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## Exploring the Co-development of Reading Fluency and Reading Comprehension: A Twin Study

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### Abstract

The present study explores the co-development of two related but separate reading skills, reading fluency and reading comprehension, across grades 1–4. A bivariate biometric dual change score model was applied to longitudinal data collected from 1784 twin pairs between the ages of 6 and 10 years. Grade 1 skills were influenced by highly overlapping genetic and environmental factors. Growth in both skills was influenced by highly overlapping shared environmental factors. Cross-lagged parameters indicated bidirectional effects, with stronger effects from fluency to comprehension change than from comprehension to fluency change.

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Reading comprehension is a dynamic process facilitated by fast and accurate word reading (Cain & Oakhill, 2009). The ability to successfully comprehend text is associated with greater overall academic competence and proficiency continuing beyond formal education (Berkman, Sheridan, Donahue, Halpern, & Crotty, 2011; Hernandez, 2011). Developmental models suggest that children progress through several stages on the road to adept reading ability (Chall, 1983). Under Chall’s widely accepted theory of the stages of learning to read, children pass through two major developmental phases: “learning to read” followed by “reading to learn.” Stages 0 to 2 constitute the “learning to read” or pre-reading phase of development. During these stages children develop knowledge of print structure, basic understanding of the rules of language, word decoding skills and practice fluent reading skills. Stage 3 represents the transition from the “learning to read” phase to the “reading to learn” phase and is comprised of the mastery of fluent reading skills along with the integration of new knowledge and information from what is being read. The 4<sup>th</sup> and 5<sup>th</sup> stages expand on stage 3 with reading comprehension strategies increasingly contributing to the successful integration of new ideas, understanding complex concepts and making judgments about content that is read (Chall, 1983). Failure to reach proficiency by 4<sup>th</sup> grade suggests a failure to transition from stage 2 to 3 of Chall’s developmental model of reading. This failure puts students’ “reading to learn” comprehension skills at risk and indicates

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severe challenges to future academic success (Chall & Jacobs, 2003). Increased identification and understanding of broad factors that influence the development of reading comprehension skills is crucial to assisting students through the “learning to read” stage.

Reading fluency or the ability to read connected text with speed and accuracy has been identified as a component skill that is principal in the development of reading comprehension (Adams, 1990; Fuchs, Fuchs, Hosp, & Jenkins, 2001). Oral reading fluency has been used as a predictor of current and future reading comprehension ability with correlations ranging from .48 to .76 (Good, Simmons, & Kame’enui, 2001; Kim, Petscher, Schatschneider, & Foorman, 2010; Petscher & Kim, 2011; Roberts, Good, & Corcoran, 2005; Roehrig, Petscher, Nettles, Hudson, & Torgesen, 2008). Moreover, both initial skill level and growth rate in reading fluency can be used to predict reading comprehension. Kim et al (2010) demonstrated this using multilevel growth modeling which indicated that both initial reading fluency status and growth in reading fluency were significant predictors of reading comprehension, longitudinally.

The relation between reading fluency and reading comprehension is not always conceptualized as unidirectional, however, and there is some evidence that better comprehension leads to faster and more efficient word-level reading (Jenkins, Fuchs, Van Den Broek, Espin, & Deno, 2003; Smith, 2012). Some previous investigations using reaction times have found that readers use context to assist with word recognition and better understanding of context leads to improved word-reading speed and accuracy (Perfetti, Goldman, & Hogaboam, 1979; Perfetti & Roth, 1980), but investigations using more naturalistic settings (i.e. classrooms instead of lab settings) have provided mixed conclusions (Bowey, 1984; Jenkins et al., 2003).

These conflicting findings of whether reading fluency leads to reading comprehension or vice versa allow for the additional possibility of bidirectional, dynamic, co-development between the two. The “interactive model” of reading development posits that the subcomponent skills of reading work in synthesis with each other and that the initiation of higher-order skills is not dependent on the successful execution of lower-level skills (Stanovich, 1980). Namely, higher-order processes at any level are able to compensate for shortages in lower-level processes. Since its proposal, however, the interactive theory of reading has undergone limited empirical testing (Stanovich, 2000).

Although all of these models of reading development are theoretically plausible, to test them properly requires specialized data and methods. To fully test the interactive model of reading requires both reading comprehension and fluency to be measured simultaneously and longitudinally. Testing this theory using the proper data and methods can elucidate whether there is a unidirectional influence of fluency on reading comprehension or reading comprehension on fluency versus a bidirectional influence. Using longitudinal data allows for more accurate measurement of developmental processes over cross-sectional or other data collection methods, and can be used in conjunction with advanced statistical modeling techniques such as latent change score models. In addition to identifying whether there are unidirectional or bidirectional influences between constructs, it is important to account for whether or not change occurs within reading fluency or reading comprehension over time.

Otherwise it could not be determined whether any resulting unidirectional or bidirectional influences were leading to increasing or decreasing rates of change.

Latent change score models provide the opportunity to examine the functional form of change over time and can model dynamic change within and across multiple variables concurrently (Ferrer & McArdle, 2010; McArdle, 2009). Multivariate dual change score models are able to explore the dynamic relations between multiple constructs by estimating several types of change: constant change for each construct, proportional or time-point-to-time-point change for each construct and cross-lagged change between constructs. Constant change captures the average growth rate over multiple time points and proportional change captures variance in the rate of change from time point to time point. Finally, cross-lagged estimates capture how time-specific levels in one trait relate to subsequent change in another. Commonly, these influences are referred to in terms of leading and lagging indicators. When skill level changes in one trait primarily influence ensuing changes in another trait, that trait is considered a leading indicator of the other. The second trait is considered a lagging indicator as changes in this trait lag behind changes in the other. These models of inter-individual differences in intra-individual change have been applied to research on the relations between general verbal knowledge (e.g. Ferrer, McArdle, Shaywitz, Holahan, Marchione, & Shaywitz, 2007; Ferrer, Shaywitz, Holahan, Marchione, Shaywitz, 2010; Reynolds & Turek, 2012) or more specific vocabulary knowledge (e.g. Quinn, Wagner, Petscher, and Lopez, 2015) and reading comprehension. Understanding levels of change in and between reading fluency and reading comprehension through dual change score modeling can help to elucidate the processes by which these constructs co-develop, allowing for a test of the interactive model of reading development.

Beyond the phenotypic literature, the behavioral genetic literature has explored the extent to which genetic and/or environmental influences play a role in the relation between, and development of, reading comprehension and fluency. In particular, twin studies are unique in that they allow for the variance among traits to be decomposed into genetic and environmental influences by comparing the known similarities between monozygotic and dizygotic twin pairs. Sources of variance can be categorized as additive genetic influences (or heritability; A), shared environmental influences (i.e., non-genetic influences that make siblings more similar; C), and nonshared environmental influences (i.e., non-genetic effects that make siblings different, plus error; E). Both reading fluency and reading comprehension have been found to be moderately to highly heritable ( $h^2=.29-.84$  and  $.32-.82$ , respectively) with low and mostly non-significant shared environmental influences and low to moderate and significant nonshared environmental influences ( $e^2=.29-.39$  and  $.30-.54$ , respectively; Hart, Petrill, & Thompson, 2010; Keenan, Betjemann, Wadsworth, DeFries, & Olson, 2006; Logan, Hart, Cutting, Deater-Deckard, Schatschneider, & Petrill, 2013; Petrill et al., 2012). Recent applications of genetically sensitive latent growth models have found inconsistent etiological influences on reading growth (Christopher et al., 2013a; Hart, Logan, Soden-Hensler, Kershaw, Taylor, & Schatschneider, 2013; Logan et al., 2013; Petrill et al., 2010a), with some findings indicating both significant genetic and shared environmental influences on growth in reading (Hart et al., 2013; Logan et al., 2013; Petrill et al., 2010b) and another concluding that primarily genetic influences were present within the U.S. and Australian samples, but some significant shared-environmental influences were present within a

Scandinavian sample (Christopher et al, 2013b). Beyond the growth factor, overlapping genetic influences between initial reading levels and growth in reading have been found (Hart et al., 2013; Petrill et al., 2010b), but unique genetic influences on reading growth beyond those for initial skill level have been identified as well (Logan et al., 2013). Additionally, shared environmental influences have been found both to overlap between initial reading levels and rate of change (Hart et al., 2013) and to contribute uniquely to growth in reading (Petrill et al., 2010a).

