Published in final edited form as:
Ann Dyslexia. 2013 April ; 63(1): 25–43. doi:10.1007/s11881-011-0055-z.

Genetic and Environmental Influences on Writing and their Relations to Language and Reading

Richard K. Olson,
Department of Psychology and Neuroscience, and Institute for Behavioral Genetics, University of Colorado at Boulder

Jacqueline Hulslander,
Department of Psychology and Neuroscience, and Institute for Behavioral Genetics, University of Colorado at Boulder

Micaela Christopher,
Department of Psychology and Neuroscience, and Institute for Behavioral Genetics, University of Colorado at Boulder

Janice M. Keenan,
Department of Psychology, University of Denver

Sally J. Wadsworth,
Institute for Behavioral Genetics, University of Colorado at Boulder

Erik G. Willcutt,
Department of Psychology and Neuroscience, and Institute for Behavioral Genetics, University of Colorado at Boulder

Bruce F. Pennington, and
Department of Psychology, University of Denver

John C. DeFries
Department of Psychology and Neuroscience, and Institute for Behavioral Genetics, University of Colorado at Boulder

Abstract

Identical and fraternal twins (N = 540, age 8 to 18 years) were tested on three different measures of writing (Woodcock-Johnson III Tests of Achievement-Writing Samples and Writing Fluency; Handwriting Copy from the Group Diagnostic Reading and Aptitude Achievement Tests), three different language skills (Phonological Awareness, Rapid Naming, and Vocabulary), and three different reading skills (Word Recognition, Spelling, and Reading Comprehension). Substantial genetic influence was found on two of the writing measures, Writing Samples and Handwriting Copy, and all of the language and reading measures. Shared environment influences were generally not significant, except for vocabulary. Non-shared environment estimates, including measurement error, were significant for all variables.

Genetic influences among the writing measures were significantly correlated (highest between the speeded measures Writing Fluency and Handwriting Copy), but there were also significant independent genetic influences between Copy and Samples and between Fluency and Samples. Genetic influences on writing were significantly correlated with genetic influences on all of the language and reading skills, but significant independent genetic influences were also found for

Correspondence concerning this article should be addressed to Richard Olson, Department of Psychology box 345, University of Colorado, Boulder, CO 80309. Richard.Olson@Colorado.EDU.

Copy and Samples, whose genetic correlations were significantly less than 1.0 with the reading and language skills. The genetic correlations varied significantly in strength depending on the overlap between the writing, language, and reading task demands. We discuss implications of our results for education, limitations of the study, and new directions for research on writing and its relations to language and reading.

Keywords

genes; environment; writing; language; reading; sex differences; twins

The Colorado Learning Disabilities Research Center (CLDRC) has been studying the genetic and environmental etiologies of reading and related skills since 1990 by comparing the similarities of identical and fraternal twins. Until 2006, our focus was on the reading skills of word recognition, spelling, and reading comprehension, and their relations to language, executive function, and attention. Beginning in March 2006 we added three writing measures to our test battery. We now have writing data from 81 identical and 189 fraternal twin pairs age 8 to 18. This paper is the first report of results from our phenotypic and behavior-genetic analyses of writing skills and their relations to language and reading skills in this sample.

Writing assessment and the remediation of writing deficits have received increasing attention in recent years (Berninger et al., 2002; Harris & Graham, this issue; Hooper et al., this issue; Miller & McCardle, 2011a). Research on writing disabilities is motivated by their constraint on communication, academic progress, and more recently on scores in high-stakes tests of writing to determine student and school progress (Jenkins, Johnson, & Hileman, 2004). Also, it is apparent that growth in writing and spelling is bi-directionally related to growth in reading (Graham, Harris, & Fink, 2002; Fitzgerald & Shanahan, 2000). Therefore, it is surprising that except for spelling, our search of the literature could not locate any published twin studies of genetic and environmental influences on writing other than a study using teachers' global impressions of writing (Kovas, Haworth, Dale, & Plomin, 2007). Because the present study uses objective assessments of specific writing skills, we are thus providing the first twin study to examine genetic and environmental influences on writing and its component skills.

We begin by first reviewing the logic of twin studies and the behavior-genetic methods used in the present study, including a review of results from our previous twin studies of individual differences in reading and language. We then discuss theory and evidence supporting selection of our three measures of writing skills. Then we turn to some specific hypotheses for genetic and environmental influences on individual differences in these writing skills and hypotheses on how they might be related to specific language and reading skills.

Our behavior-genetic analyses compare the correlations or variance-covariance matrices for identical and fraternal twins to estimate the relative influences of genes, shared family environment, and non-shared or unique environment. Identical twins are monozygotic (MZ), developing from a single sperm and egg, so they share all their genes. In the present and most twin studies, they also share their family environment, so any difference from a perfect correlation for MZ twins indicates the influence of non-shared or unique environmental factors, including measurement error. Fraternal twins are dizygotic (DZ), developing from different sperm and eggs, so they share half their segregating genes on average, and like the MZ twins, the DZ twins also share their family environment. Thus, a comparison of the correlations for the MZ and DZ pairs can be used to estimate the relative influence of genetic and shared-environment factors on individual differences. For example, if genes were the only influence on individual differences after unique environment, the expected DZ correlation would be half that of the MZ correlation, because the DZ twins share half their genes on average. The degree to which the DZ twin correlation exceeds half the MZ correlation provides an index of shared environment influences on individual differences (see Plomin, DeFries, McClearn & McGuffin, 2008, for the assumptions of behavior genetic analyses).

Previous studies of individual differences in the CLDRC sample and in a separate population sample of younger Colorado twins have shown strong genetic and relatively weak environmental influences on individual differences in reading skills (Betjemann et al., 2008; Betjemann, Keenan, Olson, & DeFries, 2011; Byrne et al., 2009; Gayán & Olson, 2003; Keenan, Betjemann, Wadsworth, DeFries, & Olson, 2006; Olson et al., 2011;). Similar results have been reported from recent twin studies in the U.K. (e.g., Kovas et al., 2007) and Ohio (e.g., Harlaar et al., 2010).

Several studies have used twin data to estimate genetic and environmental correlations between different reading and language measures. For example, the reading measures of word recognition and reading comprehension are largely influenced by the same genetic factors, though there are also significant independent genetic influences on reading comprehension that are separate from genetic influences on word recognition (Betjemann et al. 2008, 2011; Harlaar et al., 2010, Keenan et al., 2006). The genetic independence is strongest in older children and when reading comprehension is assessed on long passages, compared to passages of one or two sentences (Betjemann et al. 2011). Individual differences in oral language comprehension seem to be the source of this independence: genetic influences on listening comprehension were strongly correlated with those on reading comprehension, but significantly less so with those on word recognition. Taken together, the genetic influences on word recognition and listening comprehension accounted for all of the genetic influence on reading comprehension.

Our theoretical perspective on writing and its etiology is related to our present theoretical perspective on reading. We view reading as a multi-component process that includes skills in translating print to implicit or explicit speech codes for words, accessing meaning of those words in conjunction with syntactic information, holding this information in working memory and combining it with prior knowledge to build a situation model of the overall meaning of the text. Similarly, writing can be decomposed into component skills of fluency and accuracy in mapping words on to print, organizing those printed words into syntactically correct and meaningful sentences, and structuring the text to coherently and efficiently convey the intended overall meaning to the reader.

