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# Evidence-Based Reading and Writing Assessment for Dyslexia in Adolescents and Young Adults

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## Abstract

The same working memory and reading and writing achievement phenotypes (behavioral markers of genetic variants) validated in prior research with younger children and older adults in a multi-generational family genetics study of dyslexia were used to study 81 adolescent and young adults (ages 16 to 25) from that study. Dyslexia is impaired word reading and spelling skills below the population mean and ability to use oral language to express thinking. These working memory predictor measures were given and used to predict reading and writing achievement*: Coding* (storing and processing) heard and spoken words (phonological coding), read and written words (orthographic coding), base words and affixes (morphological coding), and accumulating words over time (syntax coding); *Cross-Code Integration* (phonological loop for linking phonological name and orthographic letter codes and orthographic loop for linking orthographic letter codes and finger sequencing codes), and *Supervisory Attention* (focused and switching attention and self-monitoring during written word finding). Multiple regressions showed that most predictors explained individual difference in at least one reading or writing outcome, but which predictors explained unique variance beyond shared variance depended on outcome. ANOVAs confirmed that research-supported criteria for dyslexia validated for younger children and their parents could be used to diagnose which adolescents and young adults did (*n*=31) or did not (*n*=50) meet research criteria for dyslexia. Findings are discussed in reference to the heterogeneity of phenotypes (behavioral markers of genetic variables) and their application to assessment for accommodations and ongoing instruction for adolescents and young adults with dyslexia.

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### Keywords

developmental dyslexia; predictor working memory components; word decoding and reading outcomes; word spelling outcomes; family genetics studies; adolescents and young adults

## Understanding and Defining Dyslexia

### Biological and behavioral bases of dyslexia

Considerable progress has been made in understanding the biological bases of dyslexia, a specific reading disability affecting accuracy and rate of decoding unfamiliar words, identifying familiar words, and spelling words. See Lyon, Shaywitz, and Shaywitz (2003) for this research-supported definition of dyslexia adopted by the International Dyslexia Association (IDA). On the one hand, brain imaging research has shown differences in the brains of individuals with and without dyslexia during reading and spelling tasks (e.g., for reviews, see NICHD, n.d., Berninger & Richards, 2010; Paulesu, Danelli, & Berlingeri, 2014; Pollack, Luk, & Christodoulou, 2015). On the other hand, twin studies have shown that there are heritable as well as environmental influences on both word reading and spelling disabilities (e.g., Astrom, Wadsworth, Olson, Wilcutt, & DeFries, 2012; Byrne et al., 2009; Olson, Byrne, & Samuelson, 2009; Olson et al., 2013; Stevenson, Graham, Fredman, & Mcloughlin, 1987), beginning in early literacy (e.g., Byrne et al., 2009; Lyytinen et al., 2004) and continuing across literacy development (e.g., Samuelson et al., 2008). Other genetic research methods such as segregation, aggregation, and karyotyping of gene candidates have identified modes of transmission, chromosome linkage, and variants (alleles) in specific locations on chromosomes, respectively (for review, see Raskind, Peters, Richards, Eckert, & Berninger, 2012). These methods are typically applied in association studies or family genetics studies (usually multiple families, but sometimes a single very informative family with longstanding history).

However, genetics research is not just about genes and chromosomes at the genetic level of analysis. It is also about the behavioral expression of genetic bases at the phenotypic level of analysis. Phenotypes are clinically administered measures that are thought to be behavioral markers of the underlying genetic variable/s. Indeed, the twin, segregation, aggregation, and gene candidate studies use phenotypes in their analyses to relate genetic mechanisms to their behavioral expression. The studies at the genetic level of analysis have shown that dyslexia is a heterogeneous disorder (e.g., Grigorenko et al., 1997; Raskind et al., 2012; Roeske et al., 2011; Schulte-Korne et al., 1998; Smith, Kimberling, Pennington, & Lubs, 1983; Smith-Spark, Fisk, Fawcett, & Nicolson, 2003; Velayos-Baeza, Levecque, Kobayashi, Holloway, & Monaco, 2010; Wigg et al., 2004; Wilcke et al., 2012). Likewise, phenotype studies of the behavioral markers show that dyslexia is a heterogeneous disorder (for review of the evidence, see Berninger & Richards, 2010; Raskind et al., 2012). That is, not all individuals with dyslexia show impairment in exactly the same genetic variants or related behavioral phenotypes.