A recent paper has also used simplex modeling to examine the time point to time point development of reading fluency (Hart et al., 2013). Simplex modeling is able to reflect change incrementally, where status at one time point takes into account the most recent time point rather than all previous time points included together. This work indicated stable as well as novel genetic influences on reading development from 1<sup>st</sup> through 5th grades, but only stable shared environmental influences during this period (Hart et al., 2013). The results of these previous genetically sensitive studies of reading development have provided initial evidence of the genetic and environmental influences on reading development using latent growth curve and simplex modeling techniques as separate models. Biometric dual change score models are newer and valuable developmental tools because they are able to simultaneously combine the representation of how initial status influences constant cumulative development captured by latent change score models with the incremental or time point to time point changes represented with simplex modeling, while also modeling cross-lagged influences between multiple constructs. Importantly, these models also account for genetic and environmental influences on growth.

The current study extends previous phenotypic and behavioral genetic research on reading development by exploring the co-development of reading fluency and reading comprehension using biometric latent change score modeling. Initially, a bivariate phenotypic dual change score model (DCSM) was fit to the data. Following phenotypic analyses, the bivariate DCSM was modified to include estimates of biometric influences on the mean growth across the time points. The addition of the biometric component to the DCSM allows for the decomposition of influences on growth in reading skills into genetic and environmental sources (McArdle & Hamagami, 2003). This allows for a full test of the interactive theory of reading development, as well as information on the unique and overlapping influences of genes and environment on this developmental process.

## Methods

### Participants

Participants were obtained from the Florida Twin Project on Reading, a cohort-sequential twin project in Florida (Taylor & Schatschneider, 2010; Taylor, Hart, Mikolajewski, & Schatschneider, 2013). Achievement data from Florida's Progress Monitoring and Reporting Network (PMRN), a statewide educational database, were used for all analyses. Zygosity was determined by a 5-item questionnaire (Lykken, Bouchard, McGue, & Tellegen, 1990) sent to families of twins identified through the PMRN based on a match of children in the database on last name, birth date, and school. For the current study, scores from The Dynamic Indicators of Basic Early Literacy Skills (DIBELS) and the Stanford Achievement

Test: Tenth Edition (SAT-10) on grades 1 through 4 were obtained from the PMRN database. These assessments were administered by trained school staff during the 2003–2004 to 2007–2008 school years and uploaded into the PMRN database. DIBELS scores were obtained during the spring (February through May) of each school year and SAT-10 scores were also collected during the spring (April). Recruitment into the Florida Twin Project on Reading was conducted in stages. Therefore, twins were able to enter the project at any grade and not all twins who entered in the 2003–2004 school year were followed to 2007–2008. Reading scores from DIBELS and SAT-10 were obtained for 1784 twin pairs (615 MZ, 1169 same sex and opposite sex DZ) in 1<sup>st</sup> through 4<sup>th</sup> grades. Table 1 displays the number of participants with DIBELS and SAT-10 data by grade and zygosity along with mean ages at each grade level. Participants ranged in age from 6 years of age in grade one to 10 years of age in grade four with females representing 49.6% of the sample. The racial and ethnic make-up of this sample included 51% White, 16.7% Black, 4.6% Multiracial, 1.7% Asian, and 2% Other, with 23.9% of the full sample identifying as Hispanic. The percentage of twins who qualified for Free or Reduced Lunch status was 56%.

## Measures

**Dynamic indicators of basic early literacy skills: oral reading fluency (DIBELS ORF)**—The Dynamic Indicators of Basic Early Literacy Skills (DIBELS) Oral Reading Fluency (ORF) is a measure of fluency (reading-rate) and accuracy while reading grade-level connected text (Good & Kaminski, 2002; Good et al., 2001). This assessment is administered by allowing participants one minute to read a passage with words omitted, substituted, and hesitations of more than three seconds scored as errors. Oral reading fluency is scored as the number of correct words read within the passage. Test-retest reliabilities ranged from .92 to .97 and criterion-related validity ranged from .52–.91 (Good & Kaminski, 2002).

**Stanford achievement test: tenth edition (SAT-10)**—The SAT-10 (Brace, 2003) is a widely used standardized measure of reading comprehension. Teachers administer this untimed assessment to groups of students in participating schools. Students read narrative and expository passages then respond to a total of 54 multiple choice items. The reliability coefficient for SAT-10 on a representative, nation-wide sample of students was .88. Content, criterion-related, and construct validity were established with other standardized assessments of reading comprehension (Brace, 2003). The SAT-10 subtests are vertically equated so that each has its own scale score, which provides the opportunity for comparisons across levels and the ability to measure performance over time. This feature serves to make the SAT-10 measure one that facilitates developmental modeling of reading comprehension ability.

## Analyses

A bivariate DCSM allows for the estimation of several types of change. Constant change parameters (represented by the RF and RC slopes in Figure 1) capture the overall growth rate over multiple time points and time-point-to-time-point change (represented by the latent difference scores labeled with  $\delta$  in Figure 1) capture change within construct between time-points. The means of the constant change factors are represented by  $\mu_x$  and  $\mu_y$ . Proportional effects of levels of construct a particular time point on its subsequent time-point-to-time

point change are represented by  $\beta_x$  and  $\beta_y$ . Finally, dynamic relations between constructs indicate the extent to which change in level of performance for one construct could account for subsequent change in the other construct and are represented as  $\gamma_x$  and  $\gamma_y$ .

Initially, a phenotypic model based on the bivariate dynamic model proposed by McArdle & Nesselrode (2003) was fit to the data (see Figure 1). Next, the phenotypic model was modified to allow for biometric modeling on the constant change factors, using a correlated factors approach. The correlated factors approach decomposes the variance of the intercept and slope factors from the constant change portion of the model into additive genetic influences ( $h^2$ ), shared environmental influences ( $c^2$ ) and nonshared environmental influences ( $e^2$ ), represented by A, C, and E (respectively) latent factors. Simultaneously, correlations between the latent genetic ( $rA$ ), shared environmental ( $rC$ ), and nonshared environmental ( $rE$ ) factors were estimated. This biometric extension of the dual change score model allowed for an estimation of the univariate genetic and environmental influences of each of the constant change factors, as well as the genetic and environmental correlations between the constant change factors.

