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ORIGINAL RESEARCH

# Genetic Covariation Between the Author Recognition Test and Reading and Verbal Abilities: What Can We Learn from the Analysis of High Performance?

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**Abstract** The Author Recognition Test (ART) measures print exposure and is a unique predictor of phonological and orthographic processes in reading. In a sample of adolescent and young adult twins and siblings (216 MZ/430 DZ pairs, 307 singletons; aged 11–29 years) ART scores were moderately heritable (67%) and correlated with reading and verbal abilities, with genes largely accounting for the covariance. We also examine whether high (and low) (i.e. 1SD above the mean) represents a quantitative extreme of the normal distribution. Heritability for high ART was of similar magnitude to the full sample, but, a specific genetic factor, independent from both low ART performance and high reading ability, accounted for 53–58% of the variance. This suggests a distinct genetic etiology for high ART ability and we speculate that the specific genetic influence is on orthographical processing, a critical factor in developing word recognition skills.

**Keywords** Print exposure · Verbal abilities · Reading · Twins · Quantitative genetics

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## Introduction

Scientific interest in reading spans basic processes of reading (e.g. Coltheart et al. (2001) dual route model), comprehension (Nation 2008), and the development and transmission of knowledge (Hirsch 1999). A core topic is to understand why individuals vary in measures of reading and other verbal abilities. Here we examine the nature of variation in print exposure, a proxy measure for reading activity and a robust and unique predictor of reading and spelling ability (Stanovich and West 1989), and its covariation with measures of reading and verbal ability in a large population twin sample. We extend this to both ends of the normal distribution (i.e. high and low), and in particular examined whether the heritability of high reading ability, as indexed by print exposure and standard reading & spelling tests, is similar to that found in the normal distribution, and further, the specificity of genes influencing high ability.

The Author Recognition Test (ART) (Stanovich and West 1989) was designed to provide a measure of print exposure that circumvents the tendency of respondents to give socially desirable answers when asked about reading volume (Paulhus 1984). It is a significant predictor of word recognition skill and processing efficiency, in particular in relation to irregular words, and taps phonological processing, orthographic processing (the ability to form, store, and access orthographic representations–i.e. the symbols/letters of the written language), and other processes that may reflect knowledge of vocabulary (Stanovich and West 1989). Since its development, performance on the ART has been associated with reading and spelling ($r$ ranging from .24 to .46) (Burt and Fury 2000; Stanovich and West 1989), as well as a wide range of measures including spelling ability, vocabulary, reading rate and comprehension (Aacheson et al. 2008; Masterson and Hayes 2007), suggesting that print exposure contributes to abilities such as general knowledge and verbal intelligence (Cunningham and Stanovich 1992).

The first evidence of a genetic influence on print exposure was found in the Colorado Learning Disabilities Research Centre (CLDRC) study, using the title recognition test (Olson and Byrne 2005), in which participants aged 8–18 years of age were asked to identify the titles of popular books. Twin correlations (MZ $r = 0.55$ vs. DZ $r = 0.24$) suggested that print exposure is under moderately strong genetic control, with a heritability of 0.52 (Olson and Byrne 2005). Subsequently, in a large study of 3039 twin pairs, reading scores at age 7 were found to explain 41% of the variance in ART at age 10, with the ART score at 10 (years) explaining 9% of reading achievement variance at 12 (years) (Harlaar et al. 2007). The heritability of the ART in children (age 10) was found to be low (0.10), with the main sources of variance attributed to shared (49%) and unique (41%) environment, suggesting, for example, that access to books may be important factor in the development of reading habits during childhood. However, while shared environment can strongly influence cognitive traits in children, it tends to account for much less of the variance in adulthood, where there is a strong genetic influence (Deary et al. 2006; Plomin and Spinath 2004).

In genetic studies of cognition a question of interest is whether the extremes (e.g. high/low ability within the normal range) are influenced by the same genes as those influencing the full distribution of abilities, or if the extremes are associated with a distinct genetic etiology (Plomin and Kovas 2005). If high ability is the quantitative extreme of the same genetic effects influencing the normal range, similar heritability for high ability would support a single distribution hypothesis, or the theory of ‘generalist genes’ (Plomin and Kovas 2005). The case for a single distribution would be further strengthened if genes influencing high ability were found to fully covary with those influencing low ability, and vice versa.

Previous studies of high general cognitive ability in children support a single distribution hypothesis (i.e. MacArthur Longitudinal Twin Study (MALTS) Cherny et al. 1992; Twins Early Development Study (TEDS) Kovas et al. 2007b; MALTS Petrill et al. 1998; TEDS Ronald et al. 2002) as does the study of low reading and mathematics ability (Kovas et al. 2007a, b). Similarly, a study of high reading ability in a sample of 8–18 year olds suggested a continuous distribution of genetic influence (Boada et al. 2002). While these studies offer important insights, they are limited in their diversity in relation to sample origin, sample age, and range of specific abilities examined.

