Ann. of Dyslexia (2010) 60:265–288
DOI 10.1007/s11881-010-0044-7

Predicting individual differences in reading comprehension: a twin study

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Received: 12 December 2009 / Accepted: 12 August 2010 / Published online: 3 September 2010

Abstract We examined the Simple View of reading from a behavioral genetic perspective. Two aspects of word decoding (phonological decoding and word recognition), two aspects of oral language skill (listening comprehension and vocabulary), and reading comprehension were assessed in a twin sample at age 9. Using latent factor models, we found that overlap among phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension was primarily due to genetic influences. Shared

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environmental influences accounted for associations among word recognition, listening comprehension, vocabulary, and reading comprehension. Independent of phonological decoding and word recognition, there was a separate genetic link between listening comprehension, vocabulary, and reading comprehension and a specific shared environmental link between vocabulary and reading comprehension. There were no residual genetic or environmental influences on reading comprehension. The findings provide evidence for a genetic basis to the "Simple View" of reading.

Keywords Environment · Genetics · Reading comprehension · Simple View · Twins

Predicting individual differences in reading comprehension: a twin study

By the end of elementary school, the primary goal of literacy learning is "reading for meaning". For example, the National Assessment of Educational Progress (US Department of Education, 2005) stipulates that a "proficient" reading level at fourth grade entails that the reader is able to demonstrate an overall understanding of text. Additionally, "when reading text appropriate to fourth grade, they should be able to extend the ideas in the text by making inferences, drawing conclusions, and making connections to their own experiences". Despite concerted efforts by teachers and parents, there are substantial individual differences in the extent to which children meet these expectations. In the present study, we used a behavioral genetic design to determine which skills contribute to individual differences in reading comprehension and how these skills are related to each other, drawing on the Simple View of reading (Gough & Tunmer, 1986; Hoover & Gough, 1990).

According to the Simple View, proficient reading represents the product of two factors. One is word decoding, or the process of translating print to words. The other is listening comprehension, or understanding spoken language. Both word decoding and listening comprehension are necessary for successful reading comprehension, but neither skill is sufficient without the other. This makes intuitive sense: When word decoding skills are weak, words are likely to be misidentified and fewer cognitive resources can be devoted to the processing of meaning. Even if all the words can be correctly decoded, however, text comprehension will be compromised if the meanings of those words are largely unknown. As such, word decoding and listening comprehension can be seen as proximal but largely independent predictors of reading comprehension (Gough & Tunmer, 1986).

The Simple View has gained support from several sources (Kirby & Savage, 2008). First, regression and structural equation modeling analyses have demonstrated that most of the variance in reading comprehension can be accounted for by word decoding and listening comprehension, yet they each also make significant unique contributions to reading comprehension (e.g., Aaron, Joshi, & Williams, 1999; Catts, Hogan, & Adlof, 2005; Cutting & Scarborough, 2006; Kendeou, van den Broek, White, & Lynch, 2009). Second, although children with reading difficulties often struggle with both word decoding and reading comprehension, this is not always the case: a significant minority of children have deficits in poor decoding despite relatively good levels of reading comprehension (*dyslexia*), whereas other children show the opposite pattern, having deficits in reading comprehension despite relatively good decoding skills (specific reading comprehension difficulties; e.g., Catts, Adlof, & Weismer, 2006; Share & Leikin, 2004; Torppa et al., 2007). Finally, the independence of word decoding and comprehension processes is suggested by intervention studies. Although robust improvements in word decoding deficits have been demonstrated in many studies, these effects have not always transferred to reading comprehension (e.g., Edmonds et al., 2009; Lovett et al., 1994). This suggests that some components of successful comprehension may not be developed through interventions that focus chiefly on word decoding (Cutting & Scarborough, 2006).

Limited specification of word decoding and listening comprehension

Despite evidence supporting the Simple View of reading, it has been subject to criticism. One ambiguity is whether word decoding should refer to phonological decoding (the ability to serially translate graphemes into phonemes) or to word recognition (the ability to recognize whole words; Kirby & Savage, 2008). Hoover and Gough (1990) used measures of phonological decoding to index word decoding in their presentation of the Simple View. However, it has been suggested that word recognition provides a more complete representation of the word decoding component (Ouellette & Beers, 2009). Phonological decoding provides one route to word decoding, particularly in the beginning stages of learning to read. But for words that have inconsistent orthographic–phonological mappings (i.e., exception words, such as two and meringue), phonological decoding strategies will not work; instead, children must learn to memorize these words, or use contextual cues (e.g., sentence context, word order; Harm & Seidenberg, 2004). Furthermore, as children gain proficiency in word decoding, the orthographic representations of words become more closely integrated with phonological and semantic information, such that the "lexical representations" of those words are more complete (Perfetti & Hart, 2002). This enables children to recognize words automatically, as "sight words". It is clear, therefore, that word decoding may be accomplished by several means, including phonological decoding, contextual facilitation, and recognition of whole word orthography. Accordingly, it has been suggested that including word recognition may improve the prediction of reading comprehension within the Simple View of reading.

A counter-argument to the view that word recognition should be subsumed under the word decoding component of the Simple View is that word recognition depends on nonphonological factors (e.g., semantic and orthographic features of words). Under a strict interpretation of the Simple View, the semantic component of word recognition would be seen as a part of listening comprehension (Kirby & Savage, 2008). Consequently, word recognition may be redundant when both phonological decoding and listening comprehension are assessed. However, the evidence for this view is inconclusive. Braze, Tabor, Shankweiler, and Mencl (2007) found that a measure of phonological decoding accounted for unique variance in the reading comprehension of young adults (16–24-year-olds), whereas a measure of word recognition did not. Ouellette and Beers (2009) found that both phonological decoding and word recognition made unique contributions to reading comprehension in first grade, whereas only word recognition had a unique predictive effect in sixth grade. Finally, in a sample of fourth-grade children, Ouellette (2006) reported that word recognition accounted for significant unique variance in reading comprehension beyond the effects of phonological decoding, but this effect was no longer significant when measures of both vocabulary knowledge and phonological decoding were taken into account. These findings suggest that some portion of the variance in word recognition is shared with listening comprehension. Nonetheless, there may be unique, possibly age-dependent, effects of word recognition on reading comprehension, above and beyond the effects of phonological decoding.

In a similar vein, it has been proposed that the role of listening comprehension should be "unpacked". Within the Simple View, listening comprehension is essentially taken to represent "all of verbal ability" (Kirby & Savage, 2008). However, listening comprehension is clearly multifaceted. Vocabulary, syntactic knowledge, pragmatic skills, and background knowledge are needed to enable the individual to understand speech in ways that honor the grammar of the language and that are sensitive to contextual factors (e.g., nonliteral use of language). Consequently, using global or single indicators of listening comprehension may obscure the identification of the most relevant aspects of oral language skill in reading. A number of studies suggest that vocabulary should be included in the Simple View, as a separate but related aspect of listening comprehension. Having a wide and deep vocabulary facilitates word decoding, provides opportunities for elaborating on text and making inferences, and facilitates retrieval of background information that may be relevant for reading comprehension (Wilson & Anderson, 1986). Supporting the importance of vocabulary for reading comprehension, Verhoeven and van Leeuwe (2008) found that both vocabulary and listening comprehension influenced later reading comprehension in a cross-lagged panel design. Specifically, word decoding, vocabulary, and listening comprehension in first grade directly influenced reading comprehension 1 year later (i.e., at grades 2 and 4, respectively). There were also direct effects of vocabulary at grades 3 and 5 on reading comprehension at grades 4 and 6, respectively. Other studies, using a hierarchical regression approach, have shown that vocabulary may account for unique variance in reading comprehension independent of listening comprehension. For example, Ouellette and Beers (2009) found that vocabulary predicted reading comprehension independent of phonological awareness, word decoding, irregular word recognition, and listening comprehension among students in grade 6, but not among first-grade students. Similarly, Braze et al. (2007) found that vocabulary made a unique contribution to reading comprehension in young adults independent of phonological decoding and oral sentence comprehension. On the basis of these findings, it has been suggested that a "not-so-simple" view of reading that includes vocabulary is needed (Ouellette & Beers, 2009).

In summary, separate lines of research suggest that the Simple View of reading should be expanded, such that the word decoding component includes both phonological decoding and word recognition and that vocabulary is assessed in addition to listening comprehension. In the current study, we sought to examine this proposal by considering the etiological bases of the relationships among factors predicting reading comprehension. A key motivation for taking this approach is that it provides a testing ground for hypotheses about the relationships among predictors of reading comprehension suggested by the Simple View and their relationship with reading comprehension itself.

Behavioral genetic studies of reading comprehension

Twin studies have provided robust evidence that individual differences in reading and language skills are due to both genetic and environmental factors (Lewis et al., 2006). Specifically, genetic factors account for between 30% and 85% of the variance in phonological decoding, word recognition, and reading comprehension scores (e.g., Betjemann et al., 2008; Byrne et al., 2009; Harlaar, Spinath, Dale, & Plomin, 2005; Petrill, Deater-Deckard, Thompson, DeThorne, & Schatschneider, 2006). Lower genetic estimates (between 0% and 50%) have been reported for measures of listening comprehension (Keenan, Betjemann, Wadsworth, DeFries, & Olson, 2006; Kovas et al., 2005; Hohnen & Stevenson, 1999). *Nonshared* environmental factors, that is, nongenetic factors that are unique to each individual, also contribute to individual differences in reading and listening comprehension. Reported estimates of nonshared environmental influences are typically confounded by measurement error and thus are likely to be inflated. However, even studies that have used latent factors (Betjemann et al., 2008), which separate common measure variance from measurement error, have found significant nonshared environmental influences, indicating that this is an important source of variance. In contrast, shared environmental factors, referring to nongenetic factors that contribute to resemblance among siblings, are typically small and nonsignificant.