Phenotypic and biometric model fitting were conducted in Mplus 7.31 (Muthén & Muthén, 1998–2012), with missing data handled using Full-Information Maximum Likelihood (FIML) estimation. Observed raw scores for DIBELS and standard scores for SAT-10 were developmentally z-scored based on the means and standard deviations from the first time point (1<sup>st</sup> grade) in line with recent studies using dual change score approaches to modeling reading comprehension and component skills developmentally (Quinn et al., 2015). Data for the two measures were scaled differently and by developmentally z-scoring each measure the unit of change could be conceptualized as standardized relative to the variability observed at the first time point. Each model's fit was evaluated using multiple criteria: the chi-square statistic ( $\chi^2$ ), the root mean square of approximation (RMSEA), Bentler's Comparative Fit Index (CFI; Hu & Bentler, 1999) and the Tucker-Lewis Index (TLI). Better fitting models are indicated by chi-square values lowest and closest to the degrees of freedom. Chi-square values that are non-significant are preferred, however, this statistic is highly sensitive to large sample sizes and should be evaluated with caution (Kline, 2011). Values of the CFI and TLI above .95 indicate close model fit, whereas, for the RMSEA, values less than .08 indicate adequate model fit (Browne, Cudeck & Bollen, 1993).

## Results

Table 1 presents the descriptive information (means, standard deviations, minimum and maximum values) calculated on raw scores from grades one through four. Mean scores for both reading fluency and reading comprehension show a developmental pattern of increasing performance with the rate of increase slowing over time. Variability for reading fluency remains relatively fixed while variability in reading comprehension shows a gradual decrease over time. Table 2 presents correlations between all time-points of reading fluency and reading comprehension, which were high and significant. Correlations within each construct were also high and significant, with some indication of them decreasing in magnitude across time points.

## Bivariate Latent Change Score Model

A full, bidirectional bivariate dual change score model with proportional and cross-lagged change constrained to be equal across time points was evaluated (McArdle & Nesselroade, 2003). Resulting model fit statistics indicated the model fit was good,  $\chi^2(24) = 75.424$ ,  $p < .001$ , CFI = .984, TLI = .981, RMSEA = .035 (95% CI: .026 – .044). Figure 2 displays the structure and estimates for the phenotypic model. Constant change parameters, reflected by the mean slope, for reading fluency were statistically significant, large in magnitude and positive (.65; 95% CI: .59, .70), and for reading comprehension were statistically significant, moderate in magnitude and positive (.38; 95% CI: .28, .48). Proportional change for both measures was statistically significant, negative and moderate with a smaller magnitude for reading fluency (–.80; 95% CI: –.96, –.64) than reading comprehension (–.91; 95% CI: –1.15, –.65). Cross-lagged estimates indicated a positive and large (.52; 95% CI: .25, .79) influence of initial reading fluency on subsequent change in reading comprehension and a small and significant influence from initial reading comprehension to change in reading fluency (.20; 95% CI: .03, .36). Statistically significant and moderate to large correlations were estimated between the constant change intercept factors ( $r = .90$ ; 95% CI: .83, .96), the reading comprehension intercept factor to reading fluency slope factor ( $r = .69$ ; 95% CI: .60, .78), reading fluency intercept factor to slope factor ( $r = .91$ ; 95% CI: .87, .94), and reading comprehension intercept factor to slope factor ( $r = .31$ ; 95% CI: .08, .55).

Next, the bivariate dual change score model described above was modified into a biometric dual change score model, where the correlations among the constant change factors were decomposed into additive genetic (A), shared environmental (C) and nonshared environmental (E) correlated factors. The model fit indicated a less than ideal, although acceptable, model fit;  $\chi^2(256) = 2307.75$ ,  $p < .001$ , CFI = .788, TLI = .801, RMSEA = .095 (95% CI: .091 – .098). Parameter estimates for proportional and dynamic change in the phenotypic and biometric models were very similar; therefore, the results from the rest of the model are not re-reported.

Results of biometric portion of the model are represented in Figures 3–5. Univariate heritability, shared environmental and nonshared environmental estimates are next to each constant change factor. In general, the heritability was high for intercept factors ( $h^2 = .73$  and .62), and moderate for the slope factors ( $h^2 = .42$  and .29), and subsequently, the shared environmental estimates were low for the intercept factors ( $c^2 = .16$  and .25) and high for the slope factors ( $c^2 = .52$  and .68). All nonshared environmental estimates were low ( $e^2 = .03$  – .12).

The genetic correlation (Figure 3) between the intercept factors was large and statistically significant ( $r_A = .91$ ) and between slope factors the genetic correlation was almost zero ( $r_A = -.06$ ). The genetic correlations between the intercept and slope factors across constructs were both moderate and statistically significant ( $r_A = -.37$  and .49). The genetic correlation between the intercept and slope factors of reading fluency was high and statistically significant ( $r_A = .74$ ), and the genetic correlation between the intercept and slope factors of reading comprehension was small and negative and statistically nonsignificant ( $r_A = -.16$ ).

All shared environmental correlations (Figure 4) were statistically significant, with the shared environmental correlation between the intercept factors ( $r_C = .99$ ), and between the slope factors ( $r_C = .98$ ), almost at unity. The remaining shared environmental correlations were moderate in magnitude. Lastly, the nonshared environmental correlations (Figure 5) were large and statistically significant between the intercept factors ( $r_E = .76$ ) and between the intercept and slope factors for reading fluency ( $r_E = .88$ ). The nonshared environmental correlation between the slope factor for reading fluency and the intercept factor for reading comprehension was moderate and statistically significant ( $r_E = .59$ ). The remaining nonshared environmental correlations were low to moderate, but nonsignificant.

## Discussion

The dynamic co-development between reading fluency and reading comprehension was examined using a biometric dual change score model (DCSM). The results of the bivariate DCSM elucidated several key patterns in the development and co-development of reading fluency and reading comprehension. When examining development within each reading skill from first to fourth grades, there was positive constant growth but negative proportional change (i.e., positive growth occurred across the school years but slowed over time). In total, students grew across the elementary school years, with the better initial performers growing faster across the years, and the lower performers showing greater time point to time point change. This same pattern replicates recent work using this same model with different reading skills and different samples (e.g., Hart & Quinn, 2015; Quinn et al., 2015).

The cross-lagged portion of the model examined the dynamic co-development between reading fluency and reading comprehension, testing the dynamic “interactive theory” of reading development. Results revealed a positive and large influence of initial reading fluency on subsequent change in reading comprehension. This result suggested reading fluency was a leading indicator of change in reading comprehension. The directionality of this relation corroborates much of the evidence suggesting reading fluency as a pre-cursor skill to reading comprehension (Petscher & Kim, 2011; Roehrig et al., 2008). Although smaller, there was also a reverse relation, in that reading comprehension was also an indicator of change in reading fluency. The finding of a bidirectional effect supports the interactive model of reading development (Stanovich, 1980), which allows for the co-development of lower-level and higher-level reading skills.

Importantly, reading comprehension, as measured in the early school years as in the present study, may be a somewhat different construct than reading comprehension as measured during later developmental phases (Keenan, Betjemann, & Olson, 2008). Keenan et al (2008) provided evidence that measures of reading comprehension were more likely to encapsulate precursor skills such as decoding when administered to children who were still in the ‘learning to read’ phase of development (i.e., when reading component skills are being actively instructed). While these findings held across multiple test formats (e.g. cloze, short answer, multiple choice), the current measure (SAT-10), was not included in their analyses. Thus, the weak bidirectional relation found in the present analyses may not hold when examining change across later periods of development during which reading comprehension could depend more on underlying skills such as executive functioning or general intelligence



and less on decoding (Carretti, Borella, Cornoldi, & De Beni, 2009; Sesma, Mahone, Levine, Eason, & Cutting, 2009; Swanson & Ashbaker, 2000). Indeed, the bidirectional relation found may be due to reading comprehension, as measured here, relying heavily on decoding.