However, many family genetics studies of dyslexia have focused on participants at a single developmental level (children, adolescents, or adults), the genetic level of analysis, and a

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single phenotype. Scerri et al. (2010) conducted linkage analyses on 264 families in the UK and 155 families in the U.S., each with at least one child with dyslexia. Lind, Luciano, Wright, Montgomery, Martin, and Bates (2010) performed linkage and association studies on the reading and spelling abilities of adolescent twins in 522 families not selected on basis of reading disability. Petryshen, Kaplan, Hughes, Tzenova, and Field (2002) examined a susceptibility gene in 96 families each with two or more siblings diagnosed with phonological coding dyslexia. Field and Kaplan (1998) studied a reported chromosome locus for dyslexia in 79 families each with two or more siblings diagnosed with phonological coding dyslexia.

Although each of these representative family studies and others have made substantial contributions at the level of genetic analyses, relatively little family genetics research has been devoted to whether and how the heterogeneous phenotypic behavioral expression may change across development. The cutting edge in genetics research has advanced beyond exclusive focus on the genome and DNA sequencing inherited at birth to transcription, translation, and epigenetic change in behavioral expression at the phenotypic level (see Berninger, 2015; Cassiday, 2009; Riddhough & Zahn, 2010, introduction and whole special issue). However, one multi-generational family genetics study of dyslexia found evidence for the heterogeneous phenotypes during early and middle childhood and early adolescence (Berninger et al., 2006) and in the middle age adult parents (Berninger et al., 2006; Berninger, Raskind, Richards, Abbott, & Stock, 2008). Possible phenotypic heterogeneity was not examined in adolescence and young adulthood even though the sample included family members at this developmental level. The current study aims to fill in that missing developmental level at a time when there are increasing expectations for all to pursue postsecondary education.

### Research-based definition of dyslexia—reading and spelling achievement phenotypes

In that multigenerational family genetics study, children in grades 1 to 9 (ages 6 to 14) were identified who met research criteria for dyslexia. Referred to as probands, these children qualified their families to participate if they were below the population mean (the most average score in the sample on which the norms for interpreting scores are based) on at least two word level reading and/or spelling skills, which also had to be at least one standard deviation (15 standard score points) below their verbal reasoning.

Verbal Comprehension Index was used to assess verbal reasoning based on prior research with referred (Greenblatt, Mattis, & Trad, 1990) and unreferred populations (Vellutino, Scanlon, & Tanxman, 1991) showing that this measure explained more variance in academic achievement including reading than other cognitive indices including Full Scale Scores on measures of cognitive abilities. Their verbal reasoning also had to be in the average range or above (− 2/3 *SD* and above, which is top 75% of the population) for this reason. Many other neurogenetic disorders associated with academic learning problems are more prevalent in individuals with verbal reasoning below –2/3 *SD* (Batshaw, Roizen, & Lotrecchinao, 2013); these other disorders are not due to dyslexia and have a different neurogenetic basis than dyslexia (Berninger, 2015).

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Also, two or more word decoding, word reading, and word spelling skills had to fall below the population mean (absolute criterion) and at least one standard deviation (15 standard score points) below the Verbal Comprehension Index (relative criterion). The latter is a much smaller discrepancy than typically used in qualifying students for special education but provides an indication that reading and writing scores are lower than would be expected based on ability to use oral language to express thinking. However, see Niedo et al. (2014) for an alternative approach to using Verbal Comprehension Index and working memory components for predicting expected levels of reading and writing achievement.

In addition, the proband's family also had to have at least a one family member in each of three generations who struggled with reading and/or spelling; and the proband had to have a history of and current struggle with reading and/or spelling. In this multigenerational family dyslexia study, on average, the probands with dyslexia were well below the population mean (absolute criteria) and their verbal reasoning (relative criteria) on all the reading and writing outcome measures included in the test battery. Many were above the population mean in their verbal reasoning. See Berninger et al. (2006). To summarize, dyslexia is a word-level impairment that limits word decoding and spelling in individuals with strengths in using oral language to express their thinking.

## Developmental changes in reading and writing achievement phenotypes

Parents completed the same test battery as their children, which included reading and writing achievement measures. The achievement outcomes that were impaired in both children and their adult parents were rate of phonological decoding (decoding unfamiliar pronounceable pseudowords without meaning) and written word spelling. Of note, the affected parents did not show as many relative weaknesses in oral language skills as their children. Parents were generally within the normal range in aural/oral language development; their primary problems were mainly specific to written language. The notable persisting oral language weakness in affected adults was in oral repetition of aurally presented nonwords. Overall, the adults showed fewer impaired oral and written language outcomes than their children with dyslexia. Thus, there was reason to predict that some phenotypes would remain the same across development, but some would change during adolescence; but not all hallmark phenotypes would disappear over the course of development.