It is also possible to use twin studies to examine the extent to which genetic and environmental influences overlap among word decoding, listening comprehension, and reading comprehension (Keenan et al., 2006). The Simple View leads to several predictions for behavioral genetic studies. First, given that word decoding and listening comprehension are correlated predictors of reading comprehension, we may expect to find that these skill domains reflect common etiological factors—genetic, environmental, or both. Second, the notion that word decoding and listening comprehension make independent contributions to reading comprehension leads to the prediction that word decoding and listening comprehension also have partly different etiologies with reading comprehension. For example, some genetic effects may be specific to discourse processes involved in comprehending spoken and written language, resulting in a genetic link between listening and reading comprehension. The same could be true of environmental effects. Finally, the notion that word decoding and listening comprehension jointly account for most of the variance in reading comprehension leads to the prediction that there are no unique genetic and environmental influences on reading comprehension independent of genetic and environmental influences that account for the covariance among word decoding, listening comprehension, and reading comprehension.

To date, only Keenan et al. (2006) have explicitly examined the etiological relationships among word decoding, listening comprehension, and reading comprehension. This study was based on a sample of 8- to 17-year-old twins in Colorado, USA. Three measures were used to examine each domain, and composite scores of word decoding, listening comprehension, and reading comprehension were derived from these measures. Genetic factors that influenced both word decoding and listening comprehension accounted for 37% of the variance in reading comprehension. A further 14% of the variance in reading comprehension was due to genetic influences on listening comprehension independent of word decoding. There was no evidence for a third source of genetic variance influencing reading comprehension only. That is, word decoding and listening comprehension together accounted for all of the genetic variance in reading comprehension. A different picture emerged for environmental influences. Shared environmental influences were minimal (accounting for 11% to 18% of the variance in the composite scores) and were not significantly different from zero. Nonshared environmental influences, which included the effects of measurement error, were of moderate effect size (accounting for 24% to 32% of the variance in the composite scores) and largely measure specific. These findings indicate that the genetic—but not environmental—etiology of the covariance among word decoding, listening comprehension, and reading comprehension mirrors the pattern of phenotypic covariance suggested by the Simple View of reading.

The current study

Against this background, the current study sought to extend the work of Keenan et al. (2006) in two ways. First, we used measures of phonological decoding and word recognition to index word decoding and measures of vocabulary and listening comprehension to assess oral language ability (used here to denote the ability to use receptive and expressive language in ways that communicate ideas, organization, and structure). We were interested in determining whether each subcomponent made a significant unique contribution to reading comprehension. Second, we used latent factors as dependent measures. This approach is highly informative because it enables separation of the genetic and environmental influences on each task into those influencing the target ability (e.g., listening comprehension) and those influencing measurement error and measure-specific components of the tasks (e.g., arising from the task demands of individual listening comprehension tests). In addition, estimates of relationships involving latent variables are more reliable (Loehlin, 2004). We focused on twins at the end of elementary school.

We addressed three questions pertaining to the Simple View of reading. First, to what extent do genetic and environmental factors account for the overlap among word decoding, oral language, and reading comprehension skills? Second, is there evidence for genetic or environmental links between oral language and reading comprehension, independent of word decoding? Third, to what extent are there genetic and environmental influences on reading comprehension independent of both word decoding and oral language? In addressing these questions, we considered whether the proposed subcomponents of word decoding and oral language (phonological decoding, word recognition, listening comprehension, and vocabulary) each accounted for unique variance in reading comprehension and how they were related to reading comprehension.

Based on Keenan et al. (2006), we expected three trends to emerge: (1) evidence for significant genetic overlap across all three domains; (2) a specific genetic link between oral language skills and reading comprehension, independent of word decoding; and (3) no evidence for significant residual genetic influences on reading comprehension. We were unclear what to expect in terms of environmental overlap. Despite the negative results reported by Keenan et al. (2006), other research suggests that nonphonological language processes are correlated with reading due to both genetic and environmental factors (e.g., Hayiou-Thomas, 2008; Hayiou-Thomas, Harlaar, Dale, & Plomin, 2006). By taking a more differentiated approach to the assessment of word decoding and listening comprehension, conducting analyses at the level of latent variables, and using a sample of twins in a narrow age range, we seek to provide a more detailed picture of the factors underlying individual differences in reading comprehension, at least as they apply to literacy learning at the end of elementary school.

Methods

Sample

The Western Reserve Reading Project (WRRP) is an ongoing unselected twin study of reading and related cognitive skills. The total sample comprises 436 monozygotic (MZ) and same-sex dizygotic (DZ) twin pairs from Ohio and Pennsylvania who were recruited through media advertisements, school nominations, Ohio state birth records, and Mothers of Twins Clubs (for further details, see Petrill et al., 2006). Twins have been assessed annually, beginning in kindergarten or first grade. The present data are from the first 220 twin pairs who participated in the fifth assessment wave (average age 9.86 years, SD 0.89 years). This sample consisted of 89 MZ pairs (44.6% male) and 131 DZ pairs (42.1% male). Twins were individually tested by two different examiners during a home visit, lasting approximately 3 hours.

Twin zygosity was determined using polymorphic DNA markers obtained from buccal swabs. For a handful of families who did not consent to DNA testing, zygosity was determined by a measure of twin physical similarity reported to be 95% accurate when compared to DNA analyses (Price et al., 2000). Although slightly positively skewed (skew= 0.049), parental education levels varied widely and were similar for fathers and mothers: 12% high school or less, 18% some college, 30% bachelor's degree, 24% some post-graduate education or degree, and 5% not specified. Most families were two-parent married households (92%) and nearly all were White (92% of mothers, 94% of fathers). The majority of twin families were Caucasian (92%).

Measures

We separated word decoding into phonological decoding and word recognition, and oral language ability into listening comprehension and vocabulary. These four subcomponents were used to predict reading comprehension. Two measures were used to tap each domain. All measures were standard psychometric tests, with established reliability and validity. However, for the purpose of providing reliability estimates for the current study, we report MZ correlations for each measure. Because MZ twins are naturally matched on both their genetic and shared environmental background, any differences between them must be due to nonshared environmental influences and measurement error. MZ correlations therefore provide a lower-bound estimate of test reliability.

Phonological decoding was assessed using the Word Attack subtest from the Woodcock Johnson Reading Mastery Tests—Revised (WRMT-R; Woodcock, 1987) and the Phonemic Decoding Efficiency (PDE) subtest from the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999). In both tests, participants read aloud a list of pronounceable nonwords. WRMT-R Word Attack is untimed, whereas the TOWRE PDE subtest has a time limit of 45 seconds. These tests require children to apply their knowledge of the alphabetic principle to read words that follow English orthography (MZ twin correlations—0.82 for WRMT-R Word Attack, 0.79 for TOWRE PDE test).

Word recognition was assessed using the Word Identification subtest of the WRMT-R (Woodcock, 1987) and the Sight Word Efficiency (SWE) subtest from the TOWRE (Torgesen et al., 1999). In both tests, participants read aloud a list of individual words graded in difficulty. Mirroring the phonological decoding measures, WRMT-R Word Identification is untimed, whereas the TOWRE SWE subtest has a time limit of 45 seconds. Both tests assess the ability to recognize words as sight words (MZ twin correlations—0.82 for WRMT-R Word Identification, 0.73 for TOWRE SWE test).

Listening comprehension was assessed using the Narrative Comprehension subtest from the Test of Narrative Language (TNL; Gillam & Pearson, 2004) and the Understanding Spoken Paragraphs subtest from the Clinical Evaluation of Language Fundamentals (CELF; Semel, Wiig, & Secord, 2003). The TNL Narrative Comprehension test assesses the ability to recall and understand information in stories; CELF Understanding Spoken Paragraphs assesses the ability to interpret factual and inferential information presented in spoken paragraphs (MZ twin correlations—0.49 for TNL Narrative Comprehension, 0.54 for CELF Understanding Spoken Paragraphs).

Vocabulary was assessed using the Word Classes subtest from the CELF (Semel et al. 2003) and the Boston Naming Test (BNT; Goodglass & Kaplan, 2001). CELF Word Classes assesses knowledge of word meanings by requiring the child to listen to three or four words and indicate which two words are most closely related to each other. This test may be seen as a measure of vocabulary depth (i.e., extent of semantic representation of words). The BNT is a measure of expressive vocabulary in which the child is asked to name as many objects as possible in a series of 60 line drawings. This can be seen as a measure of vocabulary breadth (MZ twin correlations—0.80 for CELF Word Classes, 0.56 for BNT).

Reading comprehension was assessed using the Passage Comprehension subtest from the WRMT-R (Woodcock, 1987) and the Reading Comprehension subtest of the Peabody Individual Achievement Test (PIAT; Markwardt, 1997). WRMT-R Passage Comprehension uses a cloze procedure in which the child must study a short passage (two to three sentences long) and identify a key word missing from the passage. The PIAT Reading Comprehension subtest requires participants to read a list of increasingly difficult sentences and then choose a picture, from an array of four, that best matches the meaning of the sentence. Both measures assess literal reading comprehension (MZ twin correlations—0.73 for WRMT-R Passage Comprehension, 0.60 for PIAT Reading Comprehension).

Analysis

The phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension tests were used as indicators of latent phenotypic factors in structural equation models (SEM). There were two parts to our analyses. First, we examined the associations among the latent phenotypic factors in order to determine the joint and unique contributions of phonological decoding, word recognition, listening comprehension, and vocabulary to the variance in reading comprehension. Second, we used quantitative genetic modeling to examine the genetic and environmental factors underpinning the relationships among the five factors. Models were estimated from the raw data using full-information maximum likelihood, which yields maximum-likelihood estimates for path coefficients while taking missing data into account. All analyses were undertaken in the SEM program *Mx* (Neale, Boker, Xie & Maes, 2006). Three statistics were used to ascertain model fit: the Akaike Information Criterion (AIC; Akaike, 1987), the Bayesian Information Criterion (BIC; Raftery, 1995), and the Deviance Information Criterion (DIC; Speigelhalter, Best, Carlin, & van der Linde, 2002). These are indices of relative fit, where smaller values indicate better model fit (i.e., the model that reproduces the observed variances and covariances with as few unknown estimated parameters as possible). We designated model parameters as significant if their 95% confidence intervals (CI) did not include zero.