Interventions targeting reading fluency have a history of effective improvement of reading comprehension skills in elementary school children and children with learning disabilities (Chard, Vaughn, & Tyler, 2002; Rasinski, Samuels, Hiebert, Petscher & Feller, 2011). However, a review examining how fluency-based interventions effect reading comprehension outcomes in older children (grades 6–12) revealed only a small number of interventions led to minimal gains in reading comprehension, suggesting other factors such as background knowledge or working memory may influence comprehension more as children get older (Wexler, Vaughn, Edmonds, & Reutebuch, 2008). The bi-directional nature of the co-development found within the present study further suggests that changes in reading comprehension may also contribute to the rate of change in reading fluency, and that building the two skills simultaneously may result in the greatest gains for general reading development. Interventions in which repeated text readings have been used to improve reading fluency skills have long been utilized by educational researchers and practitioners, with mixed results (Levy, Abello, & Lysynchuk, 1997; O'Connor, White, & Swanson, 2007; Therrien, Kirk, & Woods-Groves, 2012). The majority of these previously used fluency training models have neglected to include comprehension-building methods, however, and the current results suggest perhaps adding specific comprehension strategies to reading fluency training during development may serve to augment these practices and to capitalize on the nature of the co-development of reading fluency and reading comprehension.

Results of the biometric portion of the model suggest that genetic and environmental influences that underlie first grade reading fluency are almost completely the same as the genetic and environmental influences that underlie first grade reading comprehension. To our knowledge, this is the first bivariate genetically sensitive model of reading development over time, although work using bivariate genetically sensitive modeling of time-point specific reading skills measured in the early school grades has also showed high genetic correlations (e.g., Petrill et al., 2006; Plomin & Kovas, 2005). Although not always supported (e.g., Gayán & Olson, 2003), shared environmental overlap has also been seen in other samples (Petrill et al., 2005), and using different variables in this same sample (Little & Hart, in press). It is not surprising to find this, as reading fluency and reading comprehension are closely related reading skills, and the high genetic correlation could represent shared genes for reading related skills or those for more general traits such as executive function or working memory that underlie reading skill (Miller, Keenan, Betjemann, Willcutt, Pennington, & Olson, 2013; Plomin & Kovas, 2005). The high shared environmental correlation could represent the extensive shared reading environment the twins share (e.g., home, kindergarten), and the high nonshared environmental correlation could represent peer influences (e.g., affiliation with academically oriented peers) and could also indicate time-specific variations that are shared with both measures given near the same time, such as illness, and test environment differences between twins.

Interestingly, there were no shared genes, yet almost completely overlapping shared environmental influences, between the growth factors of reading fluency and reading comprehension. This suggests that how children grew in reading skills across the school years was almost entirely shared through the shared environment, such as the school (e.g., Greenwald, Hedges, & Laine, 1996) and family (e.g., Xu & Corno, 2003) environment, and not through shared genes, such as those related to learning processes (e.g., *g*). This finding mirrors and extends previous genetically sensitive univariate growth curve work which has indicated high shared environmental estimates on the growth factor of various reading skills (e.g., Hart et al., 2013; Logan et al., 2013), though other research has shown significant genetic influence on univariate growth (Christopher et al., 2013a and b). This finding shows that whatever these shared environmental influences are on the growth of reading skills, they are shared across reading skills.

Finally, the results from the biometric modeling between intercept and growth factors indicates that in general there are some shared genetic and environmental influences, but also independent genetic and environmental influences on each, as indicated by genetic and environmental correlations much less than unity. This mirrors previous work (e.g., Logan et al., 2013), and indicates that there may be different underlying skills involved at the start and then in building reading fluency and reading comprehension, and perhaps represents different instructional practices used for reading fluency compared to reading comprehension.

Limitations of the present study include the use of single-indicator latent factors of reading fluency and reading comprehension. The measures chosen to represent reading fluency and reading comprehension, though widely used and reliable, do not capture the full breadth and depth of these constructs. Multiple indicators were not available at all time points for the present analyses, therefore, single indicator latent factors were created using model constraints similar to those imposed with previous single-indicator latent change score models (Ferrer et al., 2007; 2010; Reynolds & Turek, 2012). Furthermore, the time points used in the present analyses were limited to the 'learning to read' phase of reading development. Future investigations may find a different pattern of results between reading fluency and reading comprehension using a series of developmental time points occurring later than those in the present analyses.

Finally, it is important to note that this study was conducted using measures of English orthography and other studies examining orthographies that are either more or less transparent may not follow the same pattern of results that were found within the present sample. Following this initial examination of the early stages of reading development, the co-development of reading fluency and reading comprehension can be further explored across multiple orthographies, by extending the number of measures for each construct as well as extending the developmental period and increasing the sample to include other languages.

The current study builds on previous literature by using a biometric bivariate dual change score model to investigate the genetic and environmental influences responsible for initial skill levels and growth in reading, while accounting for proportional and coupled change. In

general, where students started was genetically and environmentally mediated (by the same genes and environments), students grew across the elementary school years, mostly due to the same shared environments, with better initial performers exhibiting faster constant change across the years due to a mix of the same and different genes and environments, and lower performers showing greater time-point-to-time-point change. Future behavioral genetic studies of reading can build on these results by including additional component skills of reading in order to look for patterns of genetic and environmental influences overlapping between initial status and change over time with multiple reading-related skills. Furthermore, future studies may explore the etiologies of reading component skills at different developmental trajectories to further examine the nature of the unique genetic and environmental influences that were present for reading fluency and reading comprehension.

The current investigation provided the unique opportunity to present novel evidence for the leading role that reading fluency has on ensuing change in reading comprehension, and to a lesser extent, vice versa, under an interactive model of development, which has important practical and theoretical implications. Theoretically, support of the interactive model of reading allows for future conceptualization of reading fluency and reading comprehension as acting bi-directionally on each other's development, rather than acting strictly from reading fluency to reading comprehension or from reading comprehension to reading fluency. Practically, these findings suggest future directions for facilitating the development of reading fluency and reading comprehension by implementing instructional techniques that support the dynamic nature of their co-development. The inclusion of the biometric portion of the model also allowed for both theoretical and practical conclusions to be drawn when considering the genetic and environmental influences on the development of reading fluency and reading comprehension. Given the consistency of these results to the literature related to the genetics of the growth of reading, there is building support that a developmentally sensitive theory concerning the role of the genetic and environmental influences on reading should be put forth. Practically, these results also support a building literature indicating that the growth of reading is greatly influenced by the environment, supporting the importance of instructional approaches when teaching reading.