In the present study we investigated the genetic architecture of the link between print exposure, as measured by the ART, reading and spelling, and verbal IQ subtests in adolescent and young adult twins. We predicted that heritability of the ART would be higher in an adolescent and young adult sample than in the 10 year olds assessed by Harlaar et al. (2007), reflecting increased heritability of cognitive phenotypes across development (e.g. Plomin and Spinath 2004), and that verbal IQ and reading phenotypes, including ART, would share moderately overlapping genetic and environmental influences as suggested by previous studies in our, and other, laboratories (Bates et al. 2004; Bates et al. 2006; Harlaar et al. 2007; Wainwright et al. 2004). In addition, for the first time we investigate whether high (and low) ART performance represents a quantitative extreme of the normal variation. If so, genes influencing print exposure would be the same across the entire continuum, supporting the theory of ‘generalist genes’ (Plomin and Kovas 2005). Further, we examined the nature of the association between ART and word-reading skills for high performance and compared that to the association found for low performance. We hypothesized that there would be genetic influences specific to high ART performance, and speculated that these might reflect orthographic processes not captured in the reading score, as deficient orthographic processing skills may characterise less skilled readers (Stanovich and West 1989).

## Methods

### Participants

Twins and their siblings were initially recruited as part of ongoing studies of melanoma risk factors and cognition in the greater Brisbane area (Wright and Martin 2004). Data examined in the present study were collected as part of the cognition study (1996-ongoing) (e.g. Luciano et al. 2004), and a study of health and wellbeing (2002–2003) (e.g. Bates et al. 2004; Wright and Martin 2004). Participants included 646 twin pairs (216 MZ pairs and 430 DZ pairs) and 307 singleton siblings of twins, and ranged in age from 11.6 to 28.7 years of age (mean = 18.0 years ± 3.0 SD) Zygosity for twin pairs of the same sex was determined by blood groups (typed by ABO, Rh [CcDEe] and MNSs by the Red Cross Blood Transfusion Services) and genotyping of nine polymorphic microsatellite markers (AmpF1STR Profiler Plus Amplification kit; Applied Biosystems, Foster

City, California). Exclusion criteria for the cognition study included a significant head injury, neurological or psychiatric condition, history of substance abuse/dependence, and/or taking medications with significant central nervous system effects. There were no exclusion criteria for the health and wellbeing study. Informed written consent for all measures was obtained from each participant and their parents/guardian if participants were younger than 18 years of age. Ethical approval for these studies was obtained from the Human Research Ethics Committee, Queensland Institute of Medical Research.

## Measures

### *Author recognition test*

Following Burt and Fury (2000), the Author Recognition Test (ART) (Stanovich and West 1989) was given as a list of 80 names. In the current study, we modified the Burt and Fury (2000) revision of the ART, which was administrated to undergraduate psychology students, to reflect the wider IQ range in our community sample. To make the test more sensitive for those in the lower end of the IQ distribution, the number of embedded authors was increased from 40 to 60 with 20 foils. To account for the broad range of age in our participants (from 11 to 28 years of age) two lists of authors were developed—one for those under 17 years and one for those 17 years and over. Eighty-four percent of twin families received the ART as part of a mail-out questionnaire for the health and well-being study, and the remaining 16% completed it at the QIMR clinic, as part of the cognition study. Participants were asked to identify the authors and urged not to guess. The test was scored by subtracting the number of false alarms from the number of authors selected.

### *Reading and spelling*

The CORE (Bates et al. 2004) assesses regular, irregular and non-word reading through a 120 word extended version of the Castles and Coltheart (1993) test, including additional items to increase the difficulty level for an older sample. Regular and irregular word spelling was assessed by a subset of 18 regular and 18 irregular words from the CORE, which were verbally presented in a mixed order to avoid blocking effects. Test scores were calculated for each of three reading subtests and two spelling subtests by simply adding the number of correctly read and/or spelled items. Consistent with a previous study of the reading and spelling phenotypes (Luciano et al. 2007) we derived a principal component factor score (Reading & Spelling) which accounted for almost 74% of the variance. The CORE was conducted over the phone as part of the health and well-being study, and measures were available for 84% of those who completed the ART. We observed no differences in the CORE for participants who completed the ART and those who were not administered the test.

### *Verbal ability*

Verbal ability, collected as part of the cognition study, was assessed using the verbal subtests from the Multi-dimensional Aptitude Battery (MAB) (Jackson 1984), with data available for 73% of the ART sample. In the cognition study twin pairs and their siblings are tested as close as possible to their 16th birthday (mean = 16.2 years ± 0.41 SD, range 15.4–18.3). The MAB is a general intelligence test based on the WAIS-R (Wechsler 1981) and presented in a multiple choice format. Data are collected for three verbal subtests (information, arithmetic, vocabulary) and two performance subtests (spatial, object assembly) leading to the assessment of Verbal IQ (VIQ) and Performance IQ (PIQ), respectively, and Full Scale IQ (FSIQ) when combined. The test-retest reliability was reported to be equal to or above 0.95 by Jackson (1984). This test-retest robustness has been re-examined in 50 twin pairs of our sample, and yields similar reliabilities (0.89, VIQ; 0.87, PIQ; 0.90, FSIQ) (Luciano 2001). In this study we focussed on the three subtests of verbal IQ. Further details on the IQ testing procedure can be found in previous papers (e.g. Luciano et al. 2001; Wainwright et al. 2004).