Although there have been no previous behavior genetic studies of component processes in writing and their relations to reading and language, many previous phenotypic studies of non-twin children have found significant correlations between writing, language, and reading skills (reviewed by Shanahan, 2006). Now, because we are working with a sample of twins, we can take these findings one step further and decompose the phenotypic correlations into their genetic, shared environment, and unique environment etiologies. Moreover, as with the different specific reading skills that were studied by Keenan et al. (2006), we can determine whether there are qualitative differences in the genetic and environmental influences on specific writing skills. We can also determine if there are significant genetic and environmental influences on writing that are shared with reading and language, as well as influences that might be independent from those for reading or language.

The specific measures that we included within each of the writing, language, and reading categories were selected to provide a range of theoretically important sub-skills. The three writing measures ranged from simple speeded paragraph copying, to fluency in simple sentence construction including three target words, to creative sentence construction with no time limit. The copying task did not require any creative production of written text. It simply involved the mechanics of speeded copying of text by hand and children were scored on the number of correct legible letters produced in a given time limit. The writing fluency measure included a timed component, but it also required some limited creativity to include three target words in a meaningful sentence. We hypothesized that the copying and writing fluency tasks would be genetically correlated through their shared demand for speed, but that there might also be independent genetic influences on the two measures because of the additional syntactic and semantic demands of the fluency task. The writing samples task was not timed, but it made additional creative demands on organization to write a sentence to a prompt. We hypothesized that while this measure would be phenotypically and genetically correlated with the other writing measures, it would also have independent genetic influences due to its greater demand for creativity and linguistic complexity in writing.

The language measures included phoneme awareness (PA) and rapid automatic naming (RAN) of letters and numbers, because PA and RAN have been proposed to have partly independent causal influences on reading disability (Wolf & Bowers, 1999). We also included two standardized language measures of oral vocabulary. Previous research has shown that all of these language skills are phenotypically and genetically correlated, but they have independent genetic influences as well. Our hypotheses about their phenotypic and genetic correlations with writing were that RAN would be most strongly related to the speeded copying and fluency tasks, and that vocabulary would be most related to the higher creative and linguistic demands of the writing samples task.

The reading measures included oral word reading and silent reading comprehension based on prior evidence of their partial genetic independence. We also included spelling of isolated words under the reading category, assessed with both written and recognition tasks. We hypothesized that there would be different patterns of relations between reading/spelling and writing, depending on the specific measures within those categories. We predicted that the writing samples task with its higher creative and linguistic demands would be most strongly linked to reading comprehension.

Finally, we examined gender differences. Based on previous research showing superior female performance on writing tasks (e.g., Berninger, Nielsen, Abbott, Wijsman, & Rask 2008), we hypothesized that this gender difference would also be present in our twin sample. Because this hypothesis was indeed confirmed, we therefore made sure to adjust the twins' scores for both age and gender differences in our behavior-genetic analyses (McGue & Bouchard, 1984).

Method

Participants

From a larger, ongoing twin study conducted at the CLDRC (DeFries et al., 1997; Olson, 2004), 540 individual twins between 8 and 18 years of age ($M = 12.0$, $SD = 2.9$) were selected for the current analyses based on their completion of the writing test battery that we have administered since early 2006. Participants were 286 males and 254 females. The Nicols and Bilbro (1966) zygosity questionnaire (or DNA testing in ambiguous cases) indicated there were 81 monozygotic (MZ) twin pairs and 189 dizygotic (DZ) twin pairs. Seventy-seven of the DZ pairs were same sex and 112 were opposite sex. Parents identified the following ethnic categories for their participating children in these percentages

(percentages total more than 100% because multiple categories may be selected): Caucasian 92.6%, Hispanic 13.0%, Native American 4.1%, Asian 3.3%, African American 1.5%, Hawaiian/Pacific Islander 0.7%, and Other 5.6%.

For participation in the CLDRC, children were ascertained through school records from 27 Colorado school districts. Based on school test scores showing at least one twin in the unsatisfactory category (approximately the lowest 20%) on the Colorado Student Assessment Program and/or parental report of their children's reading difficutly, 106 (20%) of the individuals in the present study had a broadly defined history of reading difficulties only, 72 (13%) had a history of attention problems (ADHD) only, as assessed by parent questionnaires, teacher questionnaires, and professional interviews, and 65 (12%) had a history of both reading and attention difficulties. Some of the twins with a school history of reading difficulty had only mild or no reading deficits when tested in the laboratory, and 297 (55%) of the participants had no prior indication of reading or attention problems. When the school-history and no-school-history samples were combined, individual differences in reading standard scores were normally distributed with means and standard deviations that approximated those for the tests' norming samples (see Table 1). Therefore, this combined sample of individuals with both positive and negative histories of reading difficulties and/or ADHD is appropriate for our main analyses of individual differences across the normal range (potential limitations of the sample are considered in the Discussion).

Children were excluded from the study if a parental questionnaire revealed serious neurological problems, uncorrected vision or hearing deficits, serious social/emotional problems, or a first language other than English. Exclusion based on a first language other than English, usually Spanish, is common in our Colorado sampling area. Exclusions on the other criteria were rare.

Measures

Writing—The writing measures included the Woodcock-Johnson III Tests of Achievement – *Writing Samples* and *Writing Fluency* subtests (Woodcock, McGrew, & Mather, 2001). A third measure, *Handwriting Copy*, is from the Group Diagnostic Reading and Aptitude and Achievement Tests (Graham, Berninger, Weintraub, & Schafer, 1998).

The *Writing Fluency* (WJ Fluency) test consists of a difficulty-graded series of three target words and a simple line drawing. The items begin with the picture of a boy's head and the words "boy," "happy," and "is." The final item shows a man sitting at a desk and the words "how," "today," and "thinking." Participants are required to use three words in a complete grammatical sentence. The final score is the number of sentences meeting these requirements that are completed in 7 minutes. Its published reliability is .88 A low-bound estimate of reliability for this and other measures within the present sample is based on the MZ correlation (MZ $r = .57$).

The *Writing Samples* (WJ Samples) test is untimed and asked subjects to write a single sentence in response to the tester's oral directions along with textual and sometimes pictorial prompts. Participants are placed in a difficulty-graded list of items based on grade and proceed through items six at a time until their last 12 responses are not at ceiling. The youngest participants in this study began with an item showing pictures of a king and a queen while the tester says "This woman is a queen. Write a sentence that tells what this man is." The oldest participants began with the text "who found the" and the tester's prompt: "Write a sentence about a boy finding a lost dog. Include the words "who found the" in the middle of your sentence." The time for this test ranges from 5 to 20 minutes. Two independent raters assign 0 to 2 points to each of the final 12 responses using the published scoring key as a guide. The two raters' scores for each item are averaged and then summed across items. Its published reliability is .87 (MZ *r* = .72.).

The *Handwriting Copy* (Copy) test asked children to copy a short paragraph as quickly as they could without making mistakes. Children are scored by the consensus of two raters on the number of letters they produce within 1.5 minutes that would be legible in isolation. There is no published reliability estimate (MZ *r* = .79).

