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Longitudinal Associations Among Reading Related Skills and Reading Comprehension: A Twin Study

Florina Erbeli,

Florida Center for Reading Research, Florida State University

Sara A. Hart, and

Department of Psychology and Florida Center for Reading Research, Florida State University

Jeanette Taylor

Department of Psychology, Florida State University

Abstract

The present study investigated the etiology of longitudinal relations among kindergarten pre-reading skills, first grade word level reading skills, and seventh grade reading comprehension in 265 monozygotic and 459 dizygotic twin pairs (M_{age} = 6.29 years in kindergarten) from the Florida Twin Project on Reading. Using a quadvariate Cholesky decomposition, results showed genetic, shared, and non-shared environmental overlap between pre-reading skills, word level reading skills, and reading comprehension. In addition, genetic and shared environmental overlap was indicated among word level reading skills and reading comprehension, outside the influence of pre-reading skills. After accounting for overlapping, there remained moderate genetic and non-shared environmental influence specific to reading comprehension. Implications for reading education are discussed.

Keywords

longitudinal; reading; twins; Cholesky

Proficient reading, specifically reading comprehension, is associated with academic success (La Paro & Pianta, 2000) and poor reading is related to increased school drop-out (Daniel et al., 2006) and/or other behavior problems (Morgan, Farkas, Tufis, & Sperling, 2008). In order to prevent development of potential reading problems, it is important to understand which skills are predictive of proficient reading comprehension performance. Several pre-reading and word level reading skills in early elementary grades have been shown to be longitudinally predictive of reading achievement in late elementary and middle school grades (e.g., Muter, Hulme, Snowling, & Stevenson, 2004; Schatschneider, Fletcher, Francis, Carlson, & Foorman, 2004). Etiology of these predictions seem to be mainly associated with genetic, and to some extent environmental, factors in the period from kindergarten up to grade 4 (e.g., Byrne, 2005; Christopher et al., 2015).

Correspondence concerning this article should be addressed to Florina Erbeli, Florida Center for Reading Research, 1107 West Call Street, Tallahassee, FL, 32306. ferbeli@fcrr.org.

However, little is known about whether these same factors continue to be associated with these predictions in reading up to middle school grades (seventh grade in the current report). Such a line of research is particularly important because middle school (sixth to eighth grades in the U.S.) reading scores have a predictive value for high school academic success and have been shown to be indicators of being on-track for graduation in eleventh grade (Allensworth, Gwynne, Moore, & de la Torre, 2014). In addition, middle school reading is different compared to elementary school reading. Middle school reading is more complex, more embedded in subject matters, and more multiply determined (Biancarosa & Snow, 2006). The demands of reading gradually shift from elementary to middle school, requiring more complicated comprehension processes as children get older (Betjemann et al., 2008). Reading comprehension strategies in middle school increasingly contribute to the successful integration of new ideas, experiencing new feelings, and learning new attitudes. In middle school reading, adolescents start to confront different viewpoints and begin to analyze and criticize what they read (Chall, 1983). Thus, it is possible that the etiology of the associations between reading related skills and reading during the transition period from elementary to middle school is somewhat different. To our best knowledge, there are no published studies examining etiological factors associated with reading from elementary grades into middle school grades, but such studies are needed to extend our understanding of reading development during this important transition period. In addition to different ages under examination, the present study investigates associations across a wide age range, which has received relatively little attention in twin research in reading. Thus, this study begins to fill the gap in the literature by examining etiological (genetic and environmental) factors that are associated with relations between pre-reading and word level reading skills in early elementary school and reading comprehension in middle school.

Letter naming is consistently found to be a reliable longitudinal predictor of word level reading and reading comprehension (Scarborough, 1998). Letter naming refers to a number of different letters a kindergartner is able to name (Scarborough, 1998). Knowing the names of letters is a prerequisite to learning the correspondence of letters to sounds (Whitehurst & Lonigan, 1998), making letter naming a foundational skills for later word reading and reading comprehension. In addition to letter naming, phonological awareness has been shown to be one of the pre-reading skills in kindergarten predicting word level reading and reading comprehension (e.g., Byrne, 1998; Wagner & Torgesen, 1987). Phonological awareness refers to the awareness of the sound structure of language and it is an ability to manipulate individual phonemes, as for example counting or deleting sounds (Wagner & Torgesen, 1987). It is well established that there is a close association between phonological skills and the development of word recognition skills in reading (Castles & Coltheart, 2004) and that phonological awareness predicts subsequent reading performance (Hulme, Snowling, Caravolas, & Carroll, 2005). Letter-sound knowledge and phonemic skills form the basis of the alphabetic principle (Byrne, 1998): the ability to map letters in printed words onto the speech sounds they represent.

Once the alphabetic principle is learned, a child starts to decode words. Decoding real words and non-words (hereafter referred to as “word level reading skills”) and reading comprehension are strongly positively related, especially in children in early grades who are still mastering phonological and basic word reading skills (Hoover & Gough, 1990). It has

been indicated that decoding non-words and fluently reading real words have a high positive association with reading comprehension (e.g., Roberts, Good, & Corcoran, 2005). In particular, students' first grade oral reading fluency scores were a significant predictor of second and third grade reading proficiency (Goffreda, Clyde Diperna, & Pedersen, 2009), and individual differences in growth rate in oral reading fluency in first grade made the biggest contribution to reading comprehension in third grade (Kim, Petscher, Schatschneider, & Foorman, 2010).

Given the foundational role of pre-reading and word level reading skills in predicting later reading comprehension, it is important to gain a better understanding of etiological factors that contribute to the variance and covariance between these skills. Quantitative genetic methodology allows for an examination of the variance (independence) and covariance (overlap) of etiological influences on a particular trait (in our study reading related skills and reading). Twin studies estimate the proportion of variance in a trait that is influenced by additive genetic effects, or heritability (the combined effect of all genes which influence an outcome; h^2), shared environmental effects (environmental effects that serve to make siblings more similar; c^2), and non-shared environmental effects (environmental effects that serve to make siblings less similar, plus error; e^2).