## Multivariate modelling of ART, verbal IQ subtests and reading & spelling

Raw scores for ART showed a small positive skew, and were log transformed before analysis. Prior to statistical analyses all data were standardized and checked for univariate and family outliers using a Z-score threshold of ± 3.29 (Plomin et al. 2008; Tabachnick and Fidell 1996). For ART and Reading & Spelling two to ten individuals were dropped as univariate outliers, and one to three families were dropped at the multivariate level. Data screening was conducted using SPSS (version 15.0 for windows), except for family outliers that were detected using the %P option in Mx (Neale et al. 2003), which provides a likelihood statistic for each family conditional on the genetic model. Possible effects of birth order, zygosity, age, sex, ART type test and twin/sibling pair effects were also tested in Mx before proceeding with multivariate analyses (McGregor et al. 1999; Neale et al. 2003, 2006), and significant covariates were included in the model(s).

As the DZ twin correlations were typically equal to or greater than half the MZ correlations, an ACE Cholesky model, for additive (A) genetic effects, shared (common) environment (C), and unique environmental variance (E) was estimated in Mx (Neale et al. 2003). Genetic and shared environmental factors were then modelled in an independent pathway model (Loehlin 1996) to estimate genetic and environmental influences specific to each variable, in addition to those common across variables, with unique environmental influences left as a Cholesky decomposition. Genetic and shared environmental factors were determined by rotating the genetic and shared environment correlation matrices from the Cholesky. Matrices were varimax rotated to simple structure using SAS System for Windows 8.02 (SAS Institute Inc.1999–2001). The identification of the final independent pathway model was explored by ensuring that optimization from different sets of starting values provided consistent solutions (Neale et al. 2006).

### Bivariate threshold modelling of high (and low) ART and reading & spelling performance

ART and Reading & Spelling scores were corrected, prior to analysis in Mx, for age, sex and test type (ART only), using a stepwise linear regression in SPSS (version 15.0 for windows), which corrects for the most significant covariate first, and so on until no more covariate are eligible for inclusion. This ensures that scores are adjusted for covariates prior to individuals being assigned to either ability group. Individuals with an ART residual score one standard deviation above or below the residual mean ART score of 0 were assigned to the high or low ART proband group. A one standard deviation cut-off has been used previously to determine high and low reading performance (Boada et al. 2002), and provides a balance between maximising the power to detect extreme performance, which benefits from a larger extreme group, and minimising the inclusion of non-extreme performers. The high ART proband group included 168 individuals (MZ = 60, DZ = 108), and 97 individuals (MZ = 26, DZ = 71) were identified as high Reading & Spelling probands. The low ART proband group comprised 201 individuals (MZ = 77, DZ = 124) and 141 (MZ = 57, DZ = 84) were identified as low Reading & Spelling probands. Variation in the size of the proband groups (15–17% for ART, 10–15% for Reading & Spelling) was due to minor sample skew. For both high and low performance groups, probands were categorized as 1 and non-probands as 0. This means that an individual who is identified as a proband for high ART performance, and categorised as 1, will be identified as a non-proband for low ART performance, and categorised as 0. Tetrachoric twin correlations and thresholds were obtained in Mx (Neale et al. 2006) and a series of bivariate liability threshold models (Falconer 1965; Smith 1974) were used to estimate the genetic and environmental variance/covariance between (1) high and low performance for both ART (Fig. 2a, b) and Reading & Spelling (Fig. 2c, d), with models run twice, e.g. high/low and low/high, to look at specifics for low and high performance respectively, and (2) Reading & Spelling and ART for both high (Fig. 2e) and low (Fig. 2f) abilities.. The model predicts that co-twins of MZ probands are likely to be more concordant than the co-twin of DZ probands. Significance of path estimates was assessed using 95% confidence intervals.

## Results

### Preliminary analyses: homogeneity of sampling and fixed effects

No significant differences were found in means and variances for birth order or zygosity, with the exception of a birth order difference for Arithmetic means ($\chi^2_4 = 12.47$; $P = 0.01$) and a zygosity difference for mean ART ($\chi^2_4 = 14.11$; $P = 0.007$). While mean differences for Arithmetic were inconsistent across zygosity group and attributed to sampling error, mean ART performance showed a pattern of significant differences for zygosity. Opposite-sex females had a lower mean compared with same-sex females (8.98 vs. 10.06), whereas the mean ART score for opposite-sex males was higher than for same sex males (7.30 vs. 6.61). We therefore allowed ART means to vary for the five zygosity groups. For all variables, means and variances for siblings were equivalent to those of twins after correction for multiple testing (i.e. $P < .005$), with the exception of Reading & Spelling ($\chi^2_1 = 8.35$–$14.41$), which was attributed to sampling error due to inconsistencies. Therefore, one mean and one variance were set for the five zygosity groups for each measure, with the exception of mean ART as indicated previously.