Language—*Phonological Awareness* was assessed with a composite of two experimental measures. *Phoneme Deletion* required subjects to delete a phoneme from orally presented words or nonwords and pronounce what remained (i.e., say prot…..now say prot without the /r/ sound) (Olson et al., 1994). *Phoneme Transposition* required subjects to move the initial phoneme at the beginning of a spoken word to the end of the word, add the /ay/ sound, and pronounce the result (Olson et al., 1989). The correlation between the measures was .76 (MZ *r* = .80).

Rapid Naming was assessed with a composite measure that was based on the number of letters or numbers subjects could name in 15 seconds. The letters were presented in rows across one sheet of paper and the numbers were in rows across a second sheet of paper. The scores were based on the number of letters and numbers identified correctly. This measure was validated by Compton et al. (2002) and found to yield very similar results to the more lengthy measure of rapid naming developed by Denkla & Rudel, 1976. The correlation between letter and number naming was .73 (MZ *r* = .73).

Vocabulary was assessed with a composite measure based on the Peabody Picture Vocabulary Test (PPVT) (Dunn & Dunn, 1997) and the WISC-III or WAIS-III vocabulary subscale scores (Wechsler, 2003). The correlation between the two vocabulary measures was .78 (MZ *r* = .89).

Reading and spelling—*Word Recognition* was assessed with the Peabody Individual Achievement Test (PIAT) of word recognition (Markwardt, 1998) and our time-limited experimental measure (Olson et al. 1994). Both tests asked children to read lists of unrelated words aloud as they increased in difficulty, until error criteria were reached. The time-limited test required the response to be initiated within two seconds to be counted as correct. The correlation between the two measures was .85 (MZ *r* = .91).

Spelling was assessed with the Wide Range Achievement Test (WRAT) for spelling (Jastak & Wilkinson, 1984) and the Peabody Individual Achievement Test (PIAT) of spelling (Markwardt, 1998). The PIAT is a measure of spelling recognition while the WRAT is a measure of spelling production. The correlation between the two measures was .76 (MZ *r* . 91).

Reading Comprehension was assessed with a composite that included the Woodcock-Johnson (WJ) (III) (Woodcock et al., 2001) test of reading comprehension and the Peabody Individual Achievement Test (PIAT) of reading comprehension (Markwardt, 1998). The WJ test asked subjects to supply a missing word in short passages of one or two sentences. The PIAT test required subjects to select from one of four pictures to express the meaning of each short passage. The correlation between the measures was .71 (MZ *r* = .88).

Procedure

The present measures were embedded in a larger set that was administered to participants across a total of four approximately 2.5 hour sessions, typically on weekends. Participants were first tested in morning and afternoon sessions at the University of Colorado.

Subsequently they were tested in morning and afternoon sessions at the University of Denver within two months of their test day at the University of Colorado. Breaks were taken within and between each session to avoid fatigue. Highly trained examiners administered all measures and coded the data.

Results

Sample Performance

Mean scores, standard deviations, and ranges are presented for all measures in Table 1. The nine measures with published norms show that the present sample's means and standard deviations are close to those derived from the tests' norming samples. Thus, the present twin sample's performance in writing, reading, and language is reasonably representative of the distribution of skills in the population.

Sex Differences

We were struck by the large sex differences in writing that contrasted with the lack of significant sex differences on all of the other language and reading/spelling measures. The sex differences are presented in Table 2, including *t* tests and the Cohen's *d* effect sizes for differences on each measure. Female performance on each of the three writing measures was significantly higher than for males. Among the language and reading/spelling measures, the two spelling measures showed the largest sex difference in favor of females, though neither difference was statistically significant. To test if the sex difference for writing was significantly higher than for spelling, we created a writing composite from the three writing measures and a spelling composite from the two spelling measures. The significance of the difference in sex differences for the composites (writing $t = -7.03$ [1, 538], $p < .001$, Cohen's $d = -.61$; spelling $t = -1.87$ [1, 535], $p = .06$, Cohen's $d = -.16$) was tested in a two-factor (sex and composite) repeated-measures ANOVA. The interaction between sex and composite measure was highly significant (F = 37.28 [1, 535], $p < .001$, partial eta^2 = .065). Therefore, the sex difference for writing was significantly and substantially greater than for spelling.

For the phenotypic correlations and genetic analyses, we adjusted all variables for age, age squared, and sex. This is customary practice in behavior-genetic analyses of data from identical and fraternal twins (McGue & Bouchard, 1984). It is particularly important in this study because of its large age range and our inclusion of opposite-sex DZ twins. If we did not adjust for sex, the large sex differences in writing would lower the DZ correlations for the writing measures and lead to overestimates of genetic influence.

Phenotypic Correlations

Phenotypic correlations among the individual writing measures and the composite language and reading measures are presented in Table 3. Differences were significant for all correlation contrasts greater than .08. Of course with a sample this large, it is not surprising that all correlations are highly significant, though they vary in magnitude, and many pairs of the correlations are significantly different ($p < .05$) by Fishers Z test (uncorrected for multiple comparisons). Some of the simple pair-wise differences may be due to differences in the measures' reliabilities and are not of theoretical interest. Others may reflect a meaningful pattern of differences beyond differences in reliability. We focus here on the pairs whose statistically significant contrasts seem most theoretically significant.

Among the writing measures, the Copy and WJ Fluency speeded measures were more highly correlated (.59) than Copy with WJ Samples (.43), or WJ Samples with WJ Fluency (.50). This apparently stronger relation between the speeded writing measures is also reflected in the writing measures' relations to the speeded language task of Rapid Naming, wherein Copy and Rapid Naming (.52) and WJ Fluency and Rapid Naming (.48) are more highly correlated than the un-speeded WJ Samples and Rapid Naming (.34). Copy had the lowest correlation of the three writing measures with all of the other language and reading measures, except Rapid Naming. The greatest contrasts were between Copy and WJ Samples with Vocabulary (.34 vs. .58) and with Comprehension (.41 vs. .64). Similar to Copy, Rapid Naming had the lowest correlations with all the other language and reading measures. Thus, the speeded aspects of both Copy and Rapid Naming seem to distinguish them from the other measures. However, WJ Fluency, in spite of its speeded component, had higher correlations than either Copy or Rapid Naming with the other writing, language, and reading measures. Now we turn to the genetic and environmental etiologies of these skills.

Twin Correlations and Univariate Estimates of Genetic and Environmental Influences

The present study used the *Mx Statistical Modeling* program to analyze the variance and covariance matricies for MZ and DZ twin pairs instead of using simple comparisons of correlations to estimate genetic, shared environment, and unique environment influences (Neale, Boker, & Maes, 2002). Scores were standardized within zygosity.

The twin correlations and the *Mx* univariate estimates of genetic, shared environment, and unique environment influences for the writing skills and each of the language and reading composite skills are presented in Table 4 with their 95% confidence intervals. Note that for each measure, the MZ correlation is higher than the DZ correlation, providing suggestive evidence for genetic influence on all of the skills. Three of the skills (Copy, Phoneme Awareness, and Rapid Naming) had MZ twin correlations more than twice the correlations of the DZ twins, suggesting the possibility of non-additive genetic influences for these skills (Plomin et al., 2008). However, the possible non-additive influences are not statistically significant with the present sample size, so our *Mx* model estimated genetic (a^2), shared environment (c^2), and unique environment (e^2) influences under an additive assumption.