There has been considerable univariate research conducted on reading and reading related skills. Measures of print knowledge in preschool, kindergarten and/or first grade tend to be weakly to moderately affected by genetic factors (h^2 = .22–.40), and more substantially influenced by environmental factors (c^2 = .26–.70) (Christopher et al., 2015; Petrill et al., 2006; Petrill et al., 2007; Taylor & Schatschneider, 2010; Soden-Hensler, Taylor, & Schatschneider, 2012). For phonological awareness, on the other hand, moderate to high genetic effects (h^2 = .48–.71) and weak to moderate shared environmental effects (c^2 = .16–.43) have been reported in preschoolers, kindergarteners and/or first graders (Christopher et al., 2015; Petrill et al., 2006; Petrill et al., 2007; Taylor & Schatschneider, 2010; Soden-Hensler, Taylor, & Schatschneider, 2012). Similarly, individual differences in non-word reading appear to have greater association with genetic (h^2 = .49–.81) than environmental factors (c^2 = .01–.58), although the literature is variable in terms of the magnitude of effects (Byrne et al., 2007; Byrne et al., 2013; Logan et al., 2013; Petrill et al., 2006; Soden-Hensler, Taylor, & Schatschneider, 2012). Univariate analysis of word reading fluency reveals a pattern of influence similar to reading non-words. The heritability appears to be relatively high in early grades (h^2 = .62–.85), whereas shared environmental influences tend to fall within negligible to low range (c^2 = .01–.22) (Byrne et al., 2007; Christopher et al., 2015; Hart, Petrill, & Thompson, 2010; Hart, Soden, Johnson, Schatschneider, & Taylor, 2013; Taylor and Schatschneider, 2010). Finally, reading comprehension has been shown to demonstrate a consistently significant influence of genetics across developmental ages (h^2 = .51–.82), with shared environmental influences having mostly low and/or non-significant effects (c^2 = .00–.27) (Christopher et al., 2015; Hart et al., 2013; Keenan, Betjemann, Wadsworth, DeFries, & Olson, 2006; Logan et al., 2013).

These univariate estimates provide certain indications to what extent genes and environment influence reading related skills and reading at a particular age/grade, however moving beyond univariate towards multivariate analysis, in particular towards a longitudinal

analysis, is important. A genetically sensitive longitudinal analysis can explore individual differences in developmental relations of reading related skills and reading in two ways: first, individual differences in development of one (the same) variable can be explored at different time points (e.g., exploring individual differences in development of oral reading fluency in grades 1–5; Hart et al., 2013), and second, individual differences in developmental relations of different variables can be explored at different time points (e.g., exploring individual differences in the developmental relations between preschool print knowledge, preschool phonological awareness, and kindergarten reading; Byrne et al., 2005). Given our research question, we will employ the second approach in the present study. Using Cholesky decomposition with longitudinal data, genetic and environmental influences are first estimated between kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension. Next, genetic and environmental influences are measured among kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension after controlling for kindergarten letter naming fluency. Then, genetic and environmental influences are estimated for first grade word level reading skills and seventh grade reading comprehension after controlling for the kindergarten time point. Finally, genetic and environmental influences are measured for seventh grade reading comprehension after controlling for kindergarten and first grade time points.

There are a few reports investigating the longitudinal development of reading by exploring different reading related variables across different developmental phases. Byrne et al. (2005) concluded that preschool reading related skills shared significant genetic and shared environmental covariance with kindergarten reading skills. In particular, a single genetic factor and a single shared environmental factor influenced the association between preschool print knowledge, preschool phonological awareness, and kindergarten reading. However, preschool phonological awareness exerted genetic influence on kindergarten reading skills only through genes that it shared with preschool print knowledge. This study was expanded by bringing a fourth variable into the model, that is, preschool rapid naming (Byrne et al., 2006). Results showed that kindergarten reading was influenced to a substantial degree by genes that were common to preschool print knowledge, phonological awareness, and rapid naming. Results were interpreted as an example of what Plomin and Kovas (2005) have referred to as “generalist genes.” In addition, all preschool measures and kindergarten reading were influenced by a common shared environmental effect, and there was not a separate shared environmental source emerging in kindergarten for reading. Results suggested that the environment provided by home and/or preschool carried over to kindergarten reading (Byrne et al., 2006). Correlated factor models by Christopher and colleagues (2015) yielded similar results in that both genetic and shared environmental influences on pre-reading skills (print knowledge and phonological awareness, among others) were responsible for relations with post fourth grade reading comprehension. Conversely, in a study by Byrne and colleagues (2009), only genetic influences played a significant role in explaining the variability of reading related skills and reading. Specifically, the study examined preschool print knowledge, phonological awareness, and rapid naming and their relations to end of second grade word reading, reading

comprehension, and spelling. Most of the variability in associations in these skills was accounted for by common genetic, but not shared environmental influences. Similar results have also been obtained in older samples. For instance, in examining the etiological overlap between word reading and reading comprehension at two time points, results indicated common genetic influences between word reading at the first time point (age range of 8.0 to 15.9 years) and reading comprehension at the second time point (age range of 12.9 to 23.9) and also significant genetic influence on comprehension at the second time point, independent of that on word reading (Betjemann et al., 2008). Taken together, there are mixed results concerning shared environmental influence; but, on balance, the studies suggest the variance and covariance among reading related skills across various stages in reading development is primarily attributable to genetic effects, with some shared environmental influences, particularly in pre-reading skills.

