (PIQ) for Female (Below Diagonal) and Male (Above Diagonal) Participants, Assuming Independence of Cotwins

	1	2	3	4	5	6
1. IT	—	0.20 (0.10–0.30)	0.24 (0.14–0.34)	0.27 (0.17–0.36)	–0.29 (–0.19––0.38)	–0.35 (–0.26––0.44)
2. 2 CRT	0.20 (0.10–0.30)	—	0.54 (0.46–0.61)	0.66 (0.59–0.71)	–0.31 (–0.21––0.40)	–0.27 (–0.17––0.36)
3. 4 CRT	0.24 (0.14–0.34)	0.48 (0.39–0.55)	—	0.68 (0.62–0.73)	–0.45 (–0.36––0.53)	–0.53 (–0.45––0.60)
4. 8 CRT	0.23 (0.13–0.32)	0.61 (0.55–0.67)	0.58 (0.51–0.64)	—	–0.42 (–0.33––0.50)	–0.47 (–0.38––0.54)
5. VIQ	–0.20 (–0.10––0.30)	–0.26 (–0.17––0.35)	–0.45 (–0.37––0.52)	–0.28 (–0.19––0.37)	—	0.49 (0.41–0.56)
6. PIQ	–0.34 (–0.24––0.42)	–0.24 (–0.14––0.33)	–0.52 (–0.45––0.59)	–0.35 (–0.25––0.43)	0.55 (0.48–0.61)	—

Note. Female participants,  $N = 375$ –401; male participants,  $N = 354$ –370.

tion time and choice RT was 0.35, whereas the environmental correlation was effectively zero.

## Discussion

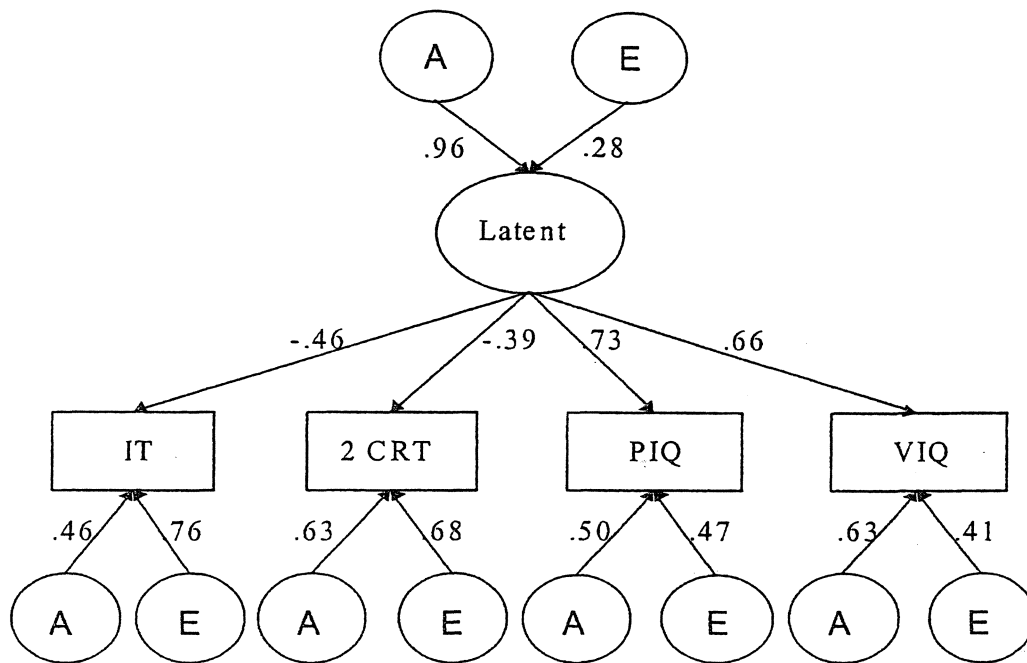
### Choice RT and IQ

The significant correlation between choice RT and psychometric intelligence is well established (Jensen & Munro, 1979; Neubauer, Riemann, Mayer, & Angleitner, 1997; Saccuzzo et al., 1994) and replicated in the