## Predictor working memory phenotypes supporting language learning

The assessment battery completed by both the probands and their parents included measures of not only reading and writing outcomes but also of working memory phenotypes associated with dyslexia (Berninger et al., 2006). These component working memory phenotypes included coding of three word-forms and syntax, two cross-code loops, and three kinds of supervisory attention.

The coding measures assessed storing and processing in working memory for the following:

- **Phonological coding** of heard words and reproducing them orally
- **Orthographic coding** of read and written word spellings or letters in them

- **Morphological coding** of the bases and affixes in both phonological (heard) and orthographic (written) forms of words
- **Syntax coding** of accumulating words over time (order of words, content words—nouns, verbs, adjectives, and adverbs, and function words—prepositions, conjunctions, pronouns, and articles)

The *time-sensitive* measures for *cross-code integration* loops in working memory assessed the following:

- **Phonological loop** for rapidly and automatically integrating orthographic codes (e.g., letters) and phonological codes (not for phoneme units but rather word-level names) (Baddeley, Gathercole, & Papagno, 1998)
- **Orthographic loop** for rapidly and automatically integrating orthographic codes (alphabet letters in memory) with serial finger movements to write them (Berninger & Richards, 2010)

The multiple supervisory attention components of working memory (Ransby & Swanson, 2003), which support language learning (Niedo, Abbott, & Berninger, 2014), included the following:

- **Focused attention** (inhibiting what is not relevant and focusing on what is relevant)
- **Switching attention** (flexibly switching focus from one relevant category to another relevant category)
- **Self-monitoring** (while searching and finding written words in long-term memory by initial letter)

### Developmental change in the phenotypes

Of the 122 probands with dyslexia in the same multi-generational study of dyslexia, 200 of their biological parents also met the research criteria for dyslexia. Based on group averages, both the children and adults with dyslexia were significantly impaired on these working memory components: phonological coding (nonword repetition), phonological loop (rapid automatic letter naming), orthographic loop (rapid automatic alphabetic writing from memory), supervisory attention for inhibition underlying focused attention, switching attention during rapid automatic naming of alternating letters and numerals, and self-monitoring (repetitions during word finding for spellings based on initial letter). Thus, many phenotypes were stable across development for the children with dyslexia and their adult parents with dyslexia—both loops, all three supervisory attention functions, and one of the coding ones—phonological.

### Inter-individual and intra-individual differences in working memory phenotypes

These group analyses were supplemented with individual analyses to determine which of the component working memory phenotypes might fall outside the normal range (often set arbitrarily at below −1 1/3 *SDs*) in individuals. These individual analyses in children revealed considerable intra-individual variation within individuals as well as inter-individual



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variation among individuals as to whether codes, loops, or supervisory attention functions of working memory were outside the normal range. Only 16 of the children were outside the normal range on all three—coding, loops, and supervisory attention. The vast majority of the children were outside the normal range on one or two of these, but that may be sufficient to disrupt the efficiency of the working memory system that depends on temporal orchestration of all three to support language learning and use. Of the three, more individual children ($n$ = 122) were outside the normal range in supervisory attention ($n$ = 102) than phonological loop ($n$ = 71). Only 28 children were outside the normal range in phonological word form coding; 57 were outside the normal range on orthographic word form coding; and 43 were outside the normal range in morphological word form.

Intra-individual variation and inter-individual variation were also observed in the 200 adults. No adult was outside the normal range on all three: 84 were not outside the normal range on coding, loops, and supervisory attention; but over half of the adults were outside the normal range on one or two of these. As with the children, falling outside the normal range on just one or two may be sufficient to disrupt the temporal efficiency of the working memory system in adults with dyslexia. Of the three, more individual adults fell outside the normal range in supervisory attention ($n$ = 70) than phonological loop ($n$ = 42) or word-form coding ($n$ = 36). Moreover, 53 were outside the normal range in phonological word form coding; 9 fell outside the normal range on orthographic word form coding, and 22 fell outside the normal range in morphological word form coding. Interestingly, whereas the children with dyslexia were more likely to fall outside the normal range in orthographic coding, their parents with dyslexia were more likely to fall outside the normal range in phonological coding.