The univariate estimates of genetic influence are significantly greater than 0 for all of the skills except for WJ Fluency, which was nearly significant, and actually becomes significant in the bivariate models to be considered later. The magnitudes of the univariate estimates with confidence intervals in brackets vary widely from .36 [.00–.67] for WJ Fluency to .87 [.67–.93] for Spelling, but even those confidence intervals overlap for our small twin sample. The conservative position is that none of the contrasts between genetic influences are statistically significant with the present sample size. The picture is quite different for the shared environment estimates, only one of which (Vocabulary) is significantly greater than 0 at .38, and the low bound of its confidence interval [.20] exceeds those for Phoneme Awareness, and Rapid Naming. Finally, the unique environment estimates are all significantly greater than 0, and in many cases, the confidence intervals do not overlap (power is much greater for unique environment estimates). However, the differences among the unique environment estimates may be due to different degrees of measurement error across the different measures, so their interpretation is uncertain.

Genetic and Environmental Correlations among Writing Measures

Although the three writing measures had significant or nearly significant genetic influence, the univariate results in Table 4 do not tell us if the same genes are involved across the measures. This question was addressed in a Cholesky decomposition model that estimated the degree to which genetic and environmental influences are shared between the three writing measures, expressed as genetic correlations (r_a), shared environment correlations (r_c), and unique environment correlations (r_e). Note that these correlations are not dependent on the magnitudes of genetic and environmental influence on the measures, but only on the degree to which their genetic influence is accounted for by the same genes, or their environmental influences by the same environmental factors. For example, two measures with very low genetic influence can still have a high genetic correlation, though the confidence interval for the genetic correlation will be larger with lower levels of genetic influence.

The genetic correlations between the writing measures with their respective 95% confidence intervals were as follows: r_a = .52 [.32–.71] for Copy and WJ Samples; r_a = .95 [.68–1.0] for Copy and WJ Fluency; r_a = .75 [.42–.95] for WJ Fluency and WJ Samples. Note that the genetic correlation for Copy and WJ Samples is quite significantly less than a perfect 1.0, and this means that there are significant genetic influences that are not shared between the two measures. The same is true for WJ Samples and WJ Fluency, though their genetic correlation was higher and thus the degree of genetic independence between those two measures was lower than for Copy and WJ Samples. In contrast, the genetic correlation for Copy and WJ Fluency was quite high and not significantly less than 1.0

The shared environment correlations derived from the Cholesky model were estimated at r_c = 1.0 [0–1.0] for both Copy and WJ Samples and for Copy and WJ Fluency. However, the confidence intervals span from 0 to 1, so these shared-environment correlations are not significantly greater than 0 or less than 1. This is because shared environment for Copy was estimated at 0 (see Table 4). In contrast, the shared environment correlation for WJ Samples and WJ Fluency (r_c = 1.0 [.53–1.0]) was significantly greater than 0, even though their individual estimates of shared environment influence in the univariate analyses were positive but not significantly greater than 0 (see Table 4). This discrepancy arose because the multivariate Cholesky has greater statistical power than univariate models to detect shared environment influences among the measures (Schmitz, Cherny & Fulker, 1998).

The unique environment correlations were r_e = .04 [0–.26] for Copy and Samples, r_e = .16 [0–.35] for Copy and WJ Fluency, and r_e = .02 [0–.22] for WJ Samples and WJ Fluency. Note that none of the unique environment correlation estimates were significantly greater than 0, even though the univariate estimates of unique environment influence on each measure were significantly greater than 0 (see Table 4). This is a result that is consistent with the possibility that measure-specific measurement error is largely responsible for the unique environment univariate estimates, thus reducing the genetic and environmental correlations.

In summary, the results from the Cholesky model for our three writing measures revealed significant genetic correlations among all three writing measures, but also significant independent genetic influences between Copy and WJ Samples and between WJ Samples and WJ Fluency. Shared environment correlations between Copy and WJ Samples and between Copy and WJ Fluency were not significantly greater than 0 or less than 1. Only WJ Fluency and WJ Samples had a shared environment correlation estimate of 1 that was significantly greater than 0. In contrast, estimates of the unique environment correlations among the writing measures were low, and none were significantly greater than 0, possibly because the unique environment estimates were largely due to measure-specific measurement error.

Genetic and Environmental Correlations between Writing Measures and the Reading and Language Measures

Now we turn to the results of a series of two-factor Cholesky models that estimated the genetic and environmental correlations of the writing measures with each of the language and reading measures. The correlations are presented in Table 5. Contrasts between the correlations are discussed for those 95% confidence intervals which did not overlap.

Genetic correlations—All of the genetic correlations were significantly greater than 0. The lowest genetic correlation was for Copy and Vocabulary (.32); the highest was between Rapid Naming and WJ Fluency (1.0). The genetic correlations with Copy were generally lower than for the other two writing measures, except for Copy with Rapid Naming (.70), which was significantly higher than Copy with Vocabulary (.32) and Copy with Comprehension (.42). Other notable patterns in the genetic correlations include the significantly higher correlations with Comprehension for WJ Samples (.81) and WJ Fluency (.83) compared to Copy (.42). Also, in contrast to the opposite pattern for Copy, the genetic correlation between WJ Samples and Rapid Naming (.43) was significantly lower than for WJ Samples and Comprehension (.81).

Another interesting pattern in the genetic correlations is that for the Copy and WJ Samples writing measures, all genetic correlations except between WJ Samples and Comprehension were significantly less than 1. This means that there was significant independent genetic influence between these two writing measures and the language and reading measures. In contrast, although the estimate of genetic influence on WJ Fluency was lower than for the other two measures (see Table 4), its genetic influence was more highly correlated with the language and reading measures, and none of the estimates were significantly less than 1.

Shared environment correlations—The confidence intervals for the shared environment correlations were generally extremely wide, encompassing 0–1.0, because the univariate shared environment estimates were generally so low and power was limited. The two interesting exceptions were the Copy and WJ Fluency correlations with Vocabulary, both significantly greater than 0, and not significantly less than 1.0. This is due in part to the fact that Vocabulary has the highest estimate of shared environment influence among the language and reading measures (see Table 4).

Unique environment correlations—We previously noted that none of the unique environment correlations among the writing measures were significantly greater than 0. The same result was found for the unique environment correlations for the three writing measures with each of the language and reading measures. As was shown in Table 4, all measures had significant unique environment influence, but Table 5 shows that the unique environment correlations were not significant between the writing measures and each of the language and reading measures. We previously suggested that the non-significant unique environment correlations among the writing measures were consistent with their unique environment estimates being largely due to measure-specific measurement error. The non-significant unique environment correlations in Table 5 are also consistent with that hypothesis.

In summary, all of the genetic correlations between the writing measures and each of the language and reading measures were significant, though they varied in magnitude in ways that are considered in the Discussion. In contrast, all but two of the shared environment correlations between the writing measures and each of the language and reading measures were not significantly different from 0 or 1, and none of the generally low unique environment correlations were significantly greater than 0.

Discussion

To our knowledge, this is the first study to explore the genetic and environmental etiologies of individual differences in component writing skills through analyses of data from identical and fraternal twins. We conducted this exploration with three different writing measures. We also included data from additional measures of language, reading, and spelling to study the etiology of their relations with writing. In addition to confirming significant phenotypic correlations between writing, language, and reading that others had described (Shanahan, 2006), we used multivariate behavior-genetic analyses to uncover their etiology, expressed as genetic, shared environment, and unique environment correlations. Before discussing the results from our phenotypic and behavior genetic analyses, we discuss the evidence and implications of the uniquely large sex differences in writing skills that were found in the present study.