Prior studies focused mostly on investigating relations between reading related skills among preschoolers up to fourth graders (e.g., Byrne, 2005; Christopher et al., 2015) or among participants with broad age ranges, including young adults (Betjemann et al., 2008). The question remains whether new genetic and shared environmental influences are expressed through reading development from early elementary up to middle school. In other words, do new sources of genetic and shared environmental effects come online during the reading development for this age span or do the effects from early reading developmental periods “carry over” in a similar way as they do for early reading up to grade four? The degree of genetic and environmental influences may increase and decrease in magnitude over time across different developmental periods. For this reason, the current study expands previous work by providing quantitative genetic analysis of longitudinal relations among kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension, using a large representative twin project. This span of schooling covers more completely the transition from early reading instruction to instruction using reading to teach other subjects. It includes the grades when adolescents are using reading to gain new content knowledge, also by reading increasingly more complex texts (Chall, 1983). To our knowledge, the present report is the first one to investigate etiological relations between early elementary reading related skills and middle school reading. Given the results of previous literature, which examined children’s reading related skills at different ages (e.g. Byrne et al., 2006), we hypothesize that genetic influences act in a “generalist” way and will impact the longitudinal associations among reading related skills and reading across all three time points. Moreover, given the rapid development of reading skills in early elementary school (Petrill et al., 2007) and a shift in the kinds of skills that are important for successful reading as children master reading skills in middle school (e.g., Dale & Crain-Thorenson, 1999), we hypothesize that independent genetic influences may emerge in first and seventh grade. Based on previous literatures’ findings that shared environment provided by home and/or preschool (Byrne et al., 2006) and by school (Hart et al., 2013) carried over to kindergarten and higher grades, we expect that common shared environmental influences will be significant among reading related skills and reading across all three time points.

Method

Participants

The present sample was drawn from a large twin sample from the Florida Twin Project on Reading (FTP-R; Taylor & Schatschneider, 2010). FTP-R is an ongoing cross-sequential twin study, which is part of the Florida Learning Disabilities Research Center at Florida State University and the Florida Center for Reading Research. The ascertainment method for the FTP-R has been described in detail elsewhere (Taylor & Schatschneider, 2010). Briefly, twins were identified through a match on last name, date of birth, and school in Florida's Progress Monitoring and Reporting Network (PMRN), a statewide database of standardized achievement tests on children in schools throughout the state of Florida. Zygosity of twin pairs was determined by a parental five-item questionnaire obtained during intake into the FTP-R. It measured the physical similarities of the twins and has shown to have high correspondence to zygosity estimates from genetic markers (Lykken, Bouchard, McGue, & Tellegen, 1990).

The data used in this study were used from the PMRN database for three cohorts of twin pairs from the FTP-R at three time points. The first time point refers to the point when twin pairs were in kindergarten, the second time point is when twin pairs were in first grade, and the third time point is when twins were in seventh grade. Thus, data for the first cohort of twins were used from the spring of the 2004–2005 (kindergarten time point), 2005–2006 (first grade time point), and 2011–2012 school years (seventh grade time point), for the second cohort from the spring of the 2005–2006, 2006–2007, and 2012–2013 school years, and for the third cohort from the spring of the 2006–2007, 2007–2008, and 2013–2014 school years. These school years were chosen to maximize sample size within the developmental ages being examined. Twins that had available data at seventh grade and at some time point earlier were considered in the present study.

The final sample included 724 pairs of twins, specifically 265 monozygotic (MZ; 134 female-female, 131 male-male) and 459 dizygotic (DZ; 123 female-female, 121 male-male, and 215 opposite sex) twin pairs. At first time point, twin pairs were on average 6 years 4 months old ($M = 6.29$, $SD = 0.44$), at second time point, 7 years 5 months ($M = 7.38$, $SD = 0.47$), and at third time point, 13 years 6 months ($M = 13.47$, $SD = 0.56$). The racial breakdown of the sample in the current study is the following: 1.4% of the twins were Asian, 22.9% Black, 21.0% Hispanic, 0.1% Native American/Pacific Islander, 3.5% Mixed, 49.7% White, and 1.4% did not report race. The percentages reported are similar to values reported by the U.S. Census Bureau for the state of Florida (https://www.census.gov/quickfacts/table/RHI125215/12,00). Regarding the socio-economic status, 37.9% of the twins did not apply or were not eligible for free or reduced lunch (annual gross income above US $43,568 for a four member family; e.g., lunch price US $2.15 in middle school in the Lake County school district, Florida), 51.7% were eligible for free lunch (annual gross income at or below US $30,615 for a four member family; free lunch), and 7.8% were eligible for reduced price lunch (annual gross income between US $30,615 and US $43,568 for a four member family; e.g., lunch price US $0.40 in Lake County) (https://www.gpo.gov/fdsys/pkg/FR-2013-03-29/pdf/C1-2013-06544.pdf). These percentages are reflective of the percentage

of public school students eligible for free or reduced price lunch in the state of Florida (56%). The estimate on the national (U.S.) level lies slightly lower, at 48% for 2010–2011 school year (https://nces.ed.gov/programs/digest/d12/tables/dt12_046.asp).

Procedure and Measures

In this study, we examined etiological associations between kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension. The Dynamic Indicators of Basic Early Literacy Skills (DIBELS) assessment includes measures relating to letter naming fluency, phoneme segmentation fluency, and word level reading skills. The Florida Comprehensive Assessment Test (FCAT) reading subtest was used as a measure of reading comprehension. DIBELS data were collected by schools using trained administrators at multiple time points (fall, winter, spring) throughout the school year and data were entered into the PMRN database. DIBELS data from spring assessment were used in the present study. FCAT data were also included in the PRMN. FCAT was administered to all students in grades 3 through 10 in the state of Florida during 10 day testing window in the spring.

All parents of twins provided informed consent for investigators to use their twins' PMRN data; the FTP-R project was approved by the Florida State University Institutional Review Board.