Results

Descriptive statistics and correlation analyses

Inspection of the data with skewness and kurtosis indices did not suggest major deviations from normality. Table 1 shows means (standard scores) and standard deviations for each measure by zygosity and for the whole sample. MZ twins scored higher on all measures except TOWRE Sight Word Efficiency and TNL Narrative Comprehension; however, effect sizes of the zygosity differences were small (Cohen, 1992).

Table 2 shows the correlations among the individual measures. All measures showed moderate to substantial correlations with reading comprehension (r=0.45–0.74). Within the word decoding domain, the phonological decoding and word recognition measures were substantially correlated (r=0.60–0.81). Within the oral language domain, the listening comprehension and vocabulary measures showed moderate correlations (r=0.48–0.54). Across domains, the phonological decoding and word recognition measures correlated moderately with listening comprehension (r=0.19–0.47) and vocabulary (r=0.38–0.55).

The next step was to examine the relationships among phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension at the level

Table 1 Means and standard deviations for whole sample and by zygosity

	Full sample		MZ twins		DZ twins		Cohen's *d*
	M (SD)	*N*	*M* (SD)	*N*	*M* (SD)	*N*	
PD1	107.81 (12.25)	438	108.07 (11.56)	177	107.85 (12.74)	261	0.02
PD2	100.03 (13.03)	423	100.37 (12.50)	169	99.87 (13.36)	254	0.04
WR1	107.05 (10.08)	434	107.48 (9.76)	176	106.72 (10.27)	258	0.08
WR2	107.18 (12.05)	437	107.05 (11.20)	177	107.35 (12.63)	260	−0.03
LC1	9.31 (3.08)	379	9.49 (3.11)	152	9.16 (3.03)	227	0.11
LC2	10.79 (2.87)	438	10.32 (2.51)	176	10.53 (2.85)	262	−0.08
VC1	42.08 (5.90)	438	42.91 (5.30)	176	41.53 (6.20)	262	0.23
VC2	10.03 (2.61)	429	10.32 (2.51)	175	9.85 (2.69)	254	0.18
RC1	103.74 (11.03)	404	104.57 (10.59)	162	103.21 (11.44)	242	0.12
RC2	106.38 (11.44)	434	106.96 (11.77)	175	106.09 (11.32)	259	0.08

PD1 Woodcock Johnson Word Attack, *PD2* TOWRE Phonemic Decoding Efficiency, *WD1* Woodcock Johnson Word Identification, *WD2* TOWRE Sight Word Efficiency, *LC1* CELF Understanding Spoken Paragraphs, *LC2* TNL Narrative Comprehension, *VC1* Boston Naming Test, *VC2* CELF Word Chains, *RC1* WRMT-R Passage Comprehension, *RC2* PIAT Reading Comprehension

of latent factors that represent the variance common to the measures used to assess each domain. We applied a Cholesky decomposition model (Neale & Cardon, 1992), analogous to a hierarchical regression model within an SEM framework. In this model (shown in Fig. 1), each predictor factor (phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension) was set to load on a second-order factor as well as $n-1$-s-order factors. The first second-order factor (n_1) explains all of the variance in the first predictor factor as well as the common variance among the predictors, while the subsequent second-order factors explain covariance among the factors independent of the $n-1$ predictor. To ensure model identification, the variance of each latent factor was constrained to unity and residual influences on the measures were not estimated. In addition, because we only had two measures per factor, we imposed equality constraints on the factor loadings.

The predictor factors were initially entered in the following order: phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension. The first second-order factor (n_1), indexed by phonological decoding, accounted for 94% (CI 0.88, 0.99) of the variance in word recognition, 32% (CI 0.19, 0.66) of the variance in listening comprehension, 55% (CI 0.30, 0.86) of the variance in vocabulary, and 70% (CI 0.58, 0.92) of the variance in reading comprehension. That is, most of the variance in reading comprehension is attributable to factors common to phonological decoding, word recognition, listening comprehension, and vocabulary. Independent of phonological decoding, there was a second factor (n_2) that accounted for 6% (CI 0.00, 0.12) of the variance in word recognition, 59% (CI 0.08, 0.79) of the variance in listening comprehension, 42% (CI 0.03, 0.68) of the variance in vocabulary, and 30% (CI 0.03, 0.42) of the variance in reading comprehension. The remaining second-order factors (n_3, n_4, n_5), influencing listening comprehension, vocabulary, and reading comprehension only, were not significant. These results indicate that the variance in reading comprehension could be explained by two factors: one reflecting the common variance among phonological decoding and the remaining factors and the second primarily reflecting the

Table 2 Phenotypic correlations among measures (with 95% confidence intervals in parentheses)

	PD1	PD2	WR1	WR2	LC1	LC2	VC1	VC2	RC1
PD2	0.82 (0.79, 0.84)								
WR1	0.81 (0.78, 0.84)	0.77 (0.73, 0.80)							
WR2	0.60 (0.54, 0.65)	0.76 (0.72, 0.79)	0.66 (0.60, 0.70)						
LC1	0.19 (0.10, 0.27)	0.23 (0.14, 0.32)	0.32 (0.24, 0.40)	0.29 (0.21, 0.37)					
LC2	0.36 (0.28, 0.43)	0.35 (0.27, 0.42)	0.47 (0.40, 0.54)	0.38 (0.30, 0.45)	0.47 (0.40, 0.53)				
VC1	0.38 (0.30, 0.46)	0.41 (0.32, 0.48)	0.53 (0.46, 0.59)	0.39 (0.31, 0.47)	0.49 (0.42, 0.56)	0.52 (0.45, 0.58)			
VC2	0.41 (0.33, 0.48)	0.40 (0.32, 0.47)	0.55 (0.49, 0.61)	0.39 (0.31, 0.46)	0.48 (0.41, 0.54)	0.54 (0.48, 0.60)	0.58 (0.52, 0.64)		
RC1	0.60 (0.54, 0.65)	0.62 (0.57, 0.67)	0.74 (0.70, 0.77)	0.59 (0.53, 0.64)	0.48 (0.41, 0.54)	0.55 (0.49, 0.60)	0.62 (0.57, 0.67)	0.67 (0.62, 0.71)	
RC2	0.54 (0.48, 0.60)	0.56 (0.50, 0.61)	0.65 (0.60, 0.70)	0.52 (0.45, 0.58)	0.45 (0.38, 0.52)	0.46 (0.40, 0.52)	0.60 (0.54, 0.65)	0.55 (0.49, 0.60)	0.67 (0.62, 0.71)

PD1 Woodcock Johnson Word Attack, *PD2* TOWRE Phonemic Decoding Efficiency, *WD1* Woodcock Johnson Word Identification, *WD2* TOWRE Sight Word Efficiency, *LC1* CELF Understanding Spoken Paragraphs, *LC2* TNL Narrative Comprehension, *VC1* Boston Naming Test, *VC2* CELF Word Chains, *RC1* WRMT-R Passage Comprehension, *RC2* PIAT Reading Comprehension

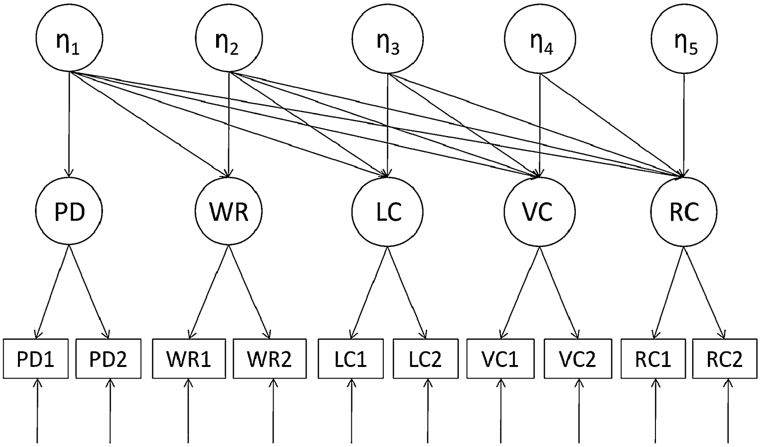


Fig. 1 Phenotypic Cholesky decomposition model

effects of oral language skill. Together, these factors accounted for all of the variance in reading comprehension. Changing the order of the factors, so that the oral language factors were entered first, resulted in a similar pattern: one factor reflecting the common variance among the five measures and a second factor primarily reflecting the effects of the word decoding factors (phonological decoding and word recognition; further details available on request from the first author).

Phenotypic correlations among the latent factors were substantial, as shown in Table 3. Mirroring the pattern of correlations among the measured variables (Table 1), reading comprehension was strongly associated with phonological decoding, word recognition, listening comprehension, and vocabulary, as suggested by the Simple View (r=0.80–0.94). There were also substantial correlations between phonological decoding and word recognition (0.96) and between listening comprehension and vocabulary (0.93). Cross-domain correlations were smaller and somewhat higher for word recognition (which correlated 0.70 with listening comprehension and 0.79 with vocabulary) than for phonological decoding (which correlated 0.52 with listening comprehension and 0.61 with vocabulary). This finding is consistent with the hypothesis that word decoding and oral language skills are independent predictors of reading comprehension, as suggested by the Simple View.