### Predicting reading and writing outcomes from working memory phenotypes for children and their middle-age adult parents

Structural equation modeling showed that, for children, first order factors from the phonological, orthographic, and/or morphological word forms each uniquely predicted 11 reading and writing outcomes; but for middle-age adults, a second order factor (reflecting interrelationships among the three first order word-form factors) was more likely to be significant in predicting the same reading and writing outcomes. Structural equation modeling also showed that the most consistent predictor of text-level reading and writing for both children and adults was the second order word-form factor. Phonological loop and supervisory attention could be modeled as separate factors in children but only as combined factors in adults. However, for adults, a unique path occurred from the residual for the first order phonological word-form factor to accuracy and rate of phonological decoding, indicating that an additional phonological process beyond the second order factor contributed uniquely to this outcome. Likewise, for adults there was a unique path from the residual for the first order orthographic word-form factor to the spelling outcome factor, indicating an additional orthographic process beyond the second order factor contributed uniquely to this outcome. Thus, developmental changes in the relationships between predictor working memory phenotypes and reading and writing outcomes were observed for children and middle age adults with dyslexia. Both coded word forms and their interrelationships were related to reading and writing. See Berninger et al. (2008).

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## Specific Research Aim and Four Research Questions

### Research aim

The specific research aim of the current study was to extend this work with younger children and older adults to study the potential heterogeneity in phenotypic expression during adolescence and young adulthood (ages 16 to 25). The multigenerational family sample was acquired on the basis of a child proband in grades 1 to 9 meeting research criteria for dyslexia on the test battery and having current and past struggles with word reading and/or spelling, and the family having a family history with at least one family member across three generations having struggled with learning to read and spell. Research has shown that both decoding during oral reading and encoding during written spelling may also be impaired in adolescents (Berninger & Miller, 2011; Lyon et al., 2003) and college students (Connelly, Campbell, MacLean, & Barnes, 2006; Wilson & Lesaux, 2001) with dyslexia. In fact, the persisting problems faced by individuals with dyslexia tends to be spelling (Lefly, & Pennington, 1991; Nergård-Nilssen & Hulme, 2014; Schulte-Korne et al., 1998; Tops, Callens, Bijn, & Brysbaert, 2014), which may be a more significant factor than word reading or phonological skills in distinguishing individuals with dyslexics from controls (Nergard-Nillson & Hulme, 2014). A study of Dutch college students with dyslexia showed that even students with dyslexia successfully attending school may still have spelling deficits that would benefit from intervention (Tops, Callen, Bijn, & Brysbaert, 2014). Thus, the aim was to evaluate whether evidence-based criteria for diagnosing dyslexia validated in earlier studies for child probands and their middle-age adult parents would also identify dyslexia in adolescent and young adults in the family genetics study.

At the same time, the aim was to evaluate whether dyslexia may express phenotypically differently in adolescents and young adults, just as some developmental differences were observed in earlier studies reviewed earlier between younger children and older adults. Some adolescents continue to have difficulty in efficiently storing and retrieving phonological codes (Birch, 2014; Felton, Naylor, & Wood, 1990), but others have other difficulties (Fletcher, Lyon, Fuchs, & Barnes, 2007) such as in silent reading rather than oral reading. In high school and postsecondary education, most written language learning activities require silent reading rather than oral reading. Some students may have impaired accuracy of oral and/or silent reading of words on untimed tasks, but others may have impaired rate of oral and silent word reading (Birch & Chase, 2004; Mapou, 2009). Lack of fluency (fast, smooth reading) may impair silent reading comprehension, but reading disabilities involving reading comprehension may have a different etiology than word-level decoding and encoding problems (see Miller, Cutting, & McCardle, 2013). Poor reading comprehension in high school students may result from weak decoding, vocabulary, and/or listening comprehension skills (Braze, Tabor, Shankweiler, & Mencl, 2007). Deficits in vocabulary and working memory that underlie childhood dyslexia may still be present in adolescents with SLDs, but word level skills may become a weaker predictor (Rose & Rouhani, 2012).

Also, during adolescence and young adulthood, some with dyslexia may have mixed reading and writing problems that include but are not restricted to spelling problems. Connelly et al.