Kindergarten letter naming fluency (LNF)—LNF is a measure of print awareness and measures children's ability to rapidly identify upper- and lowercase letters of the alphabet arranged in a random order. The score is the number of letter names named correctly in one minute. The alternate-form reliability of this measure is .89 in kindergarten. The median concurrent, criterion-related validity with the Woodcock-Johnson Readiness Cluster standard score is .75 in kindergarten (Good et al., 2004).

Kindergarten phoneme segmentation fluency (PSF)—PSF is a measure of phonological awareness and measures children's ability to segment words into phonemes. The examiner asks children to say individually each of the phonemes in three- and four-phoneme words. The number of phonemes said correctly in one minute is the index of performance. The alternate-form reliability of this measure is .79 in kindergarten and the median concurrent, criterion-related validity with the Woodcock-Johnson Readiness Cluster standard score is .56 in kindergarten. (Good et al., 2004).

First grade word level reading skills—Word level reading skills were measured using Nonsense Word Fluency (NWF) and Oral Reading Fluency (ORF) measures. NWF is a measure of alphabetic principle and phonics and measures children's ability to use letter-sound correspondence to decode words. Children are presented with printed vowel-consonant or consonant-vowel-consonant nonsense words (e.g., ov, sig, rav) and asked to verbally produce the individual letter sounds in each word, or verbally produce, or read, the whole nonsense word. The number of letter-sounds produced correctly in one minute is the final score. The alternate-form reliability is .83 in first grade and the median concurrent, criterion-related validity with the Woodcock-Johnson Readiness Cluster standard score is .51

in first grade (Good et al., 2004). ORF is a measure of accuracy and fluency and measures children's reading accuracy and speed with connected text. Children read each of three grade-level passages aloud for one minute. Words omitted, substituted, and hesitations of more than three seconds are scored as errors. Words self-corrected within three seconds are scored as accurate. The number of words read correctly in one minute from each passage is recorded, and the median value from the three passages is taken as the final score. The alternate-form reliability in first grade is .95 (Good, Kaminski, Smith, & Bratten, 2001).

Seventh grade reading comprehension—FCAT-Reading is a measure of reading comprehension and consists of several narrative and expository passages. Students are asked to read passages and answer multiple choice, short answer or long answer format items based on the content of the passage. The present analyses utilize the FCAT reading scale score, an IRT based score, for all participating twins with available data from seventh grade. FCAT scale scores range from 171–289 in seventh grade with a passing score falling within the Level 3 range (228–242 in seventh grade) (Florida Department of Education, 2014). Reliability for FCAT Reading Comprehension from Cronbach's alpha is .90 in seventh grade and the criterion-related validity with Stanford Achievement Test Series is .83 in seventh grade (Florida Department of Education, 2007).

Data Analyses

First, descriptive statistics and phenotypic correlations among all measured variables were calculated. Following that, raw data on all measures for every child were residualized on age, age-squared, gender, and SES (operationalized as free and reduced price lunch status) (McGue & Bouchard, 1984). It should be noted that non-residualized data on SES produced similar results. Residualized data were subsequently *z*-scored. Next, intraclass (ICC) and cross-twin cross-trait (CTCT) correlations were calculated by zygosity for all measured variables in the model. ICCs provide initial information about the additive genetic, shared environmental, and non-shared environmental effects associated with individual differences in each of the measured variables. The ICCs for MZ twins will be greater than the ICCs for DZ twins when genetic influences are present. The ICCs for MZ and DZ twins will be approximately equal when shared environment is influencing individual differences in a trait. An ICC for MZ twins that is less than 1.0 suggests that non-shared environmental influences are present. The CTCTs provide an initial indication of the extent to which those same sources of variance are associated with the covariation among the measured variables. The CTCT correlation is calculated by correlating a trait from one member of a pair with a different trait from his/her co-twin. Inferences drawn from comparisons of the CTCTs are the same as those described for ICCs, however they apply to influences on covariance of two measured variables. All these analyses were conducted in SAS 9.4.

Following descriptive and correlational analyses, structural equation modeling was used to examine the univariate estimates of genetic, shared environmental influences, and non-shared environmental influences on all measured variables. To examine the etiological covariation between the measures, a quadvariate Cholesky decomposition model was utilized. Based on theories of the development of reading skills, the Cholesky model was specified with kindergarten letter naming fluency as the first measured variable, followed by

kindergarten phoneme segmentation fluency as the second measured variable, then first grade word level reading skills serving as a latent variable, and finally seventh grade reading comprehension as the last measured variable in the model. In other words, the variance and covariance among kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension was decomposed into four latent biometric factors representing genetic, shared environmental, and non-shared environmental influences (A, C and E, respectively). For the quadvariate Cholesky decomposition, the first set of biometric factors represent the additive genetic (A_1), shared environmental (C_1) and non-shared environmental (E_1) influences shared among kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh reading comprehension; the second set of biometric factors (A_2, C_2, E_2) represent the genetic and environmental influences shared among kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension, after accounting for the first set of biometric factors; the third set of biometric factors (A_3, C_3, E_3) represent the genetic and environmental influences shared among first grade word level reading skills, and seventh grade reading comprehension, after accounting for the first two sets of biometric factors; finally, the fourth set of biometric factors (A_4, C_4, E_4) represent the unique influences on seventh grade reading comprehension, after accounting for the first three sets of biometric factors. The order of the variables entered into a Cholesky decomposition is arbitrary, however, in the present study, the order was driven by a theoretical perspective on the development of reading such that kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, and first grade word level reading skills are predictive of later reading comprehension. Biometric models on all available data were fit in Mplus 7.11 using the maximum likelihood estimator (Muthén & Muthén, 1998–2012). Significance of parameter estimates was based on the 95% confidence intervals not including zero.