Table 3 Phenotypic correlations among the latent PD, WR, LC, VC, and RC factors (with 95% confidence intervals in parentheses)

Factor	PD	WR	LC	VC
WR	0.96 (0.93, 0.98)			
LC	0.52 (0.42, 0.60)	0.70 (0.62, 0.76)		
VC	0.61 (0.53, 0.68)	0.79 (0.73, 0.84)	0.93 (0.88, 0.97)	
RC	0.80 (0.74, 0.84)	0.93 (0.88, 0.97)	0.87 (0.82, 0.92)	0.94 (0.90, 0.97)

PD phonological decoding, *WR* word recognition, *LC* listening comprehension, *VC* vocabulary, *RC* reading comprehension

Genetic analyses

The next stage of our analyses involved quantitative genetic modeling (Plomin, DeFries, McClearn, & McGuffin, 2008). Genetic and environmental factors can be separated using twins growing up in the same family because genetic relatedness differs by zygosity. Specifically, MZ twins are genetically identical, whereas DZ twins share, on average, 50% of their segregating genes. Genetic influences on a trait are inferred if the MZ twin correlation is greater than the DZ twin correlation. This genetic contribution is assumed to reflect the effects of additive genetic influences (A): genes that together operate in an additive manner. If nothing more than additive genetic influences affect a trait, then MZ twins should be at least twice as similar as DZ twins. If the DZ correlation is greater than half the MZ correlation, this suggests that environments that the siblings share in common must have enhanced their similarity (e.g., shared peer groups). This environmental contribution is assumed to reflect the effects of shared environmental factors (C). Shared environmental factors, unlike additive genetic influences, are assumed to be invariant across zygosity. Finally, if MZ correlation is not perfect, despite the assumptions that MZ twins are genetically identical and share the same family environments, nonshared environmental effects (E) are inferred. Nonshared environmental effects refer to nongenetic influences that reduce the similarity among family members (e.g., differential parenting or classroom experiences).

The equal shared-environments assumption

As described above, a key assumption of the twin design is that there are no zygosity differences in the extent to which twin resemblance is due to shared environmental factors that contribute to variance in the trait under study. This is known as the equal environments assumption (EEA; Plomin et al., 2008). If the EEA is violated, then the excess resemblance of MZ versus DZ twins, attributed by the twin method to genetic factors, may be due in part to environmental effects.

It is well-known that MZ twins do, in fact, show greater similarities in their environments than DZ twins (e.g., more often sharing the same friends, sharing the same rooms, dressing more alike; Loehlin & Nichols, 1976). However, these similarities are often attributable to gene–environment correlations. Specifically, because MZ twins are more similar genetically than DZ twins, they are likely to seek out or elicit more similar environmental experiences based on their genetic propensities. Gene–environment correlations are not considered a violation of the EEA (Plomin et al., 2008; Scarr & Carter-Saltzman, 1979). The EEA is only violated when the correlation between environmental similarity and trait similarity is significantly greater than zero within zygosity groups (Kendler & Gardner, 1998; Wade, Wilkinson, & Tovim, 2003).

In the current study, we tested the EEA by examining within-twin similarity in children's home literacy experiences and within-twin similarity on each of the measures. Home literacy experiences were assessed separately for each twin using the Home Literacy Environment (HLE) questionnaire (Griffin & Morrison, 1997), which was completed by parents (usually the mother) during the home visit.

We calculated absolute difference scores for twin 1 and twin 2 on the HLE questionnaire and for each of the reading and language measures. Linear regression models were then used to examine the extent to which trait similarity was predicted by zygosity and similarity in home literacy experiences. We included zygosity as a dummy variable to control for the fact that, on average, MZ twins show greater resemblance than DZ twins on reading and language tests. Results indicated that home literacy environment did not predict greater similarity for any of the measures, with the exception of CELF Word Chains ($t(2, 233)=-2.99$, $p=0.003$). Thus, although the EEA is generally tenable for the current study, the heritability of CELF Word Chains may be inflated.

Twin correlations and univariate ACE analyses

Table 4 contains two types of basic genetic information about the individual tests. The left-hand side shows the MZ and DZ correlations for each measure, which can range from −1 to 1. The right-hand side shows the proportions of variance in each measure due to genetic and environmental effects (A, C, E), as estimated through standard univariate genetic models (Neale & Cardon, 1992). Because A, C, and E are not measured directly, but inferred from pattern of twin similarity, they do not have a natural scale. Consequently, we fixed the total variance (i.e., the sum of A, C, and E) within each measure to 1.

MZ correlations were uniformly higher than the DZ correlations, and in most cases, the DZ correlations were around half the MZ correlations. These findings indicate that genetic factors are the main source of the variance of each measure, with little evidence for shared environmental effects. Additionally, MZ correlations were less than unity, thus suggesting nonshared environmental influences and measurement error. Estimates for A, C, and E confirm these patterns. All measures showed significant genetic and nonshared environmental influences, which were small to substantial in magnitude. Shared environmental factors made small but significant contributions to TNL Narrative Comprehension, CELF Word Classes, and the Boston Naming Test.

DZ correlations for four measures (TOWRE Sight Word Efficiency, CELF Understanding Spoken Paragraphs, WRMT-R Passage Comprehension, and PIAT Reading Comprehension) were less than half the MZ correlations. This pattern is consistent with the possibility of genetic dominance, which would increase the similarity of MZ twins over DZ

Table 4 Intraclass twin correlations and estimates of genetic (a^2), shared environmental (c^2), and nonshared environmental (e^2) contributions to the variance within each measure (with 95% confidence intervals in parentheses)

Measure	Intraclass twin correlations		Variance components		
	MZ	DZ	a^2	c^2	e^2
PD1	0.82 (0.74, 0.88)	0.43 (0.28, 0.57)	0.73 (0.55, 0.84)	0.11 (0.00, 0.28)	0.16 (0.12, 0.21)
PD2	0.79 (0.70, 0.86)	0.43 (0.27, 0.56)	0.71 (0.47, 0.84)	0.10 (0.00, 0.30)	0.19 (0.15, 0.26)
WD1	0.82 (0.74, 0.88)	0.43 (0.28, 0.57)	0.81 (0.55, 0.88)	0.03 (0.00, 0.27)	0.17 (0.12, 0.23)
WD2	0.73 (0.61, 0.82)	0.32 (0.16, 0.47)	0.78 (0.61, 0.84)	0.00.00, 0.14	0.22.16, 0.31
LC1	0.49 (0.28, 0.65)	0.17 (0.00, 0.36)	0.44 (0.15, 0.59)	0.07 (0.00, 0.32)	0.49 (0.38, 0.62)
LC1	0.54 (0.37, 0.67)	0.30 (0.13, 0.45)	0.38 (0.12, 0.55)	0.14 (0.03, 0.37)	0.48 (0.37, 0.60)
VC1	0.80 (0.72, 0.87)	0.61 (0.49, 0.71)	0.49 (0.29, 0.71)	0.35 (0.14, 0.52)	0.16 (0.12, 0.22)
VC2	0.56 (0.39, 0.69)	0.49 (0.34, 0.61)	0.24 (0.07, 0.51)	0.34 (0.12, 0.51)	0.42 (0.32, 0.52)
RC1	0.73 (0.61, 0.82)	0.25 (0.07, 0.42)	0.75 (0.57, 0.83)	0.00 (0.00, 0.00)	0.25 (0.17, 0.36)
RC2	0.60 (0.44, 0.72)	0.23 (0.06, 0.38)	0.58 (0.30, 0.69)	0.00 (0.00, 0.00)	0.42 (0.31, 0.56)

PD1 Woodcock Johnson Word Attack, *PD2* TOWRE Phonemic Decoding Efficiency, *WD1* Woodcock Johnson Word Identification, *WD2* TOWRE Sight Word Efficiency, *LC1* CELF Understanding Spoken Paragraphs, *LC2* TNL Narrative Comprehension, *VC1* Boston Naming Test, *VC2* CELF Word Chains, *RC1* WRMT-R Passage Comprehension, *RC2* PIAT Reading Comprehension