Sex Differences

The large sex differences that were found for our three writing measures are consistent with those from previous studies of individual differences in unselected population samples (Berninger & Fuller, 1992), and in samples selected for reading disabilities (Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008). A large norming sample study by Camarata and Woodcock (2006) included our WJ Samples and Fluency measures among many other tests of cognitive and reading ability. Their standard score difference for WJ Samples (4.0, $d = .33$) was slightly smaller than ours (5.6, $d = .40$), while their difference for WJ Fluency (7.1, $d = .44$) was nearly identical to ours (6.9, $d = .43$). They noted that their measures of general processing speed showed sex differences similar to those for WJ Fluency, and that their composite measure of general processing speed was more highly correlated with WJ Fluency (.54) than with WJ Samples (.38). We did not find significant sex differences on our Rapid Naming measures, but we did find a similar higher correlation between our Rapid Naming composite and WJ Fluency (.48) than between Rapid Naming and WJ Samples (.34). We have not been able to locate other studies of our speeded Copy measure that looked at sex differences, but we noted that Copy was also highly correlated with Rapid Naming.

The sex difference for our writing composite with an effect size of .61 was significantly greater than for the effect of sex on a spelling composite, and it was also greater than for any of the other reading and language measures. Camarata and Woodcock (2006) also found smaller sex differences on their reading and language measures compared to writing, including the un-speeded WJ Samples test, but they did not specifically analyze the statistical significance of these differences or comment on them. Others have commented that girls may have superior dexterity important for writing and/or they may differ in their amount of writing practice (Harris and Graham, this issue). At this point we do not know if the strong female advantage in writing is due primarily to direct genetic influences on basic cognitive and motor skills related to writing, or to environmental influences associated with gender-role differences in writing practice.

Our twin sample is currently far too small to have the power to detect statistically significant quantitative (i.e., strength of genetic influence) or qualitative (i.e., specific genes) differences in genetic and environmental etiology for male and female writing performance, so we simply adjusted the variables for sex and ran our behavior genetic analyses on the combined sample of male and female twins. A twin study with a much larger sample including over five thousand twin pairs found small but statistically significant quantitative and qualitative sex differences in genetic and environmental etiology for word reading fluency (Harlaar, Spinath, Dale, & Plomin, 2005). Sex differences in the genetic and environmental etiology of writing, with its uniquely large sex effect, might also be significant in a sufficiently large twin sample.

Phenotypic Correlations

The phenotypic correlations among our writing, language, and reading measures were much as others have found them (Shanahan, 2006). The speeded writing measures Copy and WJ Fluency were the most highly correlated among the writing measures, and they were most highly correlated with the speeded language measure Rapid Naming. In contrast, the un-speeded writing measure WJ Samples had the lowest correlation with Rapid Naming but the highest correlations with vocabulary and reading comprehension. Thus it appears that the un-speeded creative writing of sentences in WJ Samples may depend more on higher-level language skills shared with Vocabulary and Reading Comprehension. WJ Fluency was similar to WJ Samples in its strong correlations with Phoneme Awareness, Word Reading, and Spelling. This pattern suggests that the combined fluency and simple-sentence construction demands of WJ Fluency were similarly related to basic reading skills, but less so to the higher level language skills tapped by WJ Samples. The lower linguistic and reading demands of Copy may have led to its having the lowest correlations with all language and reading skills except for Rapid Naming. These differences between the three writing measures' correlations with each other and with the language and reading /spelling skills suggested that we might also find differences in their genetic and environmental etiologies.

Genetic and environmental influences on writing skills and their correlations

The three writing skills did not differ significantly in their levels of genetic and environmental influence by the very conservative criterion of no overlap between the 95% confidence intervals. However, the difference between the very high genetic influence on Copy and the relatively low genetic influence on WJ Fluency came close to this criterion, as did the high unique environment influence on WJ Fluency compared to the low unique environment influence on Copy. Also, WJ Fluency appeared to have the most shared environment influence, though its confidence interval encompassed 0 and overlapped substantially with those of the other writing measures.

It is not clear why WJ Fluency had a relatively high estimate for unique environment. It may have been largely due to greater measurement error, though its reported reliability was similar to that for WJ Samples. If measurement error was the cause, more reliable measurement of the skills employed in WJ Fluency could move some of its unique environment variance to the genetic and shared environment categories. As far as we can tell, the high unique environment estimate for WJ Fluency was not due to problems in scoring reliability, since both testers and scorers were carefully trained for consistency. However, testers did notice that subjects seemed to vary idiosyncratically in how they interpreted the speed demands of the WJ Fluency task. Also, there were differences in subjects' maintenance of speed and attention over the seven-minute task, particularly among the younger subjects. Thus, the low-bound reliability estimate from the MZ correlation for the younger half of the twin sample was .43, while it was .77 for the older half of the sample.

The results from our multivariate Cholesky modeling of the genetic and environmental correlations among the writing measures yielded some definitive results. The genetic correlation between Copy and Fluency was not significantly different from unity, and it was significantly higher than between Copy and WJ Samples, whose genetic correlation was significantly less than 1. Thus we can confidently say that there is at least some difference between the genes that influence Copy and the genes that influence WJ Samples. The difference may be due to the difference in speed demands for the two tasks as well as the difference in dependence on higher level language skills that we explore next section. The genetic correlation between WJ Samples and WJ Fluency was also significantly less than 1, reflecting some degree of difference in genetic etiology. This too can be explained through differences in their genetic correlations with the language and reading skills.

In contrast to the genetic correlations among the writing measures, some of which were significantly less than 1, none of the shared environment correlations were significantly less than 1, and only the shared environment correlation between WJ Samples and WJ Fluency was significantly greater than 0. This is because the shared environment estimates were quite low in this sample, particularly for Copy but also for WJ Samples, and this led to the very large confidence intervals for the genetic correlations with Copy and WJ Samples. So at present, we can only say with confidence that the shared environment influences on WJ Samples are highly correlated, at least at the low bound of the confidence interval [.53] with those on WJ Fluency. In contrast to both the genetic and shared environment correlations, the unique environment correlations were all quite low and none were significantly greater than 0 in spite of the relatively narrow confidence intervals resulting from greater power to detect unique environment. This is a common result in multivariate studies of reading and related skills (i.e., Keenan et al., 2006). We believe the low unique environment correlations between measures are largely due to measure-specific measurement error.

Writing’s Genetic and Environmental Correlations with Language and Reading

Our understanding of the differences in genetic correlations between the writing measures was clarified when we observed the writing measures’ genetic correlations with the language and reading measures. The genetic correlation between Copy and Rapid Naming was quite high, not significantly less than 1, and it was significantly higher than the genetic correlations between Copy and Vocabulary and between Copy and Comprehension. The opposite pattern was noted for the un-speeded and more linguistically complex WJ Samples test, whose lowest correlation was with Rapid Naming and whose highest correlation was with Comprehension. WJ Fluency did not show a significant differential pattern of genetic correlation across the language and reading measures. Its genetic correlation estimates were high with all of the variables and not significantly less than 1, though its highest genetic correlation was with Rapid Naming apparently due to their shared speed requirement. The confidence intervals were relatively large because genetic influence was low for WJ Fluency.