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(2006) found that college students with dyslexia wrote poorer essays in comparison with normal controls because they wrote more slowly, made more spelling errors, and wrote fewer words, but they also had poorer decoding skills and a shorter listening span than normal controls. The best predictors of their essay quality were handwriting speed and spelling accuracy. Gregg, Coleman, Davis, and Chalk (2007) confirmed and extended those findings, showing that the best predictors of the quality of essay writing in college students with dyslexia were vocabulary complexity, verbosity (length of writing), spelling, and handwriting. Accordingly, students with dyslexia are likely to be at a disadvantage on timed writing tests, especially standardized tests required for college entrance (e.g. SAT, ACT).

Prior research demonstrated a genetic basis for some of the reading and writing outcomes: oral reading accuracy and rate for real words (Chapman et al., 2004) and pseudowords (e.g., Raskind et al., 2005) and dictated spelling (Rubenstein, Matsushita, Berninger, Raskind, & Wijsman, 2011). Likewise, prior research demonstrated a genetic basis for some of the working memory predictors: nonword repetition for phonological coding (Wijsman et al., 2000), phonological loop (Rubenstein, Raskind, Berninger, Matsushita, Wijsman, 2014), and switching attention (Rubenstein et al., 2014). For this study of adolescents and young adults with multigenerational family history of dyslexia, however, the focus was on the phenotypes—the behavioral expression—rather than genetic variations—and the potential heterogeneity and developmental change of the phenotypes.

## Research questions

Developmental level (ages 16 to 25) and family membership in family with history of three generations of dyslexia history were kept constant across all participants in the current study. Participants in both groups were older siblings or cousins of the probands or other extended family members in the family genetics study. Four specific research questions were addressed.

The first research question was whether presence or absence of dyslexia would be evident in the group means for either the working memory predictor phenotypes or the reading and writing outcome phenotypes. The hypothesis was tested that, just like oral language talent can mask dyslexia in intellectually gifted children who perform at or near the population mean in reading and writing skills but show hallmark phenotype impairments associated with dyslexia (Berninger & Abbott, 2013), so might dyslexia be masked in adolescents and young adults. By this stage of development they have had more exposure to reading and writing instruction and reading and writing practice and thus may perform at or near the mean on reading and writing measures. Still, they may still struggle with reading and writing in their formal education or work environments due to impairment in one or more of the component working memory phenotypes supporting language learning and use. They may also read and write at a lower level than if they did not have the working memory phenotype impairments associated with dyslexia.

The second research question was whether each of the working memory phenotype predictors was correlated with each of the reading and writing outcomes for adolescents and young adults. Those that were correlated with specific reading or writing outcomes were used as predictors in the multiple regressions for those specific reading or writing outcomes.

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The third research question was whether each of the working memory phenotype predictors correlated with a specific reading or writing outcome would, when entered simultaneously with other working memory predictors correlated with the same reading or writing outcome, explain unique variance in that reading or writing outcome over and beyond shared variance with the other predictors. Multiple regressions, with simultaneous entry of predictor, were used instead of structural equation modeling due to the sample size available for the adolescent and young adult participants.

The fourth research question was whether the two groups—one meeting the research criteria for dyslexia and one not meeting the research criteria for dyslexia—in the same family study with three generations of history of dyslexia—differed significantly in means for the predictor working memory phenotypes and the reading and writing outcomes. If so, then dyslexia can be diagnosed in older adolescents and young adults.

## Method

### Participants

For the current study, individuals were identified who ranged in age from 16 to 25 and participated in the last two ascertainment waves (4 and 5) in an 11-year family genetics study of dyslexia. Those children who qualified the family (probands) were not included in the current study—only their older siblings or cousins or other extended family members who were at least 16 but not over 25 were included. See section on Understanding Dyslexia in the introduction for the definition of dyslexia used in diagnosing the probands, which was also used for diagnosing dyslexia in the adolescents and young adults in the current study (research question 4).

Education level for the young adult participants who did (dyslexia group) or did not (control group) meet the criteria for dyslexia ($N$ = 81) included 47.5% ($n$ = 37) with less than high school, 11.1% ($n$ = 9) with high school graduation, 21% ($n$ = 17) with community college or vocational school education, and 8.6% ($n$ = 7) with a college degree. Education level was not reported for 11.8% ($n$ = 11). There were 38 males and 43 females. Ethnicity of family of participants included 2.5% Asian American. 3.7% African American, 86.4% Caucasian American, 2.5% Hispanic, and 4.9% Other. Of all the young adult participants, 18.5% of participants were siblings of the probands who qualified the family for participation; other participants were paternal cousins (4.9%) or maternal cousins (17.3%), and 59.3% had other extended family relationships to the probands.