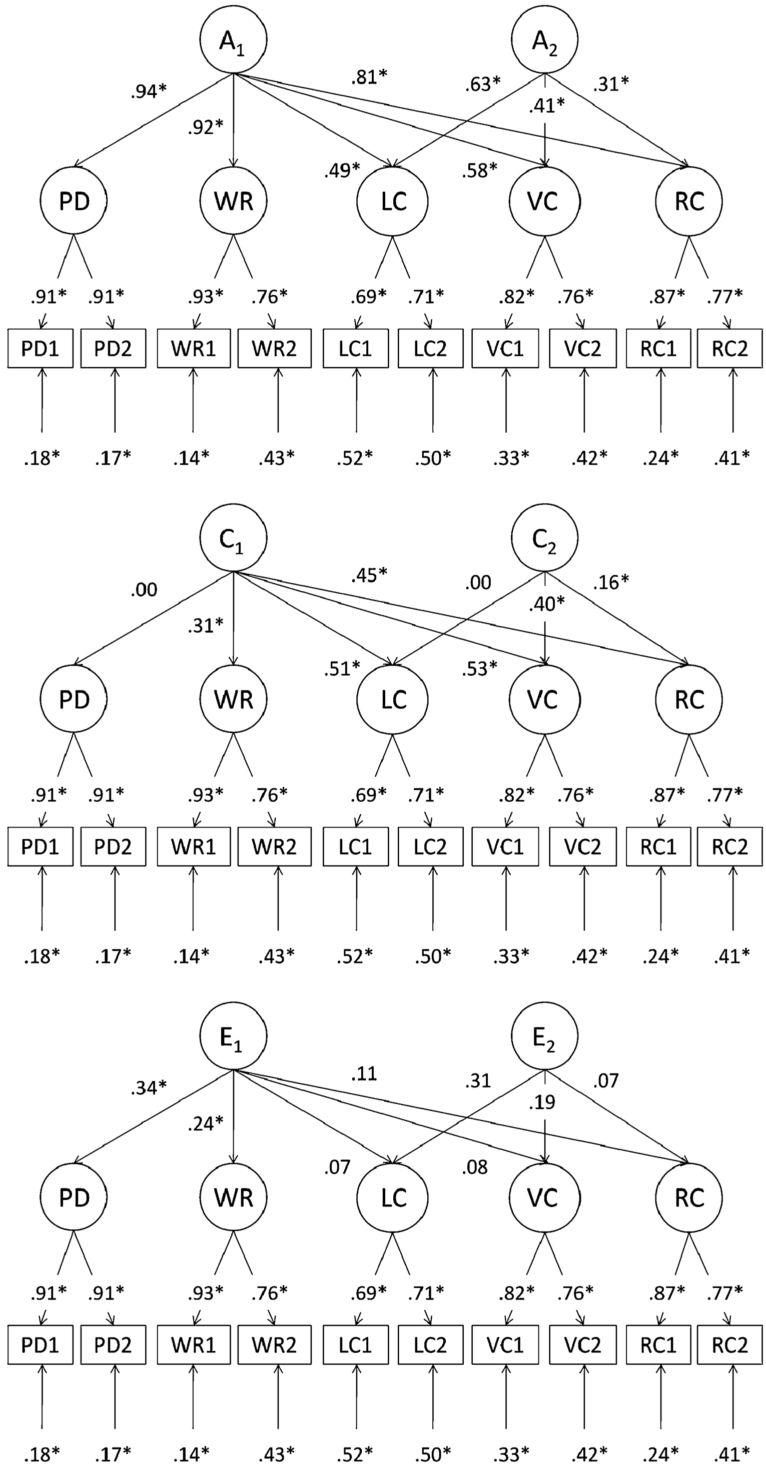
twins. However, the confidence intervals for DZ twin correlations were relatively wide. Moreover, it is well-known that statistical power to detect genetic dominance is limited in small samples (Rietveld, Posthuma, Dolan, & Boomsma, 2003). Power analyses based on our sample indicate that approximately 1,500 twin pairs would be required to detect genetic dominance accounting for 30% of the variance in our measures with 80% power (assuming genetic and nonshared environmental factors account for 60% and 10% of the variance, respectively). In light of this, as well as the fact that it is not possible to model genetic dominance and shared environmental influences simultaneously, we elected not to estimate dominant genetic influences in our model-fitting analyses. We note that our sample size also has yields relatively low power to detect shared environmental influences, at least at the level of the measured variables. For example, we only have 75% power to detect shared environmental factors accounting for 30% of the variance (again, assuming genetic and nonshared environmental factors account for 60% and 10% of the variance, respectively).

Multivariate ACE analyses

We next used multivariate genetic model fitting to examine the relationships among phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension. Our baseline model (shown in Fig. 2 for one member of a twin pair only) separated the variance and covariance among the five phenotypic factors into A, C, and E effects. Given the evidence from the Cholesky decomposition analyses that the variance in reading comprehension was best accounted for by just two factors (one common factor and a second factor primarily influencing listening comprehension, vocabulary, and reading comprehension), our initial genetic model contained two sets of latent genetic and environmental factors. The first set of factors, A_1, C_1, E_1, represent genetic, shared environmental, and nonshared environmental effects that contribute to all of the variance in phonological decoding as well as the covariance among phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension. The second latent genetic and environmental factors, A_2, C_2, E_2, represent genetic, shared environmental, and nonshared environmental effects that contribute to the covariance among listening comprehension, vocabulary, and reading comprehension, independent of their genetic links with phonological decoding and word recognition. Our model included measure-specific residual factors to account for measure-specific variance and measurement error. Due to power concerns, we did not decompose the measure-specific variance into genetic and environmental effects.

Standardized path estimates from the baseline model are shown next to the path coefficients in Fig. 2. Phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension loaded significantly on the first genetic factor (A_1), and listening comprehension, vocabulary and reading comprehension loaded significantly

Fig. 2 Standardized path coefficients from quantitative genetic model of latent phonological decoding (*PD*), ▶ word recognition (*WR*), listening comprehension (*LC*), vocabulary (*SK*), and reading comprehension (*RC*) factors (shown for one member of a twin pair). Variance in the latent PD, WR, LC, VC, and RC factors is decomposed into additive genetic influences (A), shared environmental influences (C), and nonshared environmental influences (E). Measured variables: *PD1* Woodcock Johnson Word Attack, *PD2* TOWRE Phonemic Decoding Efficiency, *WD1* Woodcock Johnson Word Identification, *WD2* TOWRE Sight Word Efficiency, *LC1* CELF Understanding Spoken Paragraphs, *LC2* TNL Narrative Comprehension, *VC1* Boston Naming Test, *VC2* CELF Word Chains, *RC1* WRMT-R Passage Comprehension, *RC2* PIAT Reading Comprehension. For each latent factor, factor loadings of the measured variables were equated to ensure model identification. Asterisk indicates that the lower 95% confidence bound is significantly greater than zero


A1
A2
.94*
.92*
.81*
.63*
.41*
.31*
.49*
.58*
PD
WR
LC
VC
RC
.91* .91*
.93* .76*
.69* .71*
.82* .76*
.87* .77*
PD1 PD2 WR1 WR2 LC1 LC2 VC1 VC2 RC1 RC2
.18* .17* .14* .43* .52* .50* .33* .42* .24* .41*
C1
C2
.00
.31*
.45*
.00
.40*
.16*
.51*
.53*
PD
WR
LC
VC
RC
.91* .91*
.93* .76*
.69* .71*
.82* .76*
.87* .77*
PD1 PD2 WR1 WR2 LC1 LC2 VC1 VC2 RC1 RC2
.18* .17* .14* .43* .52* .50* .33* .42* .24* .41*
E1
E2
.34*
.24*
.11
.31
.19
.07
.07
.08
PD
WR
LC
VC
RC
.91* .91*
.93* .76*
.69* .71*
.82* .76*
.87* .77*
PD1 PD2 WR1 WR2 LC1 LC2 VC1 VC2 RC1 RC2
.18* .17* .14* .43* .52* .50* .33* .42* .24* .41*

on the second genetic factor (A_2). That is, there is evidence for both general genetic overlap among the five factors and a genetic link specific to listening comprehension, vocabulary, and reading comprehension. A different pattern emerged for shared environmental influences. The first shared environmental factor (C_1) had significantly loadings on all factors except phonological decoding, whereas the second shared environmental factor (C_2) had significant effects on vocabulary and reading comprehension but not on listening comprehension. The effects of the nonshared environmental factors were small, although phonological decoding and word recognition loaded significantly on the first nonshared environmental factor (E_1). That is, the results provide evidence for (1) a shared environmental link among word recognition, listening comprehension, vocabulary, and reading comprehension; (2) a separate shared environmental link between vocabulary and reading comprehension; and (3) a nonshared environmental link between phonological decoding and word recognition. There were significant residual influences on all measures, reflecting measure-specific variance and measurement error.

Model-fit comparisons confirmed the general pattern of results. Compared with the baseline model (AIC 599.93, BIC −6,793.261, DIC −2,947.66), a better fit (AIC 593.430, BIC −6,801.057, DIC −2,957.14) was obtained for a reduced model that included two genetic factors (one influencing phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension; the second influencing listening comprehension, vocabulary, and reading comprehension only), two shared environmental factors (one influencing word recognition, listening comprehension, vocabulary, and reading comprehension; the second influencing vocabulary and reading comprehension only), and one nonshared environmental factor (influencing phonological decoding and word recognition only). Because the univariate models indicated that shared environmental influences were generally nonsignificant, we also examined a model that included a single shared environmental factor influencing vocabulary only. This model provided a poor fit to the data compared with the baseline model (AIC 642.79, BIC −6,779.77, DIC −2,934.01).

From our baseline model, we estimated the proportion of the total variance in each phenotypic factor due to A, C, and E (shown in Table 5). These estimates can be obtained from the standardized path coefficients shown in Fig. 2. Specifically, the total genetic variance in each factor is equal to the sum of the squared path coefficients associated with that factor. For phonological decoding and word recognition, this is simply the square of A_1. For listening comprehension, vocabulary, and reading comprehension, the total genetic variance is the sum of the squared estimates for A_1 and A_2. For example, the contribution of genetic factors to the variance in listening comprehension is 0.64 ($0.49^2+0.63^2$). As shown in Table 4, the variance in phonological decoding and word recognition was primarily due to genetic factors ($a^2=0.89$ for phonological decoding and 0.85 for word recognition). Shared environmental influences were negligible and nonsignificant for phonological decoding (0.00) and small but significant for word recognition (0.10). Nonshared environmental influences were small but significant (0.11 for phonological decoding; 0.01 for word recognition). In contrast, the variance in listening comprehension, vocabulary, and reading comprehension was due to both genetic and shared environmental influences ($a^2=0.64$ and $c^2=0.26$ for listening comprehension, $a^2=0.52$ and $c^2=0.44$ for vocabulary; $a^2=0.75$ and $c^2=0.23$ for reading comprehension). Nonshared environmental influences were small and nonsignificant (0.10 for listening comprehension, 0.04 for vocabulary, 0.02 for reading comprehension).