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## References

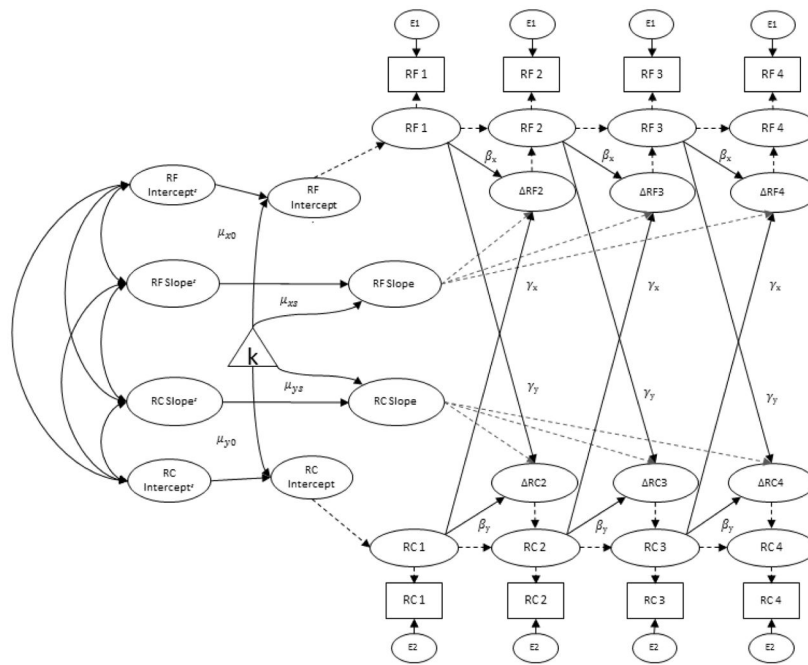
- Adams, JJ. *Beginning to read: Thinking and learning about print*. Cambridge, MA: MIT Press; 1990.
- Berkman ND, Sheridan SL, Donahue KE, Halpern DJ, Crotty K. Low health literacy and health outcomes: an updated systematic review. *Annals of Internal Medicine*. 2011; 155(2):97–107. DOI: 10.7326/0003-4819-155-2-201107190-00005 [PubMed: 21768583]
- Bowey JA. The interaction of strategy and context in children's oral reading performance. *Journal of Psycholinguistic Research*. 1984; 13(2):99–117. DOI: 10.1007/BF01067695

- Brace, H. Stanford achievement test—Tenth edition: Technical data report. Author; San Antonio, TX: 2003.
- Browne MW, Cudeck R, Bollen KA. Alternative ways of assessing model fit. *Sage Focus Editions*. 1993; 154:136–136.
- Cain, K., Oakhill, J. Reading comprehension development from 8 to 14 years: The contribution of component skills and processes. In: Wagner, RK, Schatschneider, C., Phytian-Sence, C., editors. *Beyond decoding: The behavioral and biological foundations of reading comprehension*. New York: Guilford Press; 2009. p. 143-175.
- Carretti B, Borella E, Cornoldi C, De Beni R. Role of working memory in explaining the performance of individuals with specific reading comprehension difficulties: A meta-analysis. *Learning and Individual Differences*. 2009; 19(2):245–251. DOI: 10.1016/j.lindif.2008.10.002
- Chall, JS. *Stages of reading development*. New York: McGraw-Hill; 1983.
- Chall JS, Jacobs VA. Poor children's fourth-grade slump. *American Educator*. 2003; 27(1):14–17.
- Chard DJ, Vaughn S, Tyler BJ. A synthesis of research on effective interventions for building reading fluency with elementary students with learning disabilities. *Journal of Learning Disabilities*. 2002; 35(5):386–406. DOI: 10.1177/00222194020350050101 [PubMed: 15490537]
- Christopher ME, Hulslander J, Byrne B, Samuelsson S, Keenan JM, Pennington B, ... Olson RK. Modeling the etiology of individual differences in early reading development: Evidence for strong genetic influences. *Scientific Studies of Reading*. 2013a; 17(5):350–368. DOI: 10.1080/10888438.2012.729119 [PubMed: 24489459]
- Christopher ME, Hulslander J, Byrne B, Samuelsson S, Keenan JM, Pennington B, DeFries JC, Wadsworth SJ, Willcutt E, Olson RK. The genetic and environmental etiologies of individual differences in early reading growth in Australia, the United States, and Scandinavia. *Journal of Experimental Child Psychology*. 2013b; 115:453–467. doi:10.1016/j.jecp.2013.03.008. [PubMed: 23665180]
- Ferrer E, McArdle JJ. Longitudinal modeling of developmental changes in psychological research. *Current Directions in Psychological Science*. 2010; 19(3):149–154. DOI: 10.1177/0963721410370300
- Ferrer E, McArdle JJ, Shaywitz BA, Holahan JM, Marchione K, Shaywitz SE. Longitudinal models of developmental dynamics between reading and cognition from childhood to adolescence. *Developmental Psychology*. 2007; 43:1460–1473. DOI: 10.1037/0012-1649.43.6.1460 [PubMed: 18020824]
- Ferrer E, Shaywitz BA, Holahan JM, Marchione K, Shaywitz SE. Uncoupling of reading and IQ over time: Empirical evidence for a definition of dyslexia. *Psychological Science*. 2010; 21:93–101. DOI: 10.1177/0956797609354084 [PubMed: 20424029]
- Fuchs LS, Fuchs D, Hosp MK, Jenkins JR. Oral reading fluency as an indicator of reading competence: A theoretical, empirical, and historical analysis. *Scientific Studies of Reading*. 2001; 5(3):239–256. DOI: 10.1207/S1532799XSSR0503\_3
- Gayán J, Olson RK. Genetic and environmental influences on individual differences in printed word recognition. *Journal of Experimental Child Psychology*. 2003; 84(2):97–123. DOI: 10.1016/S0022-0965(02)00181-9 [PubMed: 12609495]
- Good, R., Kaminski, R. *Dynamic Indicators of Basic Early Literacy Skills*. 6. Eugene, OR: Institute for the Development of Educational Achievement; 2002. (DIBELS) Available at <http://dibels.uoregon.edu>
- Good RH, Simmons DC, Kame'enui EJ. The importance and decision-making utility of a continuum of fluency-based indicators of foundational reading skills for third-grade high-stakes outcomes. *Scientific Studies of Reading*. 2001; 5(3):257–288. DOI: 10.1207/S1532799XSSR0503\_4
- Greenwald R, Hedges LV, Laine RD. The effect of school resources on student achievement. *Review of Educational Research*. 1996; 66(3):361. doi: 10.3102/00346543066003361
- Hart SA, Logan JA, Soden-Hensler B, Kershaw S, Taylor J, Schatschneider C. Exploring how nature and nurture affect the development of reading: An analysis of the Florida Twin Project on Reading. *Developmental Psychology*. 2013; 49(10):1971–1981. DOI: 10.1037/a0031348 [PubMed: 23294149]