**Table 10.8.** Goodness-of-Fit Statistics for the Multivariate Model of Inspection Time, Choice Reaction Time, Performance IQ, and Verbal IQ: Fit (–2 LL) of the Cholesky Models and Change in Fit ( $\chi^2$ ) of the Common Pathway Model

Model	vs.	–2 LL	<i>df</i>	$\Delta\chi^2$	$\Delta df$	<i>p</i>
i. ACE Cholesky decomposition		18,583.36	2986			
ii. AE Cholesky decomposition	i	18,599.51	2996	16.16	10	.09
iii. CE Cholesky decomposition	i	18,657.68	2996	74.32	10	<.01
<b>iv. AE Common pathway model</b>	<b>ii</b>	<b>18,611.63</b>	<b>3002</b>	<b>12.11</b>	<b>6</b>	<b>.06</b>

Note. LL = log likelihood; A = additive genetic; C = common environmental; E = unique environmental. Boldface indicates the most parsimonious model.



**Figure 10.4.** A common pathway model depicting the additive genetic (A) and unique environmental (E) relationship among inspection time (IT), choice reaction time (CRT), performance IQ (PIQ), and verbal IQ (VIQ).

present study. The correlation between two-choice RT and IQ was consistent with previous research. However, correlations between four-choice RT and IQ and eight-choice RT and IQ were at the top end of the range reported (Jensen, 1987). It may be that the correlation between four-choice RT and IQ was confounded by a learning effect as the four-choice condition was presented first without any previous practice. As for the high correlation between eight-choice RT and IQ, it is possible that the requirement of coordinating the different fingers with the varying stimulus positions actually increased the complexity of the task, invoking cognitive processes not normally required in the home-key paradigm. The high correlations between RT and SD measures within the same condition suggested that the processes measured by each were the same rather than different (see Carroll, 1993; Stankov, Roberts, & Spilsbury, 1994), and this was further implied by the genetic analysis of the two-choice condition, which found that a single factor explained the entire genetic variance in each of these measures.

This study confirmed that the relationship between choice RT and IQ was influenced by a common genetic factor as first reported by Rijdsdijk et al. (1998), in contrast to an earlier study in children by Petrill et al. (1996), who found a more important role for common environment. Multivariate model fitting indicated that the covariance between choice RT variables and full-scale IQ was mediated entirely by genes, although a single genetic factor was not sufficient to explain the covariance between all choice RT measures and IQ. The first genetic factor, which had the largest loading on two-choice RT, explained more of the variance in four- and eight-choice RTs but less of the variance in IQ than did the second genetic factor. This

first genetic factor may reflect a basic processing speed factor as the largest loading was on two-choice RT, the simplest of the choice conditions. The second genetic factor, which loaded most highly on IQ, might represent a set of information (component) processes needed to execute more complex cognitive operations. Alternatively, it may reflect strategy use, which enables more efficient performance in conditions of higher choice, and those with higher IQs are better able to form these strategies. There was no additional genetic factor influencing the relationship between eight-choice RT and IQ. This indicated that the component processes invoked by the eight-choice condition and associated with IQ were the same as those required in the four-choice condition or that the strategies used in each condition were highly similar.

The proportions of overlapping genetic variance between the RT measures and IQ were similar in magnitude to those reported by Risdijk et al. (1998) for simple RT and two-choice RT. The genetic correlation between two-choice RT and IQ ( $-0.41$ ) obtained in the present study also was comparable with theirs ( $-0.36$ ) in the two-choice condition. There was no indication of a common environment factor influencing choice RT nor the relationship between choice RT and IQ as reported by Petrill et al. (1996) in a younger sample of twins (ages 6–13 years). In fact, the point estimates indicated the presence of small shared environmental (or assortative mating) effects for both IQ and RT, although the analysis did not have power to detect them simultaneously with additive genetic effects. Further research within a longitudinal context is needed to clarify the change in influence of common environment from childhood to adolescence.