It is of note that we found evidence for significant shared environmental influences on word recognition, listening comprehension, vocabulary, and reading comprehension. This finding may seem unexpected in view of the univariate modeling analyses, which showed

Table 5 Decomposition of the total variance in PD, WR, LC, VC, and RC into effects due to genetic (A), shared environmental (E), and nonshared environmental (E) influences (with 95% confidence intervals in parentheses)

	PD	WR	LC	VC	RC
Total variance due to A	0.89 (0.82, 0.94)	0.85 (0.73, 0.90)	0.64 (0.38, 0.83)	0.52 (0.30, 0.68)	0.75 (0.55, 0.85)
A_1	0.89 (0.82, 0.94)	0.85 (0.73, 0.90)	0.24 (0.12, 0.37)	0.34 (0.22, 0.46)	0.66 (0.51, 0.75)
A_2	–	–	0.40 (0.19, 0.59)	0.18 (0.01, 0.32)	0.09 (0.02, 0.18)
Total variance due to C	0.00 (0.00, 0.06)	0.10 (0.06, 0.27)	0.26 (0.12, 0.46)	0.44 (0.30, 0.63)	0.23 (0.14, 0.43)
C_1	0.00 (0.00, 0.06)	0.10 (0.06, 0.27)	0.26 (0.12, 0.41)	0.27 (0.14, 0.42)	0.20 (0.12, 0.33)
C_2	–	–	0.00 (0.00, 0.04)	0.17 (0.08, 0.29)	0.03 (0.01, 0.07)
Total variance due to E	0.11 (0.06, 0.19)	0.06 (0.03, 0.11)	0.10 (0.00, 0.27)	0.04 (0.00, 0.14)	0.02 (0.00, 0.07)
E_1	0.11 (0.06, 0.19)	0.06 (0.03, 0.11)	0.01 (0.00, 0.09)	0.01 (0.00, 0.05)	0.02 (0.00, 0.07)
E_2			0.10 (0.00, 0.05)	0.04 (0.00, 0.13)	0.01 (0.00, 0.06)

Variance due to A_1 refers to the genetic factor loading on PD, WR, LC, VC, and RC (A_1 in Fig. 2); variance due to A_2 refers to the genetic loading on LC, VC, and RC (A_2 in Fig. 2)

PD phonological decoding, *WR* word recognition, *LC* listening comprehension, *VC* vocabulary, *RC* reading comprehension

that shared environmental influences only accounted for significant variance in three measures (CELF Word Chains, WRMT-R Passage Comprehension, and PIAT Reading Comprehension). This discrepancy likely reflects the power gained by using latent factor modeling. In quantitative genetic models, variance due to measurement error is subsumed under the nonshared environmental component. Removing measurement error (and measure-specific variance) by using latent factors reduces the proportion of variance in the latent factors due to nonshared environmental influences and increases the proportion of variance due to genetic and/or shared environmental influences. This is evident, for example, in the case of the listening comprehension measures, CELF Understanding Spoken Paragraphs and TNL Narrative Comprehension. Nonshared environmental factors accounted for around 50% of the variance in these measures, yet only 10% of the variance in the latent listening comprehension factor. In contrast, genetic and shared environmental factors accounted for much more of the variance in the listening comprehension factor compared with the individual listening comprehension measures (for genetic factors, a^2 for listening comprehension was 0.64, compared with 0.44 and 0.38 for CELF Understanding Spoken Paragraphs and TNL Narrative Comprehension, respectively; for shared environmental factors, c^2 for listening comprehension was 0.26, compared with 0.07 and 0.14 for CELF Understanding Spoken Paragraphs and TNL Narrative Comprehension, respectively). The power of latent factor analyses is also greater due to the increase in information that results from including the covariance among measures.

As well as estimating the total genetic and environmental variance in each trait, the genetic variance in listening comprehension, vocabulary, and reading comprehension can be decomposed into genetic effects that are common to phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension (A_1) and genetic effects that connect listening comprehension, vocabulary, and reading comprehension independent of phonological decoding and word recognition (A_2). Analogous estimates can be obtained for the shared and nonshared environmental variance in listening comprehension, vocabulary, and reading comprehension. These results are shown in Table 4. Because nonshared environmental influences on listening comprehension and reading comprehension were small and nonsignificant, we focus on the genetic and shared environmental results only.

The first genetic factor, A_1, accounted for 24% of the variance in listening comprehension, 34% of the variance in vocabulary, and 66% of the variance in reading comprehension. The second genetic factor, A_2, accounted for 40% of the variance in listening comprehension, 18% of the variance in vocabulary, and 9% of the variance in reading comprehension. An alternative way to express these findings is in terms of the proportion of the total genetic variance (rather than total phenotypic variance) due to common and comprehension-specific genetic factors. The total genetic variance in listening comprehension (0.64) primarily reflected comprehension-specific genetic influences (represented by A_2): Around 38% of the total genetic variance in semantic knowledge was due to A_1 (0.24/0.64=0.38), whereas around 62% was due to A_2 (0.40/0.64=0.62). Conversely, the total genetic variance in vocabulary (0.52) and reading comprehension (0.75) primarily reflected common genetic influences. Specifically, A_1 accounted for around 65% of the total genetic variance in vocabulary (0.34/0.52=0.65) and 88% of the total genetic variance in reading comprehension (0.66/0.75=0.88). In contrast, A_2 accounted for 35% of the total genetic variance in vocabulary (0.18/0.52=0.35) and 12% of the total genetic variance in reading comprehension (0.09/0.75=0.12).

A somewhat different picture emerged for shared environmental influences. The first shared environmental factor, C_1, accounted for all of the shared environmental variance in listening comprehension (26%), as well as 27% of the variance in vocabulary and 20% of the variance in reading comprehension. That is, of the total shared environmental variance in listening comprehension (0.26), 100% was due to common shared environmental influences. Of the total shared environmental variance in vocabulary (0.44), 61% was due to common shared environmental influences (0.27/0.44=0.61), whereas 39% was due to comprehension-specific shared environmental influences (0.17/0.44=0.39). Of the total shared environmental variance in reading comprehension (0.23), 87% was due to common shared environmental influences (0.20/0.23=0.87), whereas 13% was due to comprehension-specific shared environmental influences (0.03/0.23=0.13).

In summary, genetic and shared environmental influences on reading comprehension largely covaried with word recognition, listening comprehension, and vocabulary. However, there was also evidence for a separate genetic link between listening comprehension, vocabulary, and reading comprehension (accounting for 9% of the total variance in reading comprehension), as well as a separate shared environmental link between vocabulary and reading comprehension (accounting for 3% of the total variance in reading comprehension).

Discussion

The present study examined the phenotypic and etiological relationships among phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension. At a phenotypic level of analysis, our Cholesky decomposition model indicated that two factors made unique contributions to the prediction of reading comprehension. The first factor represented the covariance among phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension. Phonological decoding and word recognition had the strongest loadings on this factor (100% and 94%, respectively). The second factor represented the covariance among listening comprehension, vocabulary, and reading comprehension, independent of phonological decoding and word recognition. There were no unique sources of variance in reading comprehension after accounting for phonological decoding, word recognition, listening comprehension, and vocabulary. Overall, these findings show that word decoding (phonological decoding and word recognition) and oral language skills (listening comprehension and vocabulary) are substantially correlated, yet are also partly distinct. Together, they accounted for all of the variance in reading comprehension. This is the pattern predicted by the Simple View of reading (Gough & Tunmer, 1986; Hoover & Gough, 1990). Moreover, our results do not support previous studies (e.g., Braze et al., 2007; Ouellette & Beers, 2009; Verhoeven & van Leeuwe, 2008) suggesting that word recognition and vocabulary predict unique variance in reading comprehension. We found substantial correlations among these factors (e.g., 0.96 between phonological decoding and word recognition and 0.93 between listening comprehension and vocabulary), indicating redundancy within each domain. This result may reflect the age and reading level of our participants; unique effects of word recognition and vocabulary have generally been observed only in older samples (Braze et al., 2007; Ouellette & Beers, 2009).

At an etiological level, we found that genetic factors accounted for 52% to 89% of the variance in phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension. In addition, there was considerable genetic overlap among these phenotypic factors. The best-fitting model included one genetic factor on which all five phenotypic factors loaded and a second factor that accounted for genetic variance in listening comprehension, vocabulary, and reading comprehension independent of phonological decoding and word recognition. Of the total genetic variance in reading comprehension, 88% reflected genetic influences common to all five factors, while the remaining 12% of the genetic variance reflected genetic influences that reading comprehension shared with listening comprehension and vocabulary only.

Shared environmental influences accounted for significant variance in word recognition, listening comprehension, vocabulary, and reading comprehension, but not phonological decoding. There was evidence for two shared environmental factors that represented shared environmental overlap among the phenotypic factors. The first accounted for shared environmental overlap among word recognition, listening comprehension, vocabulary, and reading comprehension; the second accounted for shared environmental overlap between vocabulary and reading comprehension only. Overall, 87% of the total shared environmental variance in reading comprehension reflected shared environmental influences on the first shared environmental factor, while the remaining 12% reflected shared environmental influences that overlapped with listening comprehension and vocabulary, independent of phonological decoding and word recognition.

It is noteworthy that listening comprehension, vocabulary, and reading comprehension showed shared environmental overlap with word recognition but not with phonological decoding. This finding may have arisen due to the contribution of nonphonological skills to word recognition. Snowling and Hayiou-Thomas (2006) hypothesize that nonphonological language skills are more susceptible to environmental influences and thus influence reading comprehension through environmental as well as genetic pathways. To the extent that word recognition draws on nonphonological skills, variance in word recognition may be influenced by environmental influences that are important for general oral language development (e.g., the quality of verbal exchanges between parent and child; Hoff, 2006). Also of note is the second shared environmental factor, which influenced vocabulary and reading comprehension but not listening comprehension. This finding may reflect specific shared environmental effects on the acquisition of word knowledge, arising, for example, through parent tutoring during book reading (Mol, Bus, de Jong, & Smeets, 2008) and formal kindergarten programs (e.g., Justice et al., 2010).