- Hart SA, Petrill SA, Thompson LA. A factorial analysis of timed and untimed measures of mathematics and reading abilities in school aged twins. *Learning and Individual Differences*. 2010; 20(2):63–69. DOI: 10.1016/j.lindif.2009.10.004 [PubMed: 20161680]
- Hart SA, Quinn JM. The development of the Simple View of Reading. 2015 Manuscript submitted for publication.
- Hernandez, DJ. Double Jeopardy: How Third-Grade Reading Skills and Poverty Influence High School Graduation. Annie E. Casey Foundation; 2011.
- Jenkins JR, Fuchs LS, Van Den Broek P, Espin C, Deno SL. Sources of individual differences in reading comprehension and reading fluency. *Journal of Educational Psychology*. 2003; 95(4):719–729. DOI: 10.1037/0022-0663.95.4.719
- Keenan JM, Betjemann RS, Olson RK. Reading comprehension tests vary in the skills they assess: Differential dependence on decoding and oral comprehension. *Scientific Studies of Reading*. 2008; 12(3):281–300. DOI: 10.1080/10888430802132279
- Keenan JM, Betjemann RS, Wadsworth SJ, DeFries JC, Olson RK. Genetic and environmental influences on reading and listening comprehension. *Journal of Research in Reading*. 2006; 29(1): 75–91. DOI: 10.1111/j.1467-9817.2006.00293.x
- Kim YS, Petscher Y, Schatschneider C, Foorman B. Does growth rate in oral reading fluency matter in predicting reading comprehension achievement? *Journal of Educational Psychology*. 2010; 102(3): 652–667. DOI: 10.1037/a0019643
- Markus KA. Principles and Practice of Structural Equation Modeling by Rex B. Kline. *Structural Equation Modeling: A Multidisciplinary Journal*. 2012; 19(3):509–512.
- Levy BA, Abello B, Lysynchuk L. Transfer from word training to reading in context: Gains in reading fluency and comprehension. *Learning Disability Quarterly*. 1997; 20(3):173–188. DOI: 10.2307/1511307
- Little CW, Hart SA. Examining the genetic and environmental associations among spelling, reading fluency, reading comprehension and a high stakes reading test in a combined sample of third and fourth grade students. *Learning and Individual Differences*. 2016; 45:25–32. [PubMed: 26770052]
- Logan JA, Hart SA, Cutting L, Deater-Deckard K, Schatschneider C, Petrill S. Reading development in young children: Genetic and environmental influences. *Child development*. 2013; 84(6):2131–2144. DOI: 10.1111/cdev.12104 [PubMed: 23574275]
- Lykken DT, Bouchard TJ, McGue M, Tellegen A. The Minnesota twin family registry: Some initial findings. *Acta geneticae medicae et gemellologiae: twin research*. 1990; 39(01):35–70. [PubMed: 2392892]
- McArdle JJ, Nesselroade JR. Growth curve analysis in contemporary psychological research. *Handbook of psychology*. 2003
- McArdle JJ. Latent Variable Modeling of Differences and Changes with Longitudinal Data. *Annual Review of Psychology*. 2009; 60:577–605. DOI: 10.1146/annurev.psych.60.110707.163612
- McArdle JJ, Hamagami F. Structural equation models for evaluating dynamic concepts within longitudinal twin analyses. *Behavior Genetics*. 2003; 33(2):137–159. DOI: 10.1023/A: 1022553901851 [PubMed: 14574148]
- Miller AC, Keenan JM, Betjemann RS, Willcutt EG, Pennington BF, Olson RK. Reading comprehension in children with ADHD: Cognitive underpinnings of the centrality deficit. *Journal of Abnormal Child Psychology*. 2013; 41(3):473–483. DOI: 10.1007/s10802-012-9686-8 [PubMed: 23054132]
- Muthén LK, Muthén BO. Mplus. The comprehensive modelling program for applied researchers: User's guide. 2012; 5
- O'Connor RE, White A, Swanson HL. Repeated reading versus continuous reading: Influences on reading fluency and comprehension. *Exceptional Children*. 2007; 74(1):31–46. DOI: 10.1177/001440290707400102
- Perfetti CA, Goldman SR, Hogaboam TW. Reading skill and the identification of words in discourse context. *Memory & Cognition*. 1979; 7(4):273–282. DOI: 10.3758/BF03197600 [PubMed: 537503]

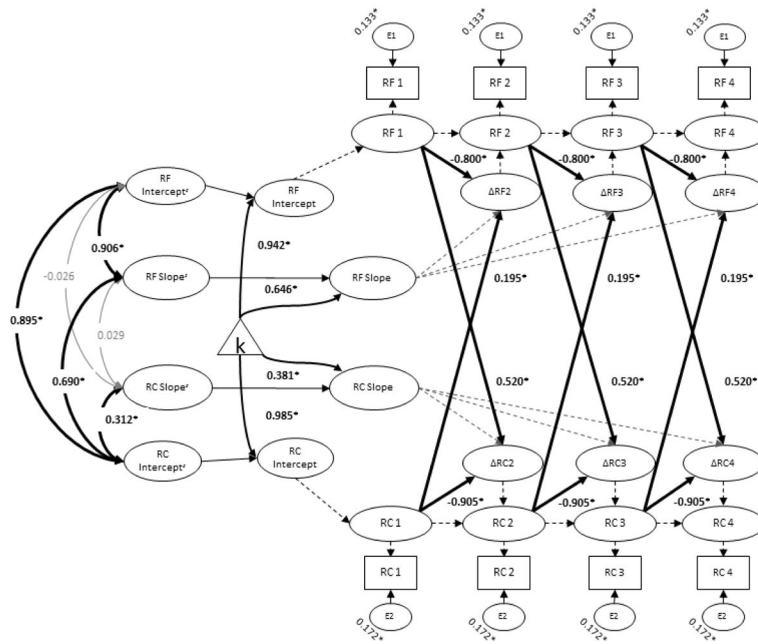
- Perfetti, CA., Roth, SF. Some Of The Interactive Processes In Reading And Their Role In Reading Skill. In: Lesgold, AM., Perfetti, CA., editors. *Interactive Processes in Reading*. Hillsdale, NJ: Erlbaum; 1981. p. 269-298.
- Petrill SA, Hart SA, Harlaar N, Logan J, Justice LM, Schatschneider C, ... Cutting L. Genetic and environmental influences on the growth of early reading skills. *Journal of Child Psychology and Psychiatry*. 2010; 51(6):660–667. DOI: 10.1111/j.1469-7610.2009.02204.x [PubMed: 20059623]
- Petrill SA, Deater-Deckard K, Thompson LA, DeThorne LS, Schatschneider C. Genetic and Environmental Effects of Serial Naming and Phonological Awareness on Early Reading Outcomes. *Journal of Educational Psychology*. 2006; 98(1):112–121. DOI: 10.1037/0022-0663.98.1.112 [PubMed: 19444324]
- Petrill S, Logan J, Hart S, Vincent P, Thompson L, Kovas Y, Plomin R. Math Fluency Is Etiologically Distinct From Untimed Math Performance, Decoding Fluency, and Untimed Reading Performance Evidence From a Twin Study. *Journal of Learning Disabilities*. 2012; 45(4):371–381. DOI: 10.1177/0022219411407926 [PubMed: 21890908]
- Petscher Y, Kim YS. The utility and accuracy of oral reading fluency score types in predicting reading comprehension. *Journal of School Psychology*. 2011a; 49(1):107–129. DOI: 10.1016/j.jsp.2010.09.004 [PubMed: 21215838]
- Plomin R, Kovas Y. Generalist genes and learning disabilities. *Psychological Bulletin*. 2005; 131(4): 592–617. DOI: 10.1037/0033-2909.131.4.592 [PubMed: 16060804]
- Quinn JM, Wagner RK, Petscher Y, Lopez D. Developmental relations between vocabulary knowledge and reading comprehension: A latent change score modeling study. *Child Development*. 2015; 86:159–175. DOI: 10.1111/cdev.12292 [PubMed: 25201552]
- Rasinski T, Samuels SJ, Hiebert E, Petscher Y, Feller K. The relationship between a silent reading fluency instructional protocol on students' reading comprehension and achievement in an urban school setting. *Reading Psychology*. 2011; 32(1):75–97. DOI: 10.1080/02702710903346873 [PubMed: 26347186]
- Reynolds MR, Turek JJ. A dynamic developmental link between verbal comprehension-knowledge (Gc) and reading comprehension: Verbal comprehension knowledge drives positive change in reading comprehension. *Journal of School Psychology*. 2012; 50:841–863. DOI: 10.1016/j.jsp.2012.07.002 [PubMed: 23245503]
- Roberts G, Good R, Corcoran S. Story retell: A fluency-based indicator of reading comprehension. *School Psychology Quarterly*. 2005; 20(3):304–317. DOI: 10.1521/scpq.2005.20.3.304
- Roehrig AD, Petscher Y, Nettles SM, Hudson RF, Torgesen JK. Accuracy of the DIBELS oral reading fluency measure for predicting third grade reading comprehension outcomes. *Journal of School Psychology*. 2008; 46(3):343–366. DOI: 10.1016/j.jsp.2007.06.006 [PubMed: 19083363]
- Sesma HW, Mahone EM, Levine T, Eason SH, Cutting LE. The contribution of executive skills to reading comprehension. *Child Neuropsychology*. 2009; 15(3):232–246. DOI: 10.1080/09297040802220029 [PubMed: 18629674]
- Smith, F. *Understanding reading: A psycholinguistic analysis of reading and learning to read*. Routledge: 2004.
- Stanovich KE. Toward an interactive-compensatory model of individual differences in the development of reading fluency. *Reading Research Quarterly*. 1980; :32–71. DOI: 10.2307/747348
- Stanovich, KE. *Progress in understanding reading: Scientific foundations and new frontiers*. New York, NY: Guilford Press; 2000.
- Swanson HL, Ashbaker MH. Working memory, short-term memory, speech rate, word recognition and reading comprehension in learning disabled readers: Does the executive system have a role? *Intelligence*. 2000; 28(1):1–30. DOI: 10.1016/S0160-2896(99)00025-2
- Taylor J, Roehrig AD, Hensler BS, Connor CM, Schatschneider C. Teacher quality moderates the genetic effects on early reading. *Science*. 2010; 328(5977):512–514. DOI: 10.1126/science.1186149 [PubMed: 20413504]
- Taylor J, Schatschneider C. Genetic Influence on Literacy Constructs in Kindergarten and First Grade: Evidence from a Diverse Twin Sample. *Behavior Genetics*. 2010; 40(5):591–602. DOI: 10.1007/s10519-010-9368-7 [PubMed: 20563747]