In addition, there were significant age, sex, and ART test type effects. Older participants had a higher mean for all variables ($\chi^2_1 \geq 8.42$; $P \leq 0.003$), females had higher mean ART and Reading & Spelling scores, while males had higher scores for Arithmetic and Information ($\chi^2_1 \geq 5.8$; $P \leq 0.01$) (Table 1), and mean ART was significantly higher for the under 17 year's test compared with the over 17 test (10.02 vs. 7.24). There were also differences in male and female variances for Reading & Spelling ($\chi^2_1 = 9.99$; $P = 0.002$), but these were not evident in a larger sample (Bates et al. 2004, 2006) and attributed to sampling error.

### Multivariate genetic analyses: ART and reading and verbal abilities

The ART was modestly correlated with the reading and verbal ability measures ($r = 0.19$–$0.42$) (Table 1). Twin

**Table 1** Means and standard deviations (SD) for females and males (*N* = number of individuals) and phenotypic correlations between the author recognition test, verbal IQ subtests (arithmetic, information, vocabulary) and reading and spelling

| Tests | Female (*N* = 609–813) | | Male (*N* = 477–673) | | Phenotypic correlations | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | (SD) | Mean | (SD) | ART | ARI | INF | VOC | R & S |
| Author recognition (ART) | 9.66 | (6.70) | 6.99 | (5.80) | – | | | | |
| Arithmetic (ARI) | 12.11 | (2.69) | 13.08 | (2.92) | 0.19 | – | | | |
| Information (INF) | 20.40 | (5.40) | 22.09 | (5.90) | 0.40 | 0.51 | – | | |
| Vocabulary (VOC) | 17.92 | (5.01) | 17.98 | (5.21) | 0.42 | 0.46 | 0.68 | – | |
| Reading & Spelling (R&S) | 0.10[a] | (0.67) | −0.10[a] | (0.83) | 0.38 | 0.40 | 0.57 | 0.53 | – |

*Note*: All correlations are significant at the 0.01 level

[a] Means (SD) are for the principal component factor which is a standardized value

correlations are reported in Table 2. MZ male and female correlations were not significantly different ($\chi^2_1 =$ 0.63–2.83), except for Reading & Spelling ($\chi^2_1 = 16.24$), which we attributed to sampling error since there were no differences in our larger sample (Bates et al. 2006). Also, no significant differences were observed between DZM, DZF, DZOS and twin/sibling correlations ($\chi^2_1 = 0.67$–$2.83$). Stronger correlations for MZs compared with DZs indicated genetic effects contributed to the variance in all measures.

The independent pathway model is shown in Fig. 1. Heritability of the ART was 0.67 (95% CI 0.49–0.85) and of similar magnitude to Reading & Spelling (0.64, CI 0.56–0.75), Arithmetic (0.54, CI 0.39–0.63), and Information (0.45, CI 0.31–0.63), but higher than Vocabulary (0.30, CI 0.18–0.48). Genes accounted for most of the covariation between ART and the other measures (85% of total covariation with Arithmetic, 76% for Information, 61% for Vocabulary, and 70% for Reading & Spelling). A common genetic factor (A1) was most influential for the verbal IQ subtests and Reading & Spelling (24–55% of variance), and accounted for 10% of the variance in ART. The second genetic factor (A2) most strongly influenced ART (36% of variance), and also influenced Information (11%), Vocabulary (5%) and Reading & Spelling (4%). A common environment factor (C1) had a significant influence on all measures except arithmetic, with the strongest loading on Vocabulary (30%). Unique environmental (E) influences accounted for the remaining variance (23–44%), with little covariation between the variables due to unique environmental effects.

## Bivariate threshold modelling of high/low performance: ART and reading & spelling

Table 3 shows means, standard deviations and ranges for both residual and raw scores of the ART and Reading & Spelling for high and low proband groups and their respective non-proband groups, as well as thresholds and tetrachoric twin correlations. For both high performance on the ART and Reading & Spelling, the twin correlations were higher in the MZs than the DZs, and similarly for low performance.

Bivariate models are shown in Fig. 2. Heritability estimates varied across models. High ART performance ranged from 0.74–0.87 (95% CIs ranged 0.40–0.90) and high Reading & Spelling ability from 0.86–0.89 (CIs 0.51–0.98). Based on these estimates, heritability for high performance was not significantly different to those for the normal distribution. Similarly, heritabilities for low ability (ART: 0.39–0.49 (CIs 0.04–0.84); Reading & Spelling: 0.36–0.43 (CIs 0.07–0.83)) did not differ significantly in

**Table 2** Twin and twin/sibling correlations (95% CI) for author recognition, verbal subtests (arithmetic, information, vocabulary) and reading & spelling