Nonshared environmental influences accounted for significant variance in phonological decoding and word recognition only (11% and 6%, respectively), and these nonshared environmental factors overlapped. A similar finding was obtained in a latent factor analysis of genetic and environmental influences on word reading skills (Gayán & Olson, 2003). Within this study, nonshared environmental factors accounted for 11% and 15% of the variance in phonological decoding and word recognition, respectively, and the nonshared environmental correlation between phonological decoding and word recognition was 0.98. That is, the nonshared environmental influences on phonological decoding correlated almost perfectly with the nonshared environmental influences on word recognition. Nonshared environmental overlap between phonological decoding and word recognition may reflect individual-specific experiences important for word decoding, such as child-specific interactions between word learning instruction practices and the child's ability level in the classroom (Connor, Morrison, & Klatch, 2004). We note that the current results do not imply that individual-specific experiences are unimportant for oral language and reading comprehension. Rather, the results suggest that they are likely to be specific to these domains, rather than overlapping.

Taken together, our findings broadly support three predictions derived from the Simple View for behavioral genetic studies: (1) there is etiological overlap among word decoding, oral language, and reading comprehension, and this primarily reflects genetic, rather than environmental factors; (2) there are etiological links between oral language and reading comprehension that are largely independent of word decoding; and (3) there are no genetic or environmental influences on reading comprehension independent of word decoding and oral language. In this regard, they provide independent replication of the findings of Keenan et al. (2006). The current findings also extend this work. Although the proposed components of word decoding (phonological decoding and word recognition) and oral language (listening comprehension and vocabulary) did not predict unique variance in reading comprehension, these components could be differentiated at the level of shared environmental influences: word recognition but not phonological decoding showed shared environmental links with listening comprehension, vocabulary, and reading comprehension, and vocabulary was linked to reading comprehension by shared environmental factors independent of listening comprehension. As suggested above, these findings may have arisen due to the differing cognitive demands of the skills tested within each component that in turn have different shared environmental origins (e.g., greater semantic involvement in word recognition vs. phonological decoding; greater emphasis on word-specific processes in vocabulary vs. listening comprehension). In light of these results, we suggest that word decoding and listening comprehension each encompass correlated but distinct skills that may be differentially linked with reading comprehension at an etiological level. That is, even though they appear to be collinear in the current study, removing word recognition and vocabulary would result in loss of etiological information relevant for understanding the relationships among specific aspects of word decoding and oral language skill.

Limitations and conclusions

Our study has several limitations. First, reading comprehension tests are not interchangeable. Reading comprehension is clearly a multifaceted construct, drawing on word decoding, listening comprehension, and a host of other skills. Tests of reading comprehension differ in the extent to which they tap these skills, depending on the length of the test stimuli (e.g., single sentence, short passage) and the nature of the test questions (e.g., multiple-choice, one-ended questions). According to Keenan et al. (2008), poor word decoding is likely to have more devastating consequences for tests using one or two sentences compared with longer text passages, as most of the words in the sentence must be accurately decoded to ensure successful comprehension. Moreover, children are less likely to benefit from contextual facilitation when they are presented with single sentences only. In a comparison of reading tests, Keenan et al. (2008) found that word decoding, rather than listening comprehension, accounted for most of the variance in PIAT Reading Comprehension and WRMT-R Passage Comprehension (the reading comprehension tests used in the current study), whereas the reverse was true for two extended discourse comprehension measures (see also Cutting & Scarborough, 2006). Keenan et al. (2008) show that the age and decoding ability level of the reader also matters: Word decoding accounted for a greater proportion of the variance in the PIAT Reading Comprehension and WRMT-R Passage Comprehension in younger readers and readers with poor word decoding skills, compared with older readers and good word decoders. For behavioral genetic studies, these findings imply that genetic links between reading comprehension and word decoding will be dependent on the reading comprehension test used and the age and decoding ability level of the reader.

A second, related issue is that most tests of reading comprehension capture only a narrow range of skills required for reading comprehension. In addition to needing good word decoding and listening comprehension skills, good readers note the structure and organization of text, monitor their understanding while reading, make predictions, integrate what they know about the topic with new learning, and make inferences. Including test that assess these specific abilities may enable us to delineate more precisely how word decoding and listening comprehension are related to specific aspects of reading comprehension. Currently, few process-based measures of reading comprehension exist that have an adequate norming sample, as well as known reliability and validity. Thus, an important priority is to develop stronger measures of the components of reading comprehension. We are currently pursuing this goal in WRRP as part of our ongoing study of reading comprehension.

A further limitation is that we focused on children at a single point in time, at age 9. The relationships among word decoding, listening comprehension, and reading comprehension are developmentally sensitive (Leach, Scarborough, & Rescorla, 2003). Among beginning readers, word decoding is the greatest limiting factor to reading comprehension. As children get older and gain proficiency in word decoding, written texts place greater demands on comprehension skills. Concomitantly, the development of reading fluency allows more cognitive resources that can be devoted to the higher-level processes needed to attain an understanding of the meaning of text. As a result, the balance between word decoding and listening comprehension shifts, with word decoding being a stronger predictor in the early school years and listening comprehension being more important as children get older (Catts et al., 2005; Keenan et al., 2008; Kendeou et al., 2009). Genetic and environmental relationships among word decoding and comprehension processes may also change. For example, given the close relationship between word decoding and reading comprehension in the early school years, genetic influences on word decoding may completely overlap with those on reading comprehension (see, e.g., Byrne et al., 2007). Further longitudinal research is needed to examine this possibility.

Notwithstanding these limitations, we suggest that the current study provides further support for the Simple View as a general framework for understanding reading comprehension. Specifically, the results confirm that successful reading comprehension depends on both word decoding and oral language skills. Additionally, in showing the genetic dissociation of word decoding and listening comprehension, the current study bolsters the recommendation that literacy instruction should explicitly focus on both sets of skills (e.g., Kendeou et al., 2009; Nation & Angell, 2006).

We emphasize that the importance of the environment is not diminished by evidence for genetic influences on a trait. This point is clearly illustrated by many medical conditions. For example, although coronary heart disease (CHD) is partly heritable, the risk for developing CHD can be substantially modified by environmental factors, especially diet, lifestyle, and pharmacologic treatment of hypertension and high lipid levels (Hu, 2009). In the same way, reading instruction and reading interventions can raise reading attainment among children, even though individual differences in reading are primarily genetic. It would be interesting to identify the specific environmental factors that underlie the covariance among phonological decoding, word recognition, listening comprehension, vocabulary, and reading comprehension and to determine the effects of manipulating these factors. Our results suggest that improving skill levels in one domain may have diffuse effects on literacy development. For example, efforts to increase oral language skills may be accompanied by improvements in both word recognition and reading comprehension. Concomitantly, the current study informs molecular genetic efforts to identify genetic variants associated with reading abilities and disabilities (Paracchini, Scerri, & Monaco, 2007). Our results provide evidence for a common genetic basis underlying word decoding, listening comprehension, and reading comprehension. This genetic overlap may be attributable to pleiotropic genetic effects—genes that influence multiple phenotypes ("generalist genes"; Plomin & Kovas, 2005). Simultaneously, the evidence for independent genetic influences on oral language and comprehension indicates that pleiotropy is not perfect. Consequently, molecular genetic efforts should use a broad range of reading measures rather than relying on single or global indicators of reading. We hope that the current study acts as a fillip for further work that considers more closely how specific environmental and genetic factors influence the diverse processes involved in reading comprehension.

Acknowledgments We gratefully acknowledge the ongoing contribution of the parents and children in the Western Research Reading Project (WRRP). WRRP is supported by NICHD grant HD38075 and NICHD/OSERS grant HD46167.

References

Aaron, P. G., Joshi, M., & Williams, K. A. (1999). Not all reading disabilities are alike. *Journal of Learning Disabilities, 32*, 120–137.

Akaike, H. (1987). Factor analysis and the AIC. *Psychometrika, 52*, 317–332.

Betjemann, R. S., Willcutt, E. G., Olson, R. K., Keenan, J. M., DeFries, J. C., & Wadsworth, S. J. (2008). Word reading and reading comprehension: Stability, overlap and independence. *Reading and Writing, 21*, 539–558.

Braze, D., Tabor, W., Shankweiler, D. P., & Mencl, M. E. (2007). Speaking up for vocabulary: Reading skill differences in young adults. *Journal of Learning Disabilities, 40*, 226–243.

Byrne, B., Coventry, W. L., Olson, R. K., Samuelsson, S., Corley, R., Willcutt, E. G., et al. (2009). Genetic and environmental influences on aspects of literacy and language in early childhood: Continuity and change from preschool to Grade 2. *Journal of Neurolinguistics, 22*, 219–236.

Byrne, B., Samuelsson, S., Wadsworth, S., Hulslander, J., Corley, R., DeFries, J. C., et al. (2007). Longitudinal twin study of early literacy development: Preschool through Grade 1. *Reading and Writing: An Interdisciplinary Journal, 20*, 77–102.

Catts, H. W., Adlof, S. M., & Weismer, S. E. (2006). Language deficits in poor comprehenders: A case for the simple view of reading. *Journal of Speech, Language, and Hearing Research, 49*, 278–293.