The confidence intervals for the shared environment estimates were extremely large, most ranging from 0 to 1. This is likely due in part to the very low shared environment estimates for the writing variables in the present sample. The only shared environment estimates that were significantly greater than 0 were between Copy and Vocabulary and between WJ Fluency and Vocabulary.

Conclusions, Limitations, and New Directions

In this first behavior-genetic study of individual differences in writing, we have clearly established significant genetic etiology for individual differences in writing, and we have clearly established that this genetic etiology is significantly shared with a broad range of language and reading skills. But it is the differences in genetic etiology, both among the writing measures and between the writing measures and the different language and reading skills that are most interesting. There were clear differences in genetic etiology (i.e., specific genes) for the speeded and linguistically simple Copy task compared to the un-speeded and more linguistically complex WJ Samples task. A similar difference in genetic etiology has been noted for different measures of reading when comparing word recognition or decoding with reading comprehension for extended text (Betjemann et al., 2008; in press; Byrne et al., 2009; Keenan et al., 2006). Another parallel result with reading is the Copy and WJ Samples’ significant difference in their genetic correlations with Comprehension that may have been due to the shared demands for more complex linguistic processing in WJ Samples and Comprehension. In reading research, the genetic correlation is very high between the linguistically demanding measures of reading and listening comprehension for extended text, compared to the genetic correlation between word recognition and listening comprehension.

Our sample of twins from the CLDRC was partly selected for deficits in reading and ADHD, so it should not be viewed as a completely unselected population sample that is most appropriate for the study of individual differences across the normal range. Nevertheless, when the twins selected for reading disability and ADHD were combined with the more numerous twins without these disorders in the CLDRC sample, the means and variances on the normed measures of reading and language were very similar to those of the norming populations for the standardized tests. As well, they were very similar to the means and variances for some of the same measures in an independent unselected sample of Colorado fourth grade twins (Olson et al., 2011), which unfortunately did not include writing measures. The CLDRC sample and the unselected sample yielded very similar estimates for genetic and environmental influences on their shared language and reading measures, so we assume that results similar to the present ones for individual differences in writing would also be found in an unselected twin sample from the Colorado front range area that includes Denver and other communities between Fort Collins and Colorado Springs.

An important caveat to keep in mind about all behavior genetic studies is that their results depend on the environmental range for the studied phenotype: samples with greater environmental range relevant for the phenotype tend to yield lower estimates for genetic influence and higher estimates for environmental influences. For example, the present study excluded children whose first language was not English. This may have narrowed the environmental range for our sample and it may have partly contributed to our very high estimates for genetic and low estimates for environmental influences. A related caveat is that our low estimates for environmental influences do not negate the possibility that extraordinary environmental interventions can have powerful influences on children's writing skills. Indeed, the paper by Harris and Graham in this special issue documents the powerful effects of the Self-Regulated Strategy Development approach for improving children's writing of extended texts.

Other limitations of the present study point to some new directions for behavior-genetic research on writing. One obvious direction is to considerably expand the present twin sample to obtain more precise estimates of genetic and environmental influences on writing and its relations with language and reading. A larger sample would improve power to detect potentially significant influences from shared environment as well as quantitative and qualitative sex differences in writing's genetic and environmental etiology. A larger sample would also support the application of behavior-genetic methods to assess the genetic and environmental etiology of high and low writing group performance, as we have done for reading in the CLDRC sample (DeFries & Fulker, 1985; 1988; Friend, DeFries, & Olson, 2008; Gayán & Olson, 2001).

Another new direction would be to expand the writing measures. The present study was limited in three ways by our measures. First, there was a confound between what we have called linguistic complexity and the speed demands of the writing tasks. It would be interesting to compare children's skill across a range of un-speeded writing tasks with different levels of linguistic complexity. Second, that range should be expanded into the higher levels of linguistic complexity and demands on executive function associated with more extended writing tasks such as those employed in the intervention studies reviewed by

Harris and Graham (this issue). Third, it would be helpful to include multiple measures of specific writing skills so that the shared variance among the skills can be modeled as latent traits without undue influence from measurement error.

Our results add to the growing evidence for biological influences on individual differences in learning rates for reading and writing skills due to genetic variation (Byrne et al., 2008; Miller & McCardle, 2011b). In the future we hope to better understand and potentially mitigate these biological constraints through continued behavior-genetic, molecular-genetic, and neuroscience research. For now, the results of genetic research can help educators understand why extraordinary environmental interventions are often needed to at least partially compensate for genetic and other biological constraints on reading and writing skills. These results should also counter unreasonable public policies that require all children to reach “grade level” in multiple academic skills, and they should help to recognize the extraordinary effort required of many children with learning disabilities to reach or more closely approach functional levels in reading and writing.

Acknowledgments

Funding was provided by the Eunice Kennedy Schriver National Institute of Child Health & Human Development, grant number HD027802. We thank the twins and their families who participated in the study. We also thank the many cooperating school districts that initially contacted the twins’ families for participation in the study.

References

Berninger VW, Abbott RD, Abbott SP, Graham S, Richards T. Writing and reading: Connections between language by hand and language by eye. Journal of Learning Disabilities. 2002; 35:39–56. [PubMed: 15490899]

Berninger, Fuller, Berninger V, Fuller F. Gender differences in orthographic, verbal, and compositional fluency: Implications for diagnosis of writing disabilities in primary grade children. Journal of School Psychology. 1992; 30:363–382.

Berninger VW, Nielsen KH, Abbott RD, Wijsman E, Raskind W. Gender differences in severity of writing and reading disabilities. Journal of School Psychology. 2008; 46:151–172. [PubMed: 19083355]

Betjemann RS, Keenan JM, Olson RK, DeFries JC. Choice of reading comprehension test influences the outcomes of genetic analyses. Scientific Studies of Reading. 2011

Betjemann RS, Willcutt EG, Olson RK, Keenan JM, DeFries JC, Wadsworth SJ. Word reading and reading comprehension: stability, overlap and independence. Reading and Writing. 2008; 21:539–558.

Byrne B, Coventry WL, Olson RK, Hulslander J, Wadsworth S, DeFries JC, et al. A behavior-genetic analysis of orthographic learning, spelling, and decoding. Journal of Research in Reading. 2008; 31:8–21.

Byrne B, Coventry WL, Olson RK, Samuelsson S, Corley R, Willcutt EG, Wadsworth S, DeFries JC. Genetic and Environmental Influences on Aspects of Literacy and Language in Early Childhood: Continuity and Change from Preschool to Grade 2. Journal of Neurolinguistics. 2009; 22:219–236. [PubMed: 20161176]

Camarata S, Woodcock R. Sex differences in processing speed: Developmental effects in males and females. Intelligence. 2006; 34:231–252.

Compton, DL.; Davis, CJ.; DeFries, JC.; Gayan, J.; Olson, RK. Genetic and environmental influences on reading and RAN: An overview of results from the Colorado Twin Study. In: Wolf, M., editor. Conference proceedings of the Dyslexia Research Foundation Conference in Extraordinary Brain Series: Time, fluency, and developmental dyslexia. Baltimore MD: York Press; 2001. p. 277-303.