Results

Descriptive Statistics and Correlational Analyses

Descriptive statistics, phenotypic, intraclass (ICC), and cross-twin cross-trait (CTCT) correlations for all measured variables are provided in Table 1. All measured variables were positively and significantly correlated. Correlation between the measures of kindergarten pre-reading skills was moderate, whereas correlation between the measures of first grade word level reading skills was strong. ICCs were consistently higher in MZ than in DZ twins for all variables, indicating presence of some genetic influences on the variation of these phenotypes. CTCTs between LNF and NWF, LNF and ORF, PSF and NWF, NWF and ORF also indicated presence of some genetic influences on the covariation among these variables. The DZ ICCs were greater than half the MZ ICCs for all variables, indicating some shared environmental effects. In addition, CTCTs indicated shared environmental influence on the covariation of PSF and FCAT, and ORF and FCAT as the magnitude of CTCT MZ and DZ correlations was similar.

Univariate Analysis

Univariate results from the structural equation model fitting of the data for each measured variable are displayed in Table 2. Results indicated significant genetic influences for all measured variables (h^2 = .44–.50). Shared environmental influences were significant for LNF (c^2 = 23) and for ORF (c^2 = 22). Results for FCAT also indicated significant shared environmental influences (c^2 = 31). All measures indicated significant non-shared environmental influences (including error; e^2 = .23–.45).

Multivariate Analyses

Results for genetic, shared environmental, and non-shared environmental influences for kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension from the quadvariate Cholesky decomposition model are presented in Table 3 and Figure 1. Results were consistent with the twin correlations. Looking at the first set of genetic and environmental factors (A_1, C_1, and E_1), results for the biometric factor A_1 indicated there was significant genetic overlap between kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension (path estimates of .60, .24, .63, and .18, respectively). In addition, there was significant shared environmental influence among kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension indicated by the biometric factor C_1 (path estimates of .53, .30, .35 and .37, respectively). For non-shared environmental influences, there was a significant overlap among kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension indicated by the biometric factor E_1 (path estimates of .60, .17, .12 and .08, respectively).

Looking at the second set of genetic and environmental factors (A_2, C_2, and E_2), results indicated significant genetic influence on kindergarten phoneme segmentation fluency, however they did not indicate significant genetic overlap between kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension (path estimates of .63, .00 and .03, respectively), above and beyond the first set of overlapping genetic influences (i.e. A_1). Within the pathways of the shared environmental factor C_2, only one of the pathways was significant. That was first grade word level reading skills specific shared environmental influence (path estimate of .18). For non-shared environmental influences, there was a significant non-shared environmental influence on kindergarten phoneme segmentation fluency, and on the overlap of phoneme segmentation fluency and first grade word level reading skills, however the non-shared environmental overlap between kindergarten phoneme segmentation fluency and seventh grade reading comprehension was non-significant and zero.

The third set of genetic and environmental factors (A_3, C_3, and E_3) suggested significant genetic overlap between first grade word level reading skills and seventh grade reading comprehension (path estimates of .43 and .26, respectively), above and beyond the first two sets of overlapping genetic influences (i.e. A_1 and A_2). There were significant shared

environmental influences between first grade word level reading skills and seventh grade reading comprehension as indicated by the biometric factor C_3 (path estimates of .38 and .50, respectively). For non-shared environmental influences, there was a significant non-shared environmental influence overlap between first grade word level reading skills and seventh grade reading comprehension (path estimates of .33 and .11, respectively).

Finally, the fourth set of genetic and environmental factors (A_4, C_4, and E_4), representing variance unique to reading comprehension (i.e. outside of the overlap with kindergarten pre-reading skills and first grade word level reading skills), showed significant genetic (path estimate of .55) and non-shared environmental effects (path estimate of .43) only.

Discussion

It is well established that pre-reading skills and word level reading skills are predictive of later reading comprehension. Genetically sensitive studies have indicated the extent to which these skills are related to later reading comprehension due to genetic and environmental factors; however, the age span of samples used in prior investigations has mostly covered preschool through fourth grade. In our study, we investigated whether new genetic and shared environmental influences come online in the reading developmental period from early elementary up to middle school. In other words, what etiological factors are associated with predictive powers of pre-reading skills on word level reading skills and later on reading comprehension? We examined etiological factors associated with longitudinal relations among kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, via first grade word-level reading skills, to seventh grade reading comprehension.

Results from the univariate analyses for kindergarten pre-reading skills and first grade word level reading skills have been supported by previous work across different projects (e.g., Hart et al., 2013; Petrill et al., 2006; Petrill et al., 2007; Soden-Hensler, Taylor & Schatschneider, 2012). Univariate results for reading comprehension are partly in line with previous work, in that genetic influences tend to be lower and shared environmental influences higher in our study, compared to previous research from the same project (e.g., Little & Hart, 2016; for a review, see Little, Haughbrook, & Hart, 2016). The reason for this might lie in age difference between the present sample and the aforementioned ones.

Results of the multivariate longitudinal model suggested that the first genetic factor (A_1) influenced kindergarten letter naming fluency, kindergarten phoneme segmentation fluency, first grade word level reading skills, and seventh grade reading comprehension. In other words, kindergarten letter naming fluency is associated with a set of genetic factors that also relate to with how well a child will discriminate phonemes in kindergarten, decode words in first grade and, furthermore, with how well he/she will comprehend a text in middle school some eight years later. This may underlie the fact that pre-reading skills, such as letter naming fluency, starting as early as in kindergarten are reliable predictors of subsequent reading in middle school. Kindergarten letter naming fluency seems to depend in part on genes that subsequently play a substantial role in middle school reading. As we hypothesized, the shared genetic component could be indicative of genetic influences on an

underlying skill such as reading ability – “generalist genes” (Plomin & Kovas, 2005). Additional research is needed to investigate the exact nature of this genetic component.