| Zygosity (*N* = full pairs) | Author recognition | Arithmetic | Information | Vocabulary | Reading & spelling |
|---|---|---|---|---|---|
| MZF (73–99) | 0.79 (0.72, 0.84) | 0.56 (0.11, 0.75) | 0.65 (0.40, 0.79) | 0.56 (0.22, 0.74) | 0.87 (0.82, 0.91) |
| MZM (54–76) | 0.71 (0.60, 0.79) | 0.71 (0.46, 0.83) | 0.74 (0.53, 0.85) | 0.77 (0.53, 0.87) | 0.65 (0.51, 0.76) |
| DZF (80–82) | 0.44 (0.27, 0.58) | 0.32 (−.04, 0.58) | 0.53 (0.16, 0.74) | 0.44 (0.01, 0.69) | 0.40 (0.22, 0.56) |
| DZM (63–83) | 0.41 (0.21, 0.57) | 0.35 (−.18, 0.68) | 0.75 (0.37, 0.88) | 0.55 (0.02, 0.79) | 0.37 (0.16, 0.53) |
| DZOS (131–137) | 0.57 (0.43, 0.65) | 0.57 (0.31, 0.73) | 0.44 (0.10, 0.67) | 0.52 (0.15, 0.72) | 0.48 (0.33, 0.59) |
| Twin/Sib (226–473) | 0.39 (0.30, 0.47) | 0.28 (0.13, 0.42) | 0.39 (0.24, 0.52) | 0.31 (0.15, 0.45) | 0.38 (0.26, 0.47) |
| MZ (130–175) | 0.75 (0.70, 0.81) | 0.64 (0.45, 0.77) | 0.70 (0.55, 0.80) | 0.65 (0.45, 0.77) | 0.78 (0.71, 0.83) |
| DZ/sib (397–606) | 0.43 (0.36, 0.49) | 0.32 (0.18, 0.45) | 0.42 (0.29, 0.54) | 0.34 (0.20, 0.47) | 0.40 (0.32, 0.48) |