Compton DL, Olson RK, DeFries JC, Pennington BF. Are all RAN created equal? Comparing the relationships among two different formats of alphanumeric RAN and various word reading skills in normally achieving and reading disabled individuals. Scientific Studies of Reading. 2002; 6(4): 343–368.

Davis CJ, Knopik VS, Olson RK, Wadsworth SJ, DeFries JC. Genetic and environmental influences on rapid naming and reading ability: A twin study. Annals of Dyslexia. 2001; 51:241–258.

DeFries JC, Filipek PA, Fulker DW, Olson RK, Pennington BF, Smith SD. Colorado Learning Disabilities Research Center. Learning Disabilities. 1997; 8:7–19.

DeFries JC, Fulker DW. Multiple regression analysis of twin data. Behavior Genetics. 1985; 15:467–478. [PubMed: 4074272]

DeFries JC, Fulker DW. Multiple regression analysis of twin data: Etiology of deviant scores versus individual differences. Acta Geneticae Medicae et Gemellologiae: Twin Research. 1988; 37:205–216.

Denckla MB, Rudel RG. Rapid "automatized" naming (R.A.N.): Dyslexia differentiated from other learning disabilities. Neuropsychologia. 1976; 14:471–479. [PubMed: 995240]

Dunn, LM.; Markwardt, FC. Examiner's manual: Peabody individual achievement test. Circle Pines, Minnesota: American Guidance Service; 1970.

Dunn, LM.; Dunn, M. Peabody Picture Vocabulary Test-III. Circle Pines, MN: American Guidance Service; 1997.

Fitzgerald J, Shanahan T. Reading and writing relations and their development. Educational Psychologist. 2000; 35:39–50.

Friend A, DeFries JC, Olson RK. Parental Education Moderates Genetic Influences on Reading Disability. Psychological Science. 2008; 19:1124–1130. PubMed Central ID# NIHMSID63472. [PubMed: 19076484]

Gayán J, Olson RK. Genetic and environmental influences on orthographic and phonological skills in children with reading disabilities. Developmental Neuropsychology. 2001; 20(2):487–511.

Gayán J, Olson RK. Genetic and environmental influences on individual differences in printed word recognition. Journal of Experimental Child Psychology. 2003; 84:97–123. [PubMed: 12609495]

Graham S, Berninger V, Weintraub N, Schafer W. The development of handwriting fluency and legibility in grades l through 9. Journal of Educational Research. 1998; 92:42–52.

Graham, S.; Harris, KR. Students with learning disabilities and the process of writing: A meta-analysis of SRSD studies. In: Swanson, HL.; Harris, KR.; Graham, S., editors. Handbook of learning disabilities. New York: Guilford Press; 2003. p. 323-344.

Graham S, Harris KR, Fink B. Contributions of spelling instruction to the spelling, writing, and reading of poor spellers. Journal of Educational Psychology. 2002; 94:669–686.

Harlaar N, Cutting L, Deater-Deckard K, DeThorne LS, Justice LM, Schatschneider C, …Petrill SA. Predicting individual differences in reading comprehension: a twin study. Annals of Dyslexia. 2010; 60:265–288. [PubMed: 20814768]

Harlaar N, Spinath FM, Dale PS, Plomin R. Genetic influences on early word recognition abilities and disabilities: A study of 7-year-old twins. Journal of Child Psychology and Psychiatry. 2005; 46:373–384. [PubMed: 15819646]

Harris KR, Graham S. "An adjective is a word hanging down from a noun": Learning to write and students with learning disabilities. Annals of Dyslexia. (this issue).

Hooper SR, Costa L, McBee M, Porter F, Anderson KL, Yerby DC, Childress A, Knuth SB. A written language intervention for at-risk second grade students: A randomized controlled trial of the process assessment of the learner lesson plans at tier 2. Annals of Dyslexia. (this issue).

Jastak, S.; Wilkinson, GS. The Wide Range Achievement Test-Revised: Administration manual. Wilmington, DE: Jastak Associates, Inc.; 1984.

Jenkins JR, Johnson E, Hileman J. When is reading also writing: Sources of individual differences on the new reading performance assessments. Scientific Studies of Reading. 2004; 8:125–151.

Keenan JM, Betjemann R, Wadsworth SJ, DeFries JC, Olson RK. Genetic and environmental influences on reading and listening comprehension. Journal of Research in Reading. 2006; 29:75–91.

Kovas Y, Haworth CMA, Dale PS, Plomin R. The genetic and environmental origins of learning abilities and disabilities in the early school years. Monographs of the Society for Research in Child Development. 2007; 72:1–144. [PubMed: 17661895]

Markwardt, FC, Jr. Peabody Individual Achievement Test–Revise-Normative Update. Circle Pines, MN: American Guidance Service; 1998.

McGue M, Bouchard TJ Jr. Adjustment of twin data for the effects of age and sex. Behavior Genetics. 1984; 14:325–343. [PubMed: 6542356]

Miller B, McCardle P. Reflections on the need for continued research on writing. Reading and Writing. 2011a; 24(2):121–132.

Miller B, McCardle P. Moving closer to a public health model of language and learning disabilities: The role of genetics and the search of etiologies. Behavior Genetics. 2011b; 41:1–5. [PubMed: 21229298]

Neale, MC.; Boker, SM.; Xie, G.; Maes, HH. Mx: Statistical Modeling. 6th Edition. VCU Box900126, Richmond, VA 23298: Department of Psychiatry; 2002.

Nichols RC, Bilbro WC. The diagnosis of twin zygosity. Acta Genetica. 1966; 16:265–275.

Olson RK. SSSR, environment, and genes. Scientific Studies of Reading. 2004; 8(2):111–124.

Olson, R.; Forsberg, H.; Wise, B.; Rack, J. Measurement of word recognition, orthographic, and phonological skills. In: Lyon, GR., editor. Frames of reference for the assessment of learning disabilities: New views on measurement issues. Baltimore: Paul H. Brookes Publishing Co.; 1994. p. 243-277.

Olson RK, Keenan JM, Byrne B, Samuelsson S, Coventry WL, Corley R, Wadsworth SJ, Willcutt EG, DeFries JC, Pennington BF, Hulslander J. Genetic and environmental influences on vocabulary and reading development from pre-kindergarten through grade 4. Scientific Studies of Reading. (in press).

Olson RK, Wise B, Conners F, Rack J, Fulker D. Specific deficits in component reading and language skills: Genetic and environmental influences. Journal of Learning Disabilities. 1989; 22:339–348. [PubMed: 2738467]

Schmitz S, Cherny SS, Fulker DW. Increase in power through multivariate analyses. Behavior Genetics. 1998; 28:357–364. [PubMed: 9926617]

Plomin, R.; DeFries, JC.; McClearn, GE.; McGuffin, P. Behavioral Genetics. 5th ed.. New York: Worth Publishers; 2008.

Shanahan, T. Relations among oral language, reading, and writing. In: MacArthur, CA.; Graham, S.; Fitzgerald, J., editors. Handbook of writing research. New York: Guilford Press; 2006.

Wechsler, D. Examiners' manual: Wechsler Intelligence Scale for Children-Fourth Edition. San Antonio, TX: The Psychological Corporation; 2003.