Above the first genetic factor, the second genetic factor (A_2) affected kindergarten phoneme segmentation fluency, however it did not influence first grade word level skills nor seventh grade reading comprehension. That occurred only through the genetic variance shared with kindergarten letter naming fluency. Such a result is consistent with the prior investigation (i.e. Byrne, 2005). Kindergarten phoneme segmentation fluency appears to have two sources of genetic influence, however only one is shared with first grade word level reading skills and seventh grade reading comprehension. The shared source is the one which also seems to influence kindergarten letter naming fluency (factor A_1). Such a result suggests that phoneme segmentation fluency (at least as operationalized in the current study) may not offer much as a stand-alone screen for possible later reading difficulties as its heritability seems to be reflecting a phenotype which is not associated with word level reading skills and reading comprehension. Ramus and Szenkovits (2008) argue that some tasks of phonological processing actually tap more into phonological access (i.e. processes by which phonological representations are accessed, such as short-term memory load, conscious awareness, and speed) than into phonological processes per se. This might also be the case for our phoneme segmentation task, which is a timed measure.

The third genetic factor (A_3) was associated with first grade word level reading skills and seventh grade reading comprehension, indicating an additional genetic factor that influences word level reading skills in first grade and reading comprehension in seventh grade, outside the overlap with pre-reading skills in kindergarten. What this implies is how well a child can decode words in early elementary school and how well he/she can comprehend a text 7 years later, independent of his/her pre-reading skills, can be attributed to genetic differences between children. Another explanation for the genetic overlap of word level reading skills and reading comprehension might, in part, be that some comprehension tests assess not only comprehension, but also decoding skills (Keenan, Betjemann, & Olson, 2008). The independent genetic influences of the A_3 factor in first grade may be measuring genetic influences, such as those associated with specific reading skills that develop incrementally during first grade (e.g., Chall, 1983), or they may represent general processing skills needed for decoding (e.g., related to increased working memory demands).

In addition to the first three genetic factors, the fourth genetic factor (A_4) associated with reading comprehension is suggestive of genetic influence affecting later reading comprehension independently from kindergarten pre-reading and first grade word level reading skills. This implies there could be some genetic effects that emerge anew for reading comprehension, which are not shared with genes for precursor reading skills. Although this model cannot identify the source of this effect and the specific time point as to when exactly “new” genetic effects for reading comprehension come online, it may be the case that skills, such as inference, comprehension monitoring, and knowledge and use of story structure, emerge anew in middle school reading. Previous research has shown these skills emerged as distinct predictors of reading comprehension in grade 6, even after the autoregressive effect of comprehension was controlled (Oakhill & Cain, 2012). In addition, since the same measures were not used across the developmental periods, it is impossible to determine

whether the unique genetic influences on comprehension are related to differences in the measures, or to developmental differences in reading, comprehension, or both. More investigation of these is necessary to further understand the nature of their distinction.

Turning to the shared environmental results from the multivariate model, the significant overlap of shared environmental influences between all the early reading related skills and later reading comprehension (factor C_1) suggests that shared environmental factors are influencing both reading related skills and reading comprehension. As we hypothesized, these results imply that general shared environmental influences at kindergarten and first grade continue to play a role in reading ability even eight years later. Thus, it is suggested that shared environmental effects are perhaps reflecting general development of reading throughout the grades, and not necessarily at each individual grade (Hart et al., 2013). Nonetheless, results highlight the importance of early environmental influences on shaping children's reading performance in later years, which is consistent with previous research (e.g., Logan et al., 2013; Christopher et al., 2015).

Within the second shared environmental factor (C_2), there was a significant path specific to first grade word level reading skills, which was not shared with any other factors in the model. According to the univariates, kindergarten phoneme segmentation fluency has just enough shared environmental effects, which are shared with kindergarten letter naming fluency, however there is no remaining shared environment to be overlapping with first grade word level reading skills and seventh grade reading comprehension.

The third shared environmental factor (C_3) indicating unique and overlapping shared environment between first grade word level reading skills and seventh grade reading comprehension suggests that possible "new" shared environmental effects emerged in first grade, independent of shared environmental influences in kindergarten. The exact sources of the shared environmental effects can only be surmised in the present study. However, according to previous research of environmental factors relating to reading achievement, they could include sources such as parental teaching (e.g., how often the parent tries to teach the child to read words and to print words in a typical week) (Sénéchal, Lefevre, Thomas, & Daley, 1998), parental influences toward creating environments of rich oral language (Burgess, Hecht, & Lonigan, 2002), chaotic home environment (Taylor & Hart, 2014), shared book reading by a teacher and a child (Piasta, Justice, McGinty, & Kaderavek, 2012), school quality (Haughbrook, Hart, Schatschneider, & Taylor, 2016), and/or school-level SES (Hart, Soden, Johnson, Schatschneider, & Taylor, 2013).

There were no significant shared environmental influences that emerged anew in middle school (fourth shared environmental factor C_4). There is evidence in the larger behavioral genetic literature that shared environmental influences decline with age (e.g., Haworth et al, 2009). The present study suggests these influences become non-significant for reading comprehension in middle school, that is, once children have mastered decoding skills (Petrill et al., 2007). Another explanation, which has been supported in the previous literature (e.g., Hart et al., 2013), could be that shared environmental influences present in the kindergarten and first grade (home and/or school level influences) carry through up to seventh grade. In

other words, seventh grade does not seem to contribute unique significant amounts of shared environment variance above and beyond that of the kindergarten and first grade.

The small non-shared environmental influences are indicative of child-specific environments and/or measurement error in kindergarten and seventh grade. In first grade, non-shared environmental effects are reflective of child-specific environments only. The measurement error is not included in the non-shared environmental estimates in first grade because a latent variable approach helps to reduce the impact of error on the estimates of decomposed variance at the factor level. Results suggested that child characteristics influenced reading scores from kindergarten to middle school, as well as independent similar influences on kindergarten pre-reading skills, first grade word level reading skills, and seventh grade reading comprehension, with very little overlap among the factors.