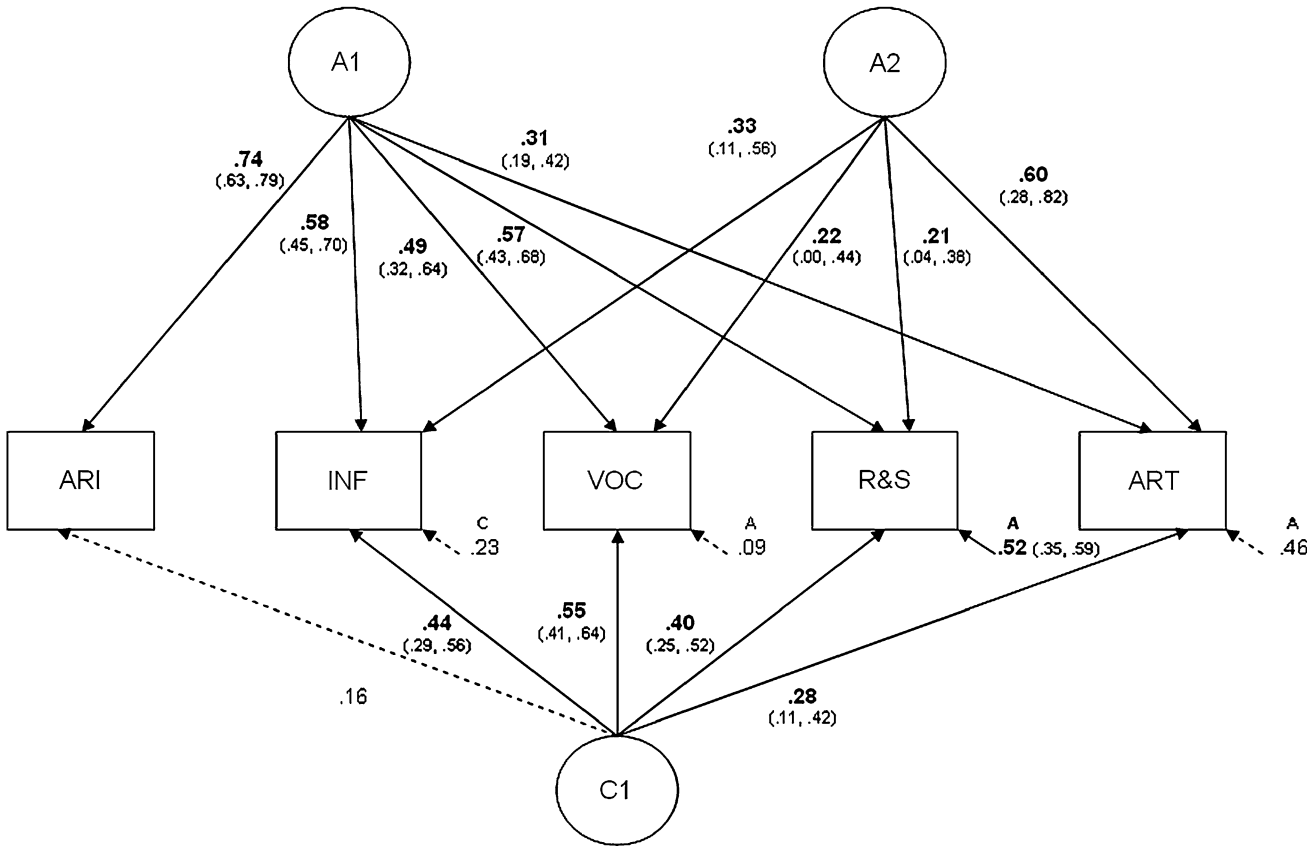


**Fig. 1** Path diagram depicting the additive and common environmental factor loading for the ART, Verbal IQ subtests (arithmetic, information, vocabulary) and reading & spelling (R&S). Estimates were standardized such that, when *squared*, they indicate the percentage of variance accounted for. Common genetic factors (A1, A2) and a common environmental factor (C1) are shown. *Arrows* below the variables denote specific genetic (A) or common environmental (C) influences. For significant estimates, 95% confidence interval are shown. Non significant paths are denoted by a dashed path. All remaining variance was influenced by unique environmental factors, which were left in Cholesky format and were strongly variable specific (covariance estimates ranged 0.14–0.01). The A and C factor structure was identified through rotation of the Cholesky A and C correlation matrices ($r_A$ ranged 0.37–0.88, $r_C$ ranged 0.61–0.98). The A factors accounted for 78% (eigenvalue = 3.89) and 13% (eigenvalue = 0.66) of the genetic variance respectively (i.e. over 90% of the genetic covariance) and the C factor accounted for 87% (eigenvalue = 4.32) of the shared environmental variance

magnitude to the normal distribution. However, bivariate models of high and low ART performance indicated a significant specific genetic influence for high ART that was independent of low ART performance, and which accounted for 53% of the total variance (71% genetic) in high ART ability (Fig. 2b). In contrast, no specific genetic factor was evident for low ART (Fig. 2a) or either high and low reading/spelling ability (Fig. 2c, d). Also, shared environmental factor influenced low (31% of total variance, Fig. 2b), but not high ART performance.

Similarly, in the high (Reading & Spelling and ART) ability analyses (Fig. 2e), a strong specific genetic influence on high ART performance (58% of total variance (i.e 79% genetic) was identified that was independent of Reading & Spelling, in addition to a common genetic factor (accounting for 86% of the variance in high Reading & Spelling and 15% in high ART). This contrasted with the analyses for low ability, where a single genetic source influenced both Reading & Spelling and ART (Fig. 2f). In addition, specific environmental influences accounted for a large amount of the variance in low ART performance (28–48% compared to 9% for high ART).

## Discussion

In the present study we showed that the Author Recognition Test (ART), a measure of print exposure, has a moderately strong genetic component ($h^2 = 0.67$), has modest correlations with measures of reading and verbal ability, and that covariation with these measures is largely due to common genetic influences. No magnitude differences in heritability were found between the normal distribution of ART or reading and spelling ability and either high or low performance for these measures. However, a series of bivariate analyses indicated a substantial genetic influence

**Table 3** Means (Standard Deviations) and ranges for residuals and raw scores for proband and non-proband groups, plus threshold and tetrachoric twin correlations for ART and reading & spelling

| Analyses | Proband | | | Non-proband | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | *N* | Mean[a] (SD) Range | Mean[b] (SD) Range | *N* | Mean[a] (SD) Range | Mean[b] (SD) Range | Threshold[c] | MZ *r* | DZ *r* |
| High ART | 168 | 1.54 (0.43) 1.00–2.96 | 18.96 (5.7) 9–38 | 983 | −0.28 (0.79) −2.82 to 0.99 | 6.47 (4.29) −1 to 20 | 1.04 | .88 | .44 |
| Low ART | 201 | −1.49 (0.39) −2.82 to −1.01 | 1.49 (1.43) −1 to 5 | 950 | 1.31 (0.78) −1 to 2.96 | 9.91 (6.12) 1–38 | 0.94 | .70 | .48 |
| High R & S | 97 | 1.22 (0.17) 1–1.67 | 0.72 (0.20) 0.27–1.10 | 851 | −0.13 (0.96) −5.2 to 0.99 | −.07 (0.75) −3.27 to 1.10 | 1.26 | .91 | .32 |
| Low R & S | 141 | −1.90 (0.80) −5.21 to −1 | −1.38 (0.65) −3.27 to −0.11 | 807 | 0.31 (0.60) −0.99 to 1.67 | 0.24 (0.47) −1.12 to 1.10 | 1.11 | .76 | .59 |

*Note*: Data presented are for twins only ($N$ = individuals); also, an individual who is identified as a proband for high ART performance will also be identified as a non-proband for low ART performance, thus the 168 high ART probands are part of the 950 non-proband low ART group, and vice versa, so that the 201 low ART probands are part of the 983 in the high ART non-proband group. The same goes for the reading and spelling analyses. Alternatively, we could have excluded the high Art probands from the low ART non-proband group, but this would have significantly reduced the power of our analyses (Risch and Zhang 1995)

[a] Mean residuals

[b] Mean raw data (for ART)/factor scores (for Reading and Spelling) are presented because mean scores showed an overlap between proband and non-proband before being adjusted for covariates

[c] All thresholds could be equated for MZ & DZ pairs, and were set equal in further analyses

that was specific to high ART ability, and independent to high reading and spelling ability. For low performers, genetic influence on ART was totally shared with that on reading and spelling.

The finding that the heritability of high performance in adolescents, for both ART and reading and spelling ability, is of similar magnitude to that found in the population sample, is in line with previous reports for high general cognitive abilities in children (Cherny et al. 1992; Kovas et al. 2007b; Petrill et al. 1998; Ronald et al. 2002) and high reading ability in children and adolescents (Boada et al. 2002). Similarly, heritabilities of low ART performance and low reading/spelling ability did not differ significantly from that of the normally distributed measure, as has been found for low mathematics ability in children (Kovas et al. 2007a). These findings are consistent with the single distribution hypothesis, or the theory of 'generalist genes' (Plomin and Kovas 2005).