The results showed that a further genetic factor (explaining 38% of variance) was needed to explain the genetic effects on full-scale IQ, suggesting that choice RT processes are related to specific components of intelligence and independent of others. The remaining variance was composed of unique environment, which was correlated as well as specific to each measure. The specific components of unique environment were far more influential than the common factors, especially in their effects on IQ. For choice RT variables, unique environment was perhaps mostly in the form of measurement error as test–retest reliability is lower than for IQ.

### *Inspection Time and IQ*

Confirming previous studies (Deary & Stough, 1996; Kranzler & Jensen, 1989; Nettelbeck, 1987), significant correlations between inspection time with verbal and performance IQs were found, although they were toward the lower range of estimates reported. This study is perhaps the largest study conducted on inspection time, and the unselected nature of the sample suggests that the correlation estimates are unbiased and stable.

Like others who have investigated elementary cognitive tasks (Baker et al., 1991; Rijsdijk et al., 1998; Wright et al., 2000), we have demonstrated in the present study that inspection time shares a substantial genetic relationship with IQ. The genetic relationship was mediated by a

latent factor that showed a larger influence on performance than verbal IQ. A psychometric factor model also adequately described the relationship among RT factor, verbal IQ, and performance IQ, but a differential genetic relationship between performance and verbal IQ was not found (Baker et al., 1991). Our finding can be accommodated within a *g* factor framework, in which the latent factor influencing inspection time, performance IQ, and verbal IQ is akin to general intelligence. Gustafsson (1984) suggested that fluid intelligence (tapped by performance subtests) is actually the *g* factor, and it may be for this reason that the latent factor influences performance IQ to a greater extent than verbal IQ. Fluid intelligence may depend on the overall proficiency of different information processes, of which inspection time is one, or may relate to an underlying biological speed mechanism which inspection time captures better than do RT variables. Alternatively, a top-down explanation, whereby higher fluid intelligence enables better inspection time performance, can be proffered.

As demonstrated, the unique environment effects on inspection time were large, but these were only weakly correlated with IQ. Strategy use (involving apparent motion cues) was invoked to explain the large uncorrelated unique environment effects in inspection time. Research has confirmed that the correlation between inspection time and IQ increases when participants using apparent motion strategies are excluded (Mackenzie & Bingham, 1985; Mackenzie & Cumming, 1986), and this may be consistent with the present genetic findings (which show that unique environment contributes slightly to the relationship between inspection time and IQ) if apparent motion cue use is actually influenced by unique environment rather than genes.

In Posthuma et al.'s (2001) study of the genetic relationship between inspection time and IQ, the performance index consisted of different tests (picture completion, block design, matrix reasoning) from those used in the present study, but a similar amount of genetic covariance between inspection time and performance IQ was explained. This confirms the generality of the genetic association across diverse IQ subtests and further suggests that the strength of the genetic association with inspection time may be dependent on a generalized fluid ability rather than specific performance group factors. Posthuma et al. also found that the variance in inspection time was largely determined by an independent unique environmental factor.

### *Choice RT, Inspection Time, and IQ*

In the present study, the correlations between inspection time and the RT variables from the choice RT task ranged between 0.20 and 0.27, agreeing with past findings of significant, albeit modest, correlations (0.11 to 0.37) between the two (Larson, 1989; Vernon, 1983). The relationship among inspection time, choice RT, performance IQ, and verbal IQ was dependent on the same latent factor, which was mostly influenced by genes. This analysis may have capitalized on the substantial covariance between the



IQ composite scores, which forced a strong underlying latent factor. This latent factor represented the *g* factor of intelligence, which presides over the performance and verbal group factors (or in this case scores), and its influence appeared greater on inspection time than choice RT.