Wolf M, Bowers PG. The double-deficit hypothesis for the developmental dyslexias. Journal of Educational Psychology. 1999; 91:415–438.

Woodcock, RW.; McGrew, KS.; Mather, N. Woodcock-Johnson III Tests of Achievement. Itasca, IL: Riverside Publishers; 2001.

Table 1

Descriptive Statistics for Measures of Writing, Language, and Literacy

	N	Min	Max	Mean (SD)
Copy *	529	0	210	102.73 (41.94)
WJ Samples	534	47	166	109.07 (14.39)
WJ Fluency	536	56	147	102.70 (16.18)
Phoneme Transposition *	537	0.30	100.00	77.87 (20.30)
Phoneme Deletion *	540	0	100	76.06 (19.46)
RAN Numbers *	540	5	63	34.30 (8.35)
RAN Letters *	540	4	55	31.91 (8.33)
Peabody Picture Vocabulary	530	56	142	107.36 (13.29)
Wechsler Vocabulary	539	1	19	11.17 (3.34)
Time-Limited Word Recognition *	540	12	192	123.31 (46.02)
PIAT Word Recognition	512	65	135	103.29 (12.65)
WRAT Spelling	534	57	146	100.77 (17.17)
PIAT Spelling	512	65	135	101.29 (14.13)
WJ Comprehension	455	55	130	101.58 (11.08)
PIAT Comprehension	512	65	135	104.71 (13.65)

Note:

* Raw scores; Wechsler Vocabulary is a standard score with a mean of 10 and SD of 3 in the norming sample, and all other values are standard scores with a mean of 100 and SD of 15. WJ = Woodcock Johnson. RAN = Rapid Automatized Naming. PIAT = Peabody Individual Achievement Test. WRAT = Wide Range Achievement Test.

Table 2

Descriptive statistics for writing, language, and literacy measures separated by sex

	Male Mean	Female Mean	*t*	df	*p*	*d*
Copy*	93.51	113.10	−5.51	527	<.001	−.48
WJ Samples	106.41	112.02	−4.58	532	<.001	−.40
WJ Fluency	99.46	106.33	−5.02	534	<.001	−.43
Phoneme Transposition*	78.01	77.72	.165	535	.87	−.01
Phoneme Deletion*	75.89	76.25	−.214	538	.83	−.02
RAN Numbers*	34.48	34.11	.513	538	.61	.04
RAN Letters*	31.38	32.50	−1.55	538	.12	−.13
Peabody Picture Vocabulary	108.35	106.25	1.82	528	.07	.16
Wechsler Vocabulary	11.23	11.11	.422	537	.67	.04
Time-Limited Word Recognition*	122.77	123.92	−.290	538	.77	−.03
PIAT Word Recognition	103.44	103.12	.285	510	.77	.03
WRAT Spelling	99.75	101.92	−1.46	532	.15	−.13
PIAT Spelling	100.33	102.35	−1.62	510	.11	−.14
WJ Comprehension	101.41	101.77	−.336	453	.74	−.03
PIAT Comprehension	105.18	104.19	.821	510	.41	.07

Note: *d* is Cohen's *d*.

Table 3

Correlations among Measures of Writing and Composite Measures of Language and Literacy

	1.	2.	3.	4.	5.	6.	7.	8.
1. Copy								
2. WJ Samples	.43							
3. WJ Fluency	.59	.50						
4. Phoneme Awareness	.39	.51	.52					
5. Rapid Naming	.52	.34	.48	.43				
6. Vocabulary	.34	.58	.51	.48	.29			
7. Word Reading	.49	.58	.62	.72	.50	.67		
8. Spelling	.51	.56	.60	.66	.51	.59	.86	
9. Comprehension	.41	.64	.55	.66	.40	.76	.78	.73

Note: All values significant at the $p < .001$ level. WJ = Woodcock Johnson.

Table 4

Twin Correlations and Univariate Estimates of Genetic, Shared Environment, and Unique Environment Influences for Writing, Language and Literacy Composites (95% Confidence Intervals in Parentheses)

	Twin Correlations		Heritability Estimates		
	MZ	DZ	a^2	c^2	e^2
Copy	.79	.25	.77 (.64–.84)	.00 (.00–.09)	.23 (.16–.33)
WJ Samples	.72	.39	.66 (.37–.80)	.06 (.00–.29)	.28 (.20–.39)
WJ Fluency	.57	.40	.36 (.00–.67)	.21 (.00–.47)	.43 (.31–.58)
Phoneme Awareness	.80	.38	.79 (.60–.85)	.00 (.00–.17)	.21 (.15–.29)
Rapid Naming	.73	.25	.70 (.54–.79)	.00 (.00–.11)	.30 (.21–.42)
Vocabulary	.89	.64	.51 (.35 –.69)	.38 (.20–.53)	.11 (.08–.16)
Word Reading	.91	.50	.81 (.62–.93)	.09 (.00–.28)	.10 (.07–.14)
Spelling	.91	.48	.87 (.67–.93)	.03 (.00–.23)	.09 (.07–.13)
Comprehension	.88	.47	.83 (.63–.92)	.05 (.00–.25)	.12 (.08–.16)

Note: WJ = Woodcock Johnson. MZ = monozygotic. DZ = dizygotic.

Table 5

Genetic and Environmental Correlations among Writing, Language, and Literacy

	Copy	**WJ Samples**	**WJ Fluency**
Genetic Correlations			
Phoneme Awareness	.49 (.36–.61)	.66 (.49–.87)	.89 (.62–1.0)
Rapid Naming	.70 (.57–.84)	.43 (.19–.62)	1.0 (.65–1.0)
Vocabulary	.32 (.11–.51)	.55 (.32–.73)	.73 (.42–1.0)
Word Reading	.55 (.43–.67)	.67 (.54–.92)	.92 (.73–1.0)
Spelling	.60 (.48–.71)	.64 (.50–.86)	.85 (.70–1.0)
Comprehension	.42 (.25–.55)	.81 (.66–1.0)	.83 (.61–1.0)
Shared Environment Correlations			
Phoneme Awareness	1.0 (.00–1.0)	1.0 (.00–1.0)	1.0 (.00–1.0)
Rapid Naming	1.0 (.00–1.0)	1.0 (.00–1.0)	1.0 (.00–1.0)
Vocabulary	1.0 (.28–1.0)	1.0 (.00–1.0)	.69 (.21–1.0)
Word Reading	1.0 (.00–1.0)	1.0 (.00–1.0)	1.0 (.00–1.0)
Spelling	1.0 (.00–1.0)	1.0 (.00–1.0)	1.0 (.00–1.0)
Comprehension	1.0 (.00–1.0)	1.0 (.00–1.0)	1.0 (.00–1.0)
Unique Environment Correlations			
Phoneme Awareness	.00 (.00–.25)	.00 (.00–.24)	.00 (.00–.11)
Rapid Naming	.02 (.00–.24)	.00 (.00–.21)	.00 (.00–.17)
Vocabulary	.10 (.00–.33)	.03 (.00–.26)	.00 (.00–.17)
Word Reading	.00 (.00–.17)	.00 (.00–.14)	.00 (.00–.13)
Spelling	.00 (.00–.23)	.00 (.00–.19)	.00 (.00–.19)
Comprehension	.14 (.00–.37)	.00 (.00–.17)	.00 (.00–.14)