- Taylor JE, Hart SA, Mikolajewski AJ, Schatschneider C. An Update on the Florida State Twin Registry. *Twin Research and Human Genetics*. 2013; 16(Special Issue 01):471–475. DOI: 10.1017/thg.2012.74 [PubMed: 23067863]
- Therrien WJ, Kirk JF, Woods-Groves S. Comparison of a reading fluency intervention with and without passage repetition on reading achievement. *Remedial and Special Education*. 2012; 33(5): 309–319. DOI: 10.1177/0741932511410360
- Wexler J, Vaughn S, Edmonds M, Reutebuch CK. A synthesis of fluency interventions for secondary struggling readers. *Reading and Writing*. 2008; 21(4):317–347. DOI: 10.1007/s11145-007-9085-7 [PubMed: 22485066]
- Xu J, Corno L. Family help and homework management reported by middle school students. *The Elementary School Journal*. 2003; :503–517. DOI: 10.1086/499737

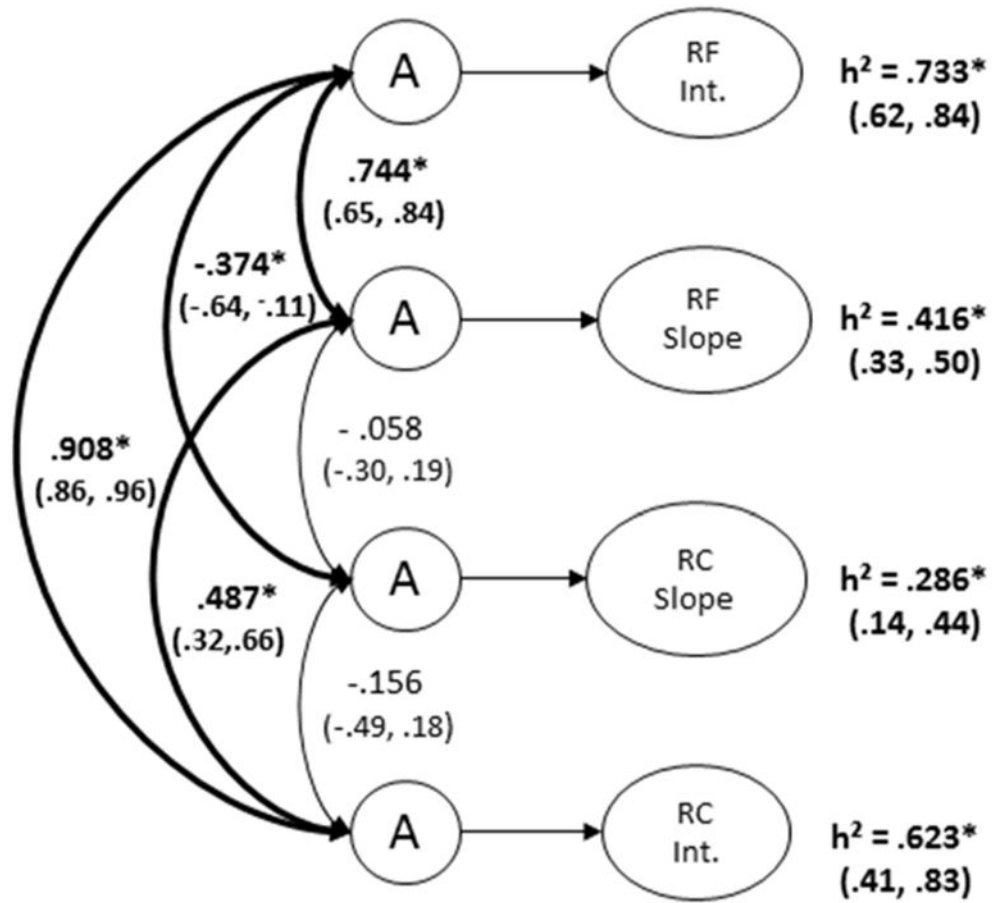


**Figure 1.** Bivariate dual change score model of Reading Fluency and Reading Comprehension for four time points. Note: RF = Reading Fluency. RC = Reading Comprehension. 1 = 1<sup>st</sup> grade. 2 = 2<sup>nd</sup> grade. 3 = 3<sup>rd</sup> grade. 4 = 4<sup>th</sup> grade. Solid lines represent freely estimated parameters. Dotted lines represent parameters set to be equal to 1. Intercepts and slopes labeled *z* have been scaled to the *z*-metric by fixing their variances to 1.0 and freely estimating their loadings such that they represent the standard deviation of the corresponding random effect.