However, similarity of heritability magnitude does not necessarily indicate that the same genes are active. Surprisingly, given the consistency of findings supporting the single distribution hypothesis, 73% of the genetic variation in high ART performance was specific to high ability, indicating a distinct genetic etiology for high, compared to low, performance. Further, our bivariate analyses showed that at a high performance level, variability in ART has considerable genetic independence from reading and spelling. A different pattern was observed for low performance, where all genetic influence on low ART performance was in common with low reading and spelling ability. The findings of a greater genetic overlap between the ART and reading and spelling at the low end of ability places itself in line with an earlier report that measures of cognitive abilities correlate more with each other in low ability groups than in high ability groups (Detterman and Daniel 1989). As discussed in Stanovich and West (1989), a minimum level of phonological skills are necessary to develop reading ability, but a second critical factor in developing word recognition skills may be orthographical processing. It may be that phonological skills are baseline to all levels of performance, as reflected in the variance common to both reading/spelling and ART. However, only high level performers may be able to access orthographical processing, as reflected in the specific genetic influence on high ART.

The heritability of ART performance estimated here is much larger than that reported for 10 year olds in the TEDS study (Harlaar et al. 2007), but is consistent with that for a sample of similar age (8–18 years) (Olson and Byrne 2005). The simplest explanation of this divergence is to assume an increasing heritability of print exposure with increasing age (i.e. $h^2 = 0.10$ at 10 years (Harlaar et al. 2007), $h^2 = 0.55$ at 8–18 years (Olson and Byrne 2005), $h^2 = 0.67$ at 12–29 years in the present study), consistent with several studies of cognitive phenotypes (e.g. Eaves et al. 1986; Plomin and Spinath 2004). The estimated effect of genes on other measures (reading and verbal abilities) were comparable with those reported in both our previous