The results of this study have implications for reading education, in particular for early detection and intervention of reading problems. If genetic influences are indicative of general reading ability or are related to general cognitive ability that “carry over” from kindergarten to first grade and eventually to middle school, children identified as at risk for future reading problems may need individualizing instruction from kindergarten on, in particular in letter knowledge, as they bring different abilities to a classroom (Byrne, 2005). Our results also indicated additional genetic factors on first grade word level reading skills outside of the overlap with kindergarten pre-reading skills. If those are suggestive of general processing skills needed for decoding, then the goal of the early elementary instruction would in part be to ameliorate deficiencies in those skills. We found that shared environmental influences were unique to kindergarten letter naming fluency and first grade reading related skills, but also overlapped significantly with middle school reading, indicating that home and school environment are salient for reading related skills development. This has implications for these environments and confirms the findings in the phenotypic literature which showed that indices of the home environment and ratings of classroom behavior (among other predictors) predicted unique variance in growth of word level skills at the start of schooling (Torgesen et al., 1999). Moreover, the informal literacy environment at home predicted growth in English receptive vocabulary from kindergarten to first grade, and parent reports of the formal literacy environment in kindergarten predicted growth in children’s English early literacy between kindergarten and first grade and growth in English word reading during first grade (Sénéchal & LeFevre, 2014). The present findings suggest that future research examine interplay between genes and environments to further highlight avenues how best to intervene in early stages of reading development.

The findings should be considered in the context of main limitations. The first concerns the generalizability. The magnitude of genetic and environmental variance of a trait and the covariance of genetic and environmental influences for two traits can depend on the nature of the environment in which the population is assessed. The present results are indicative of the environmentally diverse population of twins in Florida. Thus, the estimates might not generalize to other samples from less environmentally diverse populations. In addition, it should be noted that explicitly direct comparisons of results between studies are possible only if different studies use the same measures. Another limitation is that the kindergarten and seventh grade measures in the present study served as observed variables which might

subsume measurement error. Estimates of relations involving latent variables are more reliable as measurement error is accounted for (Loehlin, 2004), thereby reducing estimates of non-shared environment that owe to error. It would be interesting to expand the understanding of etiological longitudinal associations among reading related skills and reading by disentangling the influences on those skills across additional ages/grades (grades 2–6). That would enable to pinpoint the exact period as to when any “new” genetic and/or environmental influences come online.

Behavioral genetic work has long indicated that reading related skills are influenced by both genes and environment and, furthermore, that there is some degree of overlap in genetic and environmental factors among these skills before kindergarten via post first grade up to post fourth grade (e.g., Christopher et al., 2015). However, the development of reading skills, in particular of reading comprehension, clearly continues into middle school (Biancarosa & Snow, 2006). Thus, further longitudinal research on genetic and environmental factors associated with predictions of reading related skills prior and at the onset of formal reading instruction to reading in middle school was needed to elucidate their contributions to associations of these skills during this period of reading development. The present study revealed evidence of overlapping genetic and environmental influences shared among pre-reading and word level reading skills at the beginning of schooling with reading comprehension in middle school, in a large, diverse sample. Apart from that, moderate unique genetic and non-shared environmental influences were found for reading comprehension in middle school. These findings suggest that genetic sources, certain aspects of home and school environment and to a lesser extent child-specific aspects might play a role in understanding associations of reading related skills in early schooling with reading comprehension in middle school.

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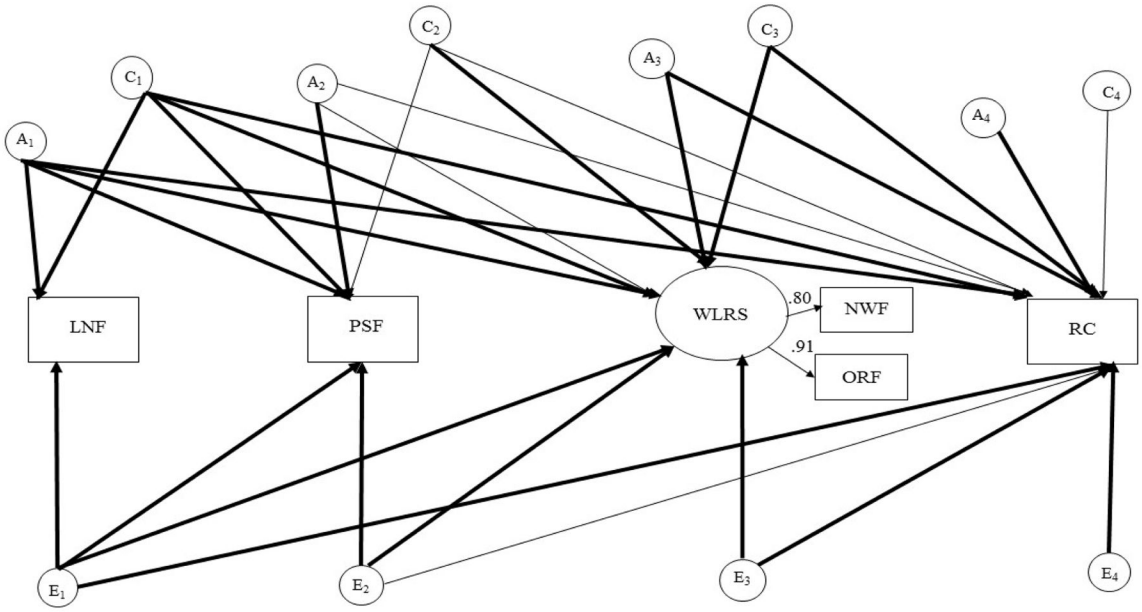

Figure 1.

Full quadvariate Cholesky decomposition model. Bolded pathways represent significance based on 95% confidence intervals. LNF = kindergarten letter naming fluency, PSF = kindergarten phoneme segmentation fluency, WLRS = first grade word level reading skills, RC = seventh grade reading comprehension, NWF = nonsense word fluency, ORF = oral reading fluency.