In the analysis of inspection time, performance IQ, and verbal IQ, a latent factor also had best described the data. The genetic variance shared by inspection time and verbal IQ in this previous analysis was only slightly lower (0.24 vs. 0.28) than that obtained when choice RT also was included, whereas the genetic covariance between inspection time and performance IQ remained unchanged (0.31). This implied that the latent factor influencing inspection time and IQ was essentially the same as the latent factor influencing inspection time, choice RT, and IQ.

Although this study showed that a unitary factor was able to explain the relationship among inspection time, choice RT, and IQ, it may be that an analysis of IQ subtest data demonstrates different genetic associations between choice RT and inspection time with various subtests. For instance, inspection time has been claimed to predict a perceptual speed factor (e.g., tapped by the digit–symbol substitution) rather than the general factor (Mackintosh, 1998). Hence, a study including subtest scores rather than composite scores will provide clearer evidence for or against the presence of a single genetic factor (or latent factor influenced by genes) mediating the relationship between diverse elementary cognitive tasks and intelligence.

That genetic factors mediated the relationship among choice RT, inspection time, and IQ supports the claim for a biological basis affecting both processing speed and higher order cognition. Jensen (1998) advocated a neural efficiency model in which factors such as oscillation speed of neuronal excitatory potentials and myelination of neurons determine the speed of information processes. A faster oscillation frequency causes the action potential to be nearer to the threshold of excitation, resulting in a faster response. Greater myelination of neurons also might promote a faster speed and efficiency of information processing because myelinated fibers are responsible for transmitting neural information to differing regions of the brain, and across the corpus callosum. Although these hypotheses have not been directly investigated, the results from the present study indicate that biological avenues of inquiry are indeed useful.

### Conclusion and Future Prospects

This study demonstrated that the significant phenotypic relationship among choice RT, inspection time, and IQ was primarily genetically mediated. A model with a single latent factor (mostly determined by additive genes) influencing choice RT, inspection time, and verbal and performance IQs could account for the covariation of these measures of elementary and higher order cognitive processes, although other models also are consistent with the data. A future analysis using IQ subtest scores will enable a clearer understanding of whether choice RT and inspection time relate to

a general genetic factor or whether they have different genetic associations with specific IQ subtests. The findings from multivariate genetic analyses of processing speed indices and IQ are informative to theorists wishing to elaborate information-processing models of intelligence.

However, greater value of the study of processing speed variables may be their key role in the molecular detection of genes influencing intelligence. The variance in IQ is most likely due to the combined action of many genes of small effect, some of which will overlap with genes for processing speed. QTL studies of cognition have thus far focused on a single measure, IQ, but much is to be gained by including multiple measures of intelligence in a QTL analysis. For instance, linkage analysis has low power to detect QTLs unless they are of major effect (20%–30% of variance), but by including multiple measures of a phenotype, the power to detect a QTL may be increased, and the prospective candidate region can be narrowed (Boomsma & Dolan, 2000; Williams et al., 1999). The increased power to detect linkage in a multivariate analysis derives from the underlying correlational structure of the phenotypes, provided this covariation is partly due to the QTL. Thus, by making use of the covariation between processing speed measures and IQ, the power to detect linkage with QTLs influencing both these facets of cognition should be increased.

As processing speed measures are theorized to index the neural speed of the brain, molecular approaches focusing on genes coding for basic structural aspects of neural wiring such as connectivity, myelin sheathing, number of ion channels, and efficiency of synaptic transmission may prove worthwhile. Explicit modeling of the multivariate genetic covariance of the processing speed and IQ measures will allow a direct test of whether candidate genes show pleiotropic effects (same gene influences variation in several measures) in multiple systems or whether gene effects on more elementary processes affect “downstream” cognition.

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