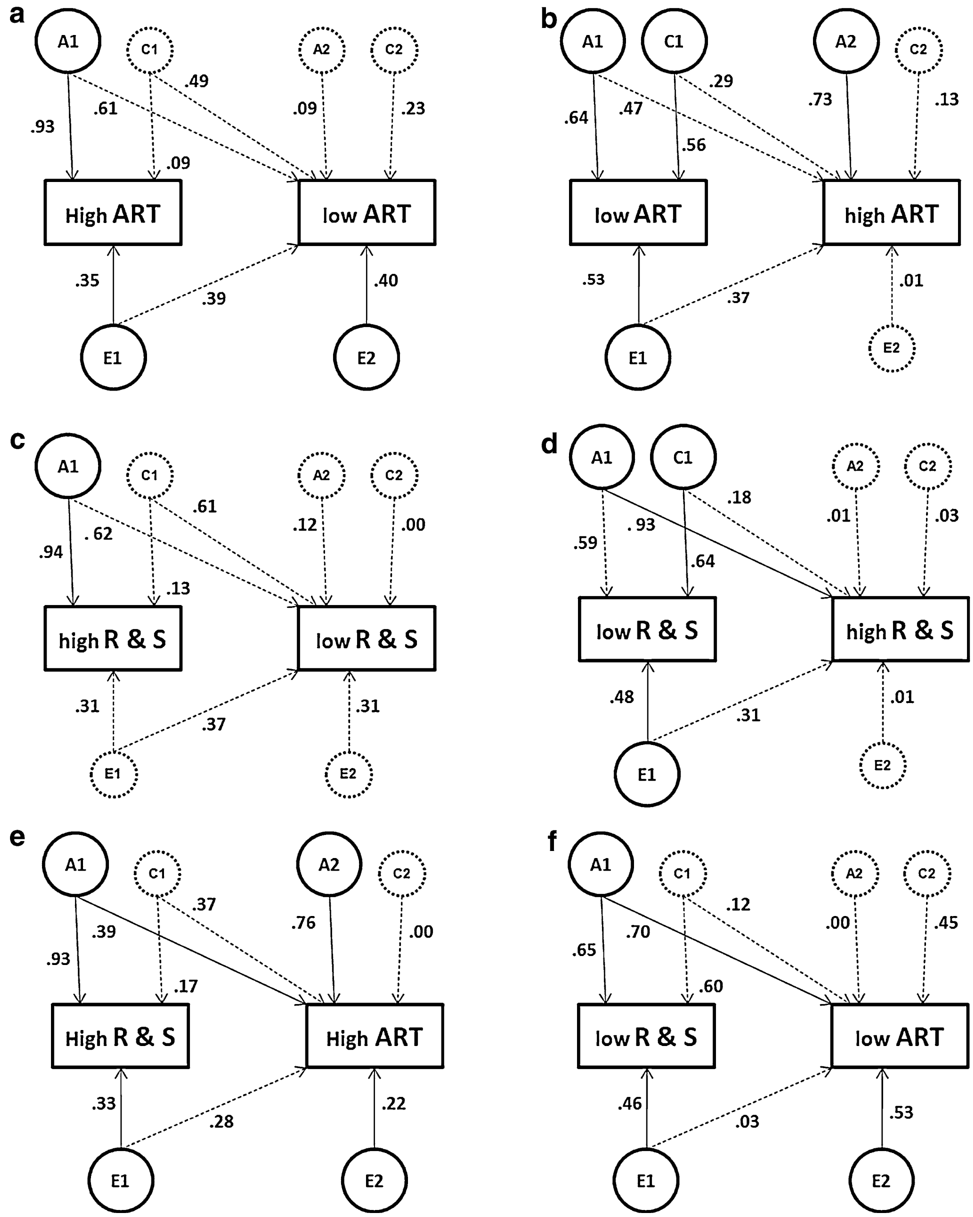


**Fig. 2** Path diagrams depicting the additive genetic (A), common (C) and unique (E) environmental factor loadings obtained from bivariate threshold models of twin pairs (only) for: **a** high and low ART performances, **b** for low and high ART performances, **c** for high and low Reading & Spelling performances, **d** for low and high reading & spelling performances, **e** for high ART and high Reading & Spelling (R & S) performances, and **f** for low ART and low Reading & Spelling performances. Estimates were standardized such that, when *squared*, they indicate the percentage of variance accounted for. Non significant paths (based on 95% confidence intervals) are denoted by a dashed path

(Bates et al. 2006; Luciano et al. 2003; Wainwright et al. 2004) and with independent (Harlaar et al. 2007; Silventoinen et al. 2006) studies.

A single common factor accounted for shared environmental sources of covariation between the measures in the normal distribution, in line with previous work (Eaves et al. 1984; Luciano et al. 2003; Wainwright et al. 2004). A single shared environmental factor in classic twin modelling has been described as a generalized effect of assortative mating that is confounded with common environment (Eaves et al. 1984). Eaves and colleagues (1984) proposed that individuals select mates based on phenotypic similarity which may include education, general intelligence and socioeconomic background. The general factor is a linear combination of the additive effects of each specific cognitive ability and therefore provides an explanation of why shared environmental variation is general rather than specific.

Mean performance on the ART increased significantly with age, notwithstanding a test effect showing that the test for those under the age of 17 was easier than the test for those aged 17 and over. In addition, females scored higher than males at all ages. It is well known that females read more fiction than males, possibly because of a greater empathy (Hoffman 1977), but other factors such as attitudes toward reading are also likely to contribute. For example, reading performance in males is generally more influenced by the level of interest in the reading material than females (Oakhill and Petrides 2007). We also found that females in opposite-sex pairs had a lower mean for ART than did females from same-sex pairs, and, reciprocally, males from opposite-sex pairs had a higher mean for ART than males from same-sex pairs, suggesting an intriguing twin dynamic in opposite sex pairs. Such a relationship has been attributed to biological (prenatal androgenisation) and/or social factors (cross-sex socialisation) (Culbert et al. 2008; Loehlin and Martin 2000; Rose et al. 2002). However, closer inspection revealed that this difference between opposite-sex and same sex pairs was found only in the 17 and over age group. Therefore prenatal androgenisation is highly unlikely to be the cause of this observation, and with the average age of departure from the parental home increasing in Australia, a change of living environment does not seem to be a probable cause for this phenomenon either. Other factors may be influencing this effect, or it may be simply due to sampling error.

We acknowledge that our study has limitations. For the high ability analyses, shared environment estimates were mostly non-significant, likely due to low power (Martin et al. 1978). In addition, we only examined high (and low) ability with a cut-off of 1 SD. This cut-off has previously been used for reading measures (Boada et al. 2002) and was chosen for its balance between maximising power and identifying possible true extremes. It is possible that distinct etiologies for high ability in measures such as reading might emerge using more extreme cut-offs. Further, a limitation of the ART may be that it does not differentiate author knowledge gained through personal reading, from that gained vicariously through other sources such as newspapers, magazines, and movies.

To conclude, the present study provides insights into the link between print exposure and both reading and verbal abilities. Our findings suggest that this link is due, to a substantial extent, to the same biological and experiential underpinnings, and are strengthened by the analysis of high (and low) ability, which provides additional evidence of the important link between print exposure and reading skills. While there was no evidence of a distinct genetic etiology for reading/spelling ability or for low performance on a print exposure test, supporting the theory of 'generalist genes' (Plomin and Kovas 2005), we found genetic independence for high compared to low print exposure scorers. We speculate that factors influencing both print exposure and reading/spelling scores may reflect common phonological processes, while factors specific to print exposure may reflect orthographic and other processes such as vocabulary knowledge (Stanovich and West 1989). If this is the case, our analyses suggest that only individuals with high print exposure scores are accessing orthographic processing skills. Also, environmental factors influenced score variation to a considerable degree in low performers. As print exposure is a strong predictor of word processing ability (Stanovich and West 1989), this has implications for reading education, suggesting that environments that promote print exposure may enhance reading ability in less skilled readers. These findings lay the basis for future molecular work, which would include a close examination of genes associated with high, but not low, print exposure scores and which may provide insights into the current finding.

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