Table 1

Descriptive Statistics, Phenotypic, Intraclass, and Cross-Twin, Cross-Trait Correlations

Measured Variables	Grade	M (SD)	N	Min	Max	Skew	1.	2.	3.	4.	1.	2.	3.	4.	5.
1. LNF	K	51.46 (17.31)	1060	1.00	110.00	0.20	1				.67**/.42**	.21**	.28**	.29**	.24**
2. PSF	K	39.81 (17.63)	1227	0.00	85.00	−0.44	.43**	1			.26**	.50**/.34**	.14**	.15**	.07**
3. NWF	1	77.04 (36.23)	1370	0.00	216.00	0.72	.52**	.29**	1		.41**	.25**	.59**/.40**	.41**	.36**
4. ORF	1	67.05 (35.64)	1372	0.00	215.00	0.64	.59**	.30**	.73**	1	.49**	.21**	.57**	.75**/.49**	.38**
5. FCAT	7	233.89 (22.14)	1448	171.00	289.00	0.27	.37**	.19**	.47**	.54**	.24**	.09**	.35**	.41**	.74**/.57**

Note.

** p<.0001,

M = mean, SD = standard deviation, N = number of twins, Min = minimum, Max = maximum, Skew = skewness. LNF = letter naming fluency, PSF = phoneme segmentation fluency, NWF = nonsense word fluency, ORF = oral reading fluency, FCAT = Florida Comprehensive Assessment Test - reading comprehension, K = kindergarten. Phenotypic correlations are presented in columns 8–11. Intraclass and cross-twin, cross-trait correlations are in columns 12–16. Intraclass correlations are on the diagonal; the first estimate is for MZ twins, the second for DZ twins. Cross-twin, cross-trait correlations are off the diagonal; the estimates for MZ twins are below the diagonal and for DZ twins above the diagonal.

Table 2

Univariate Estimates for Heritability (h^2), Shared Environmental (c^2) and Non-shared Environmental (e^2) Influences for All Measures [with 95% Confidence Intervals].

Measured Variables	Grade	h^2	c^2	e^2
LNF	K	.44* [.19–.70]	.23* [.08–.44]	.33* [.27–.42]
PSF	K	.44* [.15–.67]	.11 [.00–.32]	.45* [.37–.57]
NWF	1	.47* [.24–.70]	.15 [.00–.34]	.38* [.31–.46]
ORF	1	.50* [.37–.73]	.22* [.15–.33]	.28* [.18–.30]
FCAT	7	.46* [.31–.63]	.31* [.16–.46]	.23* [.19–.27]

Note.

* indicates significance based on confidence intervals not bounding zero.

LNF = letter naming fluency, PSF = phoneme segmentation fluency, NWF = nonsense word fluency, ORF = oral reading fluency, FCAT = Florida Comprehensive Assessment Test - reading comprehension, K = kindergarten.

Table 3

Standardized Estimates for Heritability (h^2), Shared Environmental (c^2), and Non-shared Environmental (e^2) Influences and Multivariate Modeling Path Estimates of Genetic and Environmental Influences on Kindergarten Letter Naming Fluency, Kindergarten Phoneme Segmentation Fluency, First Grade Word Level Reading Skills, and Seventh Grade Reading Comprehension [with 95% Confidence Intervals]

	Grade	Standardized Estimates	Shared Influences between 1, 2, 3, 4	Shared Influences between 2, 3, 4	Shared Influences between 3, 4	Independent Influences on 4
		h^2	A_1	A_2	A_3	A_4
1. LNF	K	.36	.60* [.53–.61]			
2. PSF	K	.45	.24* [.23–.29]	.63* [.56–.67]		
3. WLRS	1	.58	.63* [.55–.66]	.00 [.00–.00]	.43* [.36–.51]	
4. RC	7	.40	.18* [.18–.19]	.03 [.00–.07]	.26* [.20–.29]	.55* [.54–.62]
		c^2	C_1	C_2	C_3	C_4
1. LNF	K	.28	.53* [.50–.58]			
2. PSF	K	.11	.30* [.25–.30]	.13 [.00–.25]		
3. WLRS	1	.30	.35* [.24–.36]	.18* [.08–.20]	.38* [.37–.41]	
4. RC	7	.40	.37* [.36–.43]	.00 [.00–.00]	.50* [.48–.51]	.00 [.00–.00]
		e^2	E_1	E_2	E_3	E_4
1. LNF	K	.36	.60* [.58–.61]			
2. PSF	K	.44	.17* [.13–.18]	.64* [.62–.67]		
3. WLRS	1	.12	.12* [.09–.14]	.07* [.06–.09]	.33* [.31–.33]	
4. RC	7	.20	.08* [.07–.09]	.00 [.00–.04]	.11* [.10–.11]	.43* [.40–.44]

Note.

* indicates significance based on confidence intervals not bounding zero. The first set of biometric factors measures the genetic (A_1), shared environmental (C_1), and non-shared environmental (E_1) influences between letter naming fluency, phoneme segmentation fluency, word level reading skills, and reading comprehension. The second set (A_2, C_2, E_2) measures the genetic and environmental influences between phoneme segmentation fluency, word level reading skills, and reading comprehension, outside of that explained by letter naming fluency. The third set (A_3, C_3, E_3) measures the genetic and environmental influences between word level reading skills and reading comprehension, outside of that explained by letter naming fluency and phoneme segmentation fluency. Finally, the fourth set of biometric factors (A_4, C_4, E_4) measures the unique influences on reading comprehension alone, outside of the variance explained by the rest, that is letter naming fluency, phoneme segmentation fluency, and word level reading skills.

LNF = letter naming fluency, PSF = phoneme segmentation fluency, WLRS = word level reading skills, RC = reading comprehension, K = kindergarten.