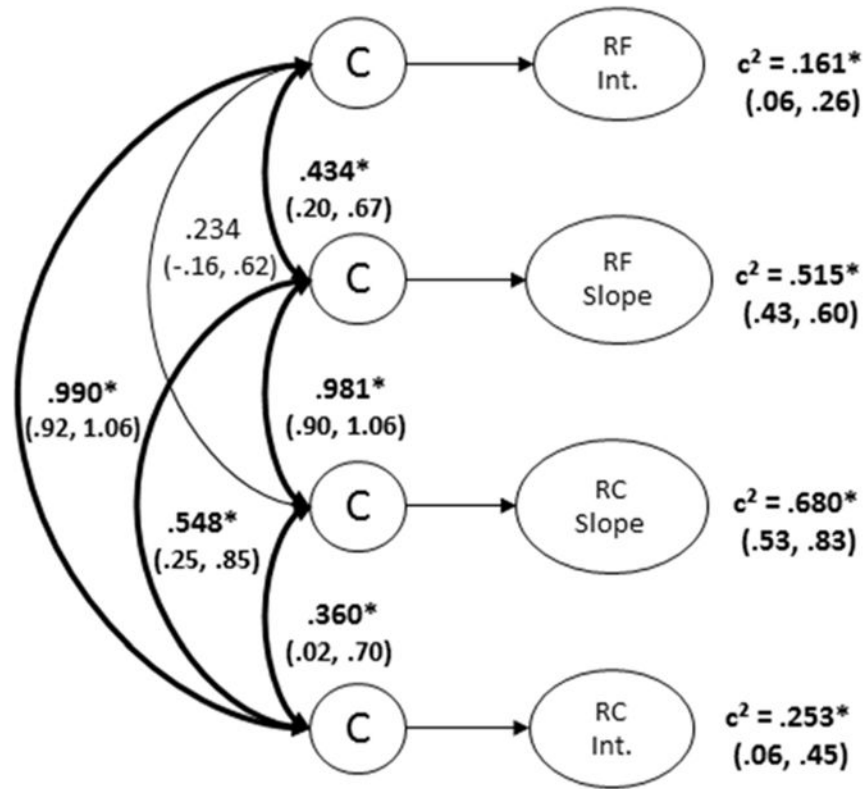




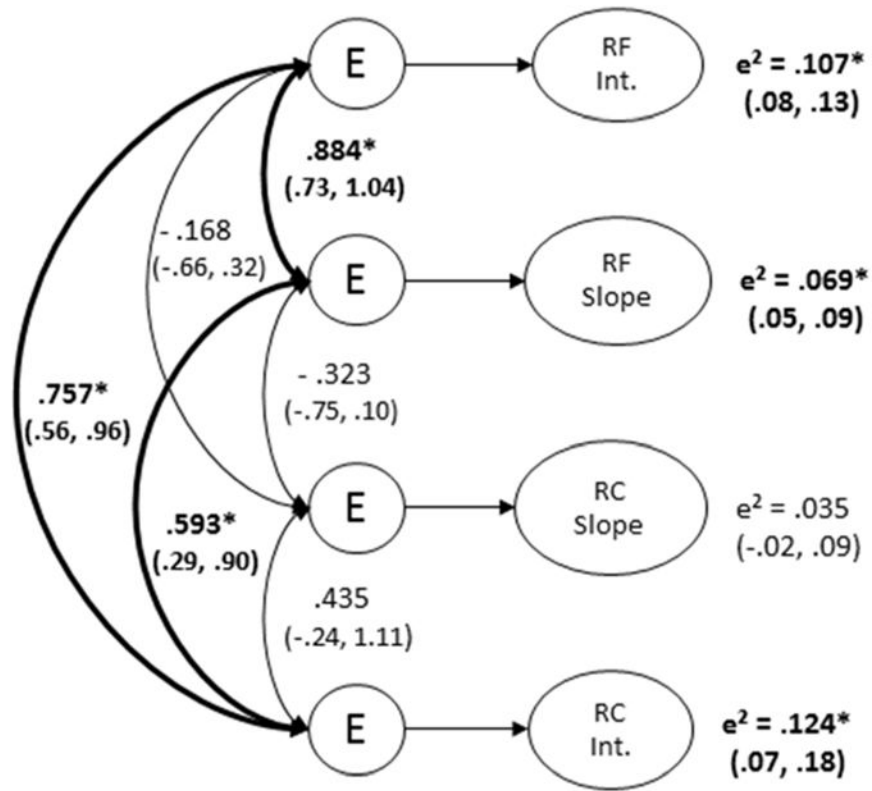
**Figure 2.** Unstandardized results for bivariate dual change score model of Reading Fluency and Reading Comprehension for four time points. Note: RF = Reading Fluency. RC = Reading Comprehension. 1 = 1<sup>st</sup> grade. 2 = 2<sup>nd</sup> grade. 3 = 3<sup>rd</sup> grade. 4 = 4<sup>th</sup> grade. Asterisks (\*) and bolded lines indicate significance at  $p < .05$ . Solid lines represent freely estimated parameters. Dotted lines represent parameters set to be equal to 1. Intercepts and slopes labeled  $z$  have been scaled to the  $z$ -metric by fixing their variances to 1.0 and freely estimating their loadings such that they represent the standard deviation of the corresponding random effect.



**Figure 3.** Univariate heritability ( $h^2$ ) and genetic correlations for reading comprehension and reading fluency intercepts and slopes. 95% confidence intervals in brackets. Asterisks (\*) and bolded pathways indicate significance at  $p < .05$ .



**Figure 4.** Univariate shared environmental estimates ( $c^2$ ) and shared environmental correlations for reading comprehension and reading fluency intercepts and slopes. 95% confidence intervals in brackets. Asterisks (\*) and bolded pathways indicate significance at  $p < .05$ .



**Figure 5.** Univariate nonshared environmental estimates ( $e^2$ ) and nonshared environmental correlations for reading comprehension and reading fluency intercepts and slopes. 95% confidence intervals in brackets. Asterisks (\*) and bolded pathways indicate significance at  $p < .05$ .

Means (M), standard deviations (SD), minimums (Min), and maximums (Max) for reading fluency and reading comprehension in grades 1 through 4.

**Table 1**

Variable	MZ					DZ				
	M	SD	Min	Max	n	M	SD	Min	Max	n
RF Grade 1	61.45	36.19	0	215	983	69.66	37.93	0	207	1832
RF Grade 2	100.61	38.50	0	208	912	108.07	38.66	0	220	1666
RF Grade 3	114.89	38.08	0	236	613	121.55	36.50	12	236	1194
RF Grade 4	116.89	38.64	3	233	215	121.02	37.08	15	216	368
RC Grade 1	557.34	51.11	437	667	302	565.54	46.70	454	667	479
RC Grade 2	604.53	42.01	494	729	200	600.78	36.68	507	729	347
RC Grade 3	636.18	41.61	503	740	380	643.90	39.06	523	763	695
RC Grade 4	652.48	36.69	581	753	94	656.65	37.16	564	753	165
Age	M	SD	n							
Grade 1	6.76	.43	889							
Grade 2	7.77	.51	852							
Grade 3	8.71	.63	700							
Grade 4	9.83	.47	264							

Note: RF = Reading Fluency. RC = Reading Comprehension. *n* = number of individuals.

Phenotypic correlations for reading fluency and reading comprehension in grades 1 through 4.

**Table 2**

Variable	1.	2.	3.	4.	5.	6.	7.
1. RF Grade 1							
2. RF Grade 2	.86*						
3. RF Grade 3	.79*	.86*					
4. RF Grade 4	.76*	.85*	.88*				
5. RC Grade 1	.73*	.66*	.62*	.64*			
6. RC Grade 2	.53*	.65*	.61*	.59*	.58*		
7. RC Grade 3	.54*	.66*	.69*	.58*	.55*	.74*	
8. RC Grade 4	.58*	.62*	.66*	.60*	.58*	.60*	.72*

Note:

\* indicates significant at  $p < .05$ .

RF = Reading Fluency. RC = Reading Comprehension.