Catts, H. W., Hogan, T. P., & Adlof, S. M. (2005). Developmental changes in reading and reading disabilities. In H. Catts & A. Kamhi (Eds.), *The connections between language and reading disabilities* (pp. 25–40). Mahwah: Lawrence Erlbaum Associates.
Cohen, J. (1992). A power primer. *Psychological Bulletin, 112*, 155–159.
Connor, C. M., Morrison, F. J., & Katch, E. L. (2004). Beyond the reading wars: The effect of classroom instruction by child interactions on early reading. *Scientific Studies of Reading, 8*, 305–336.
Cutting, L. E., & Scarborough, H. S. (2006). Prediction of reading comprehension: Relative contributions of word recognition, language proficiency, and other cognitive skills can depend on how comprehension is measured. *Scientific Studies of Reading, 10*, 277–299.
Edmonds, M. S., Vaughn, S., Wexler, J., Reutebuch, C., Cable, A., Tackett, K. K., et al. (2009). A synthesis of reading interventions and effects on reading comprehension outcomes for older struggling readers. *Review of Educational Research, 79*, 262–300.
Gayán, J., & Olson, R. K. (2003). Genetic and environmental influences on individual differences in printed word recognition. *Journal of Experimental Child Psychology, 84*, 97–123.
Gillam, R., & Pearson, N. (2004). *Test of narrative language*. Austin: Pro-Ed.
Goodglass, H., & Kaplan, E. (2001). *The Boston Naming Test* (2nd ed.). New York: Lippincott Williams & Wilkins.
Gough, P. B., & Tunmer, W. E. (1986). Decoding, reading, and reading disability. *Remedial and Special Education, 7*, 6–10.
Griffin, E. A., & Morrison, F. J. (1997). The unique contribution of home literacy environment to differences in early literacy skills. *Early Child Development & Care, 127–128*, 233–243.
Harlaar, N., Spinath, F. M., Dale, P. S., & Plomin, R. (2005). Genetic influences on early word recognition abilities and disabilities: A study of 7-year-old twins. *Journal of Child Psychology and Psychiatry, 46*, 373–384.
Harm, M., & Seidenberg, M. (2004). Computing the meanings of words in meaning: Cooperative division of labor between visual and phonological processes. *Psychological Review, 111*, 662–720.
Hayiou-Thomas, M. E. (2008). Genetic and environmental influences on early speech, language and literacy development. *Journal of Communication Disorders, 41*, 397–408.
Hayiou-Thomas, M. E., Harlaar, N., Dale, P. S., & Plomin, R. (2006). Genetic and environmental mediation of the prediction from preschool language and nonverbal ability to 7-year reading. *Journal of Research in Reading, 29*, 50–74.
Hoff, E. (2006). How social contexts support and shape language development. *Developmental Review, 26*, 55–88.
Hohnen, B., & Stevenson, J. (1999). The structure of genetic influences on general cognitive, language, phonological, and reading abilities. *Developmental Psychology, 35*, 590–603.
Hoover, W. A., & Gough, P. B. (1990). The simple view of reading. *Reading & Writing, 2*, 127–160.
Hu, F. B. (2009). Diet and lifestyle influences on risk of coronary heart disease. *Current Atherosclerosis Reports, 11*, 257–263.
Justice, L. M., McGinty, A. S., Cabell, S. Q., Kilday, C. R., Knighton, K., & Huffman, G. (2010). Language and literacy curriculum supplement for preschoolers who are academically at risk: A feasibility study. *Language, Speech, and Hearing Services in Schools, 41*, 161–178.
Keenan, J. M., Betjemann, R. S., & Olson, R. K. (2008). Reading comprehension tests vary in the skills they assess: Differential dependence on decoding and oral comprehension. *Scientific Studies of Reading, 12*, 281–300.
Keenan, J. M., Betjemann, R. S., Wadsworth, S. J., DeFries, J. C., & Olson, R. K. (2006). Genetic and environmental influences on reading and listening comprehension. *Journal of Research in Reading, 29*, 79–91.
Kendeou, P., van den Broek, P., White, M. J., & Lynch, J. S. (2009). Predicting reading comprehension in early elementary school: The independent contributions of oral language and decoding skills. *Journal of Educational Psychology, 101*, 765–778.
Kendler, K. S., & Gardner, C. O. (1998). Twin studies of adult psychiatric and substance dependence disorders: Are they biased by differences in the environmental experiences of monozygotic and dizygotic twins in childhood and adolescence? *Psychological Medicine, 28*, 625–633.
Kovas, Y., Hayiou-Thomas, M. E., Oliver, B., Dale, P. S., Bishop, D. V. M., & Plomin, R. (2005). Genetic influences in different aspects of language development: The etiology of language skills in 4.5-year-old twins. *Child Development, 76*, 632–651.
Kirby, J. R., & Savage, R. S. (2008). Can the simple view deal with the complexities of reading? *Literacy, 42*, 75–82.
Leach, J. M., Scarborough, H. S., & Rescorla, L. (2003). Late-emerging reading disabilities. *Journal of Educational Psychology, 95*, 211–224.
Lewis, B. A., Shriberg, L. D., Freebairn, L. A., Hansen, A. J., Stein, C. M., Taylor, H. G., et al. (2006). The genetic bases of speech sound disorders: Evidence from spoken and written language. *Journal of Speech, Language, and Hearing Research, 49*, 1294–1312.

Loehlin, J. C. (2004). *Latent variable models: An introduction to factor, path, and structural equation analysis* (4th ed.). Mahwah: Lawrence Erlbaum Associates.

Loehlin, J., & Nichols, R. (1976). *Heredity, environment and personality*. Austin: University of Texas Press.

Lovett, M. W., Borden, S. L., DeLuca, T., Lacerenza, L., Benson, M. J., & Brackston, D. (1994). Treating the core deficits of developmental dyslexia: Evidence of transfer of learning after phonologically- and strategy-based reading training programs. *Developmental Psychology, 30*, 805–822.

Markwardt, F. C. (1989; 1997 Normative Update). *Peabody Individual Achievement Test—revised*. Bloomington: Pearson Assessments.

Mol, S. E., Bus, A. G., de Jong, M. T., & Smeets, D. J. H. (2008). Added value of dialogic parent–child book readings: A meta-analysis. *Early Education and Development, 19*, 7–26.

Nation, K., & Angell, P. (2006). Learning to read and learning to comprehend. *London Review of Education, 4*, 77–87.

Neale, M. C., Boker, S. M., Xi, G., & Maes, H. H. (2006). *Mx: Statistical modeling* (7th ed.). Richmond: Department of Psychiatry.

Neale, M. C., & Cardon, L. R. (1992). *Methodology for genetic studies of twins and families*. Dordrecht: Kluwer Academic.

Ouellette, G. (2006). What's meaning got to do with it: the role of vocabulary in word reading and reading comprehension. *Journal of Educational Psychology, 98*, 554–566.

Ouellette, G., & Beers, A. (2009). A not-so-simple view of reading: How oral vocabulary and visual-word recognition complicate the story. *Reading and Writing, 23*, 189–208.

Paracchini, S., Scerri, T., & Monaco, A. P. (2007). The genetic lexicon of dyslexia. *Annual Review of Genomics and Human Genetics, 8*, 57–79.

Perfetti, C., & Hart, L. (2002). The lexical quality hypothesis. In L. Verhoeven, C. Elbrow, & P. Reitsma (Eds.), *Precursors of functional literacy* (Vol. 11, pp. 67–86). Amsterdam: John Benjamins.

Petrill, S. A., Deater-Deckard, K., Thompson, L. A., DeThorne, L. S., & Schatschneider, C. (2006). Reading skills in early readers: Genetic and shared environmental influences. *Journal of Learning Disabilities, 39*, 48–55.

Plomin, R., DeFries, J. C., McClearn, G. E., & McGuffin, P. (2008). *Behavioral genetics* (5th ed.). New York: Freeman.

Plomin, R., & Kovas, Y. (2005). Generalist genes and learning disabilities. *Psychological Bulletin, 131*, 592–617.

Price, T. S., Freeman, B., Craig, I., Petrill, S. A., Ebersole, L., & Plomin, R. (2000). Infant zygosity can be assigned by parental report questionnaire data. *Twin Research, 3*, 129–481.

Raftery, A. E. (1995). Bayesian model selection in social research. In P. V. Marsden (Ed.), *Sociological methodology* (pp. 111–163). Cambridge: Blackwell.

Rietveld, M. J. H., Posthuma, D., Dolan, C. V., & Boomsma, D. I. (2003). ADHD: Sibling interaction or dominance: An evaluation of statistical power. *Behavior Genetics, 33*, 247–255.

Scarr, S., & Carter-Saltzman, L. (1979). Twin method: Defense of a critical assumption. *Behavior Genetics, 9*, 527–542.

Semel, E. M., Wiig, E. H., & Secord, W. A. (2003). *Clinical evaluation of language fundamentals—4*. San Antonio: PsychCorp.

Share, D. L., & Leikin, M. (2004). Language impairment at school entry and later reading disability: Connections at lexical versus supralexical levels of reading. *Scientific Studies of Reading, 8*, 87–110.

Snowling, M. J., & Hayiou-Thomas, M. E. (2006). The dyslexia spectrum: Continuities between reading, speech, and language impairments. *Topics in Language Disorders, 26*, 108–124.

Spiegelhalter, D. J., Best, N. G., Carlin, B. P., & van der Linde, A. (2002). Bayesian measures of model complexity and fit (with discussion). *Journal of the Royal Statistical Society. Series B Statistical Methodology, 64*, 583–639.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of Word Reading Efficiency*. Austin: Pro-ed.

Torppa, M., Tolvanen, A., Poikkeus, A. M., Eklund, K., Lerkkanen, M. K., Leskinen, E., et al. (2007). Reading development subtypes and their early characteristics. *Annals of Dyslexia, 57*, 3–32.

US Department of Education, Institute of Education Sciences, National Assessment of Educational Progress (2005). The NAEP reading achievement levels by grade. Retrieved from http://nces.ed.gov/nationsreportcard/reading/achieveall.asp.

Verhoeven, L., & van Leeuwe, J. (2008). Prediction of the development of Reading comprehension: A longitudinal study. *Applied Cognitive Psychology, 22*, 407–423.

Wade, T. D., Wilkinson, J., & Ben Tovim, D. (2003). The genetic epidemiology of body attitudes, the attitudinal component of body image in women. *Psychological Medicine, 33*, 1395–1405.

Wilson, P. T., & Anderson, R. C. (1986). What they don't know will hurt them: The role of prior knowledge in comprehension. In J. Orasanu (Ed.), *Reading comprehension: From research to practice* (pp. 31–48). Hillsdale: Lawrence Erlbaum.

Woodcock, R. W. (1987). *Woodcock Reading Mastery Tests, Form G—revised*. Circle Pines: American Guidance Service.