### Measures of Working Memory Phenotypes[1]

**Verbal comprehension index—**Wechsler Adult Intelligence Scale (WAIS-R) Verbal Comprehension subtests (Information, Similarities, Vocabulary, and Comprehension subtests) (Wechsler, 1981) were given. The subtests, respectively, required the examinee to

[1]Measures were nationally standardized normed tests or researcher-designed measures at the time the data were collected during the 11-year family genetics study. Currently there are more recent nationally normed measures of many of the same reading and writing achievement measures and working memory components which can be used in translating these findings into assessment practices (e.g., Mather, Roberts, Hammill, & Allen, 2008; Wolf & Denckla, 2005) and new editions of the ones available at the time of the original data collection or in the process of being developed (e.g., WJ IV and WIAT 4).

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use oral language to (a) provide information about the world, (b) explain what two items have in common, (c) define words, or (d) answer questions to show comprehension of the everyday world. Reliability coefficients range from .91 to .95. The Index Score is thus a measures of using oral language—words, phrases, and syntax—to express thinking (Niedo et al., 2014).

**Phonological word coding—**The Comprehensive Test of Phonological Processing (CTOPP) (Wagner, Torgesen, & Rashotte, 1999) Nonword Repetition requires listening to taped spoken nonwords without meaning (i.e., pseudowords) of an increasing number of syllables and then repeating them. Raw scores were converted to standard scores for age ($M = 100$, $SD = 15$). According to the test manual, reliability is .80.

**Orthographic coding—**Expressive Coding (Berninger et al., 2006) requires viewing written pseudowords for one second, then closing eyes, and finally opening eyes to answer questions about the viewed word by writing a whole word, a single letter, or letter group. Correct answers do not require that the word be phonologically decoded because the letter or letters to be stored and produced either correspond to multiple, alternative sounds or to no sound, and if decoded would result in pronounced word with multiple spellings. Rather, correct answers require attention to and memory for the letter or letter sequences in the originally displayed written words. For example, the person being assessed sees a pseudoword (e.g., *wirf*) and has to decide, after it is no longer displayed, whether the next letter string matches it exactly (e.g., *werf* or *wirf*), a given letter was in it (e.g., *i* or *e*), or a given letter group was in it in exactly the same order (e.g., *ri* or *ir*), and then write the whole word, a single letter, or letter group, respectively. Research norms for raw scores were used because no published age or grade norms were available for this measure at the age or grade levels of the current study. Test-retest reliability for these measures in an intervention research study with younger students was .76.

**Morphological coding—**Comes From (Nagy, Berninger, & Abbott, 2006) was given that requires reading and listening to word pairs pronounced by the examiner. The task was to decide if the second word comes from (is related in meaning to) the first word. For example, one had to decide whether *corner* comes from *corn* (no), and whether *builder* comes from *build* (yes). Research norms for raw scores were used because no published age or grade norms were available for the age or grade range in the current study. Test-retest reliability for intervention studies with younger students in the research sample was .62.

**Syntactic coding—**The Clinical Evaluation of Language Fundamentals—Third Edition (CELF 3) Sentence Formulation subtest (Semel, Wiig, & Secord, 1995) was given. Three words were provided and the task was to construct an oral grammatically acceptable sentence. Raw scores were converted to scaled scores with a mean of 10 and standard score of 3 for age. According to the test manual, reliability reported in the test manual is .71.

**Phonological loop—**The Rapid Automatized Naming of alphanumeric stimuli (RAN) requires the oral naming of rows of a constant category (letters), that is, rapidly coordinating two codes—orthographic (letter) and phonological (word-level name) codes in time. The prepublication version from the Wolf Lab was used. Research norms were used for raw

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scores because no age or grade norms were available at time of data collection for the age or grade range in the current study[1]. Test-retest reliability for an intervention study with younger students in the research sample was .65.

**Orthographic loop—**The Alphabet 15 task is to write the alphabet from memory as quickly as possible in alphabetic order so that others can recognize the letters. The score is the number of legible letters in correct alphabetic order in the first 15 seconds (for review of evidence for this measure based on research over two decades, see Berninger & Richards, 2010). Raw scores were converted to *z* scores ($M = 0$, $SD = 1$) using research norms. Interrater reliability in programmatic research using this measure is .97.

**Selective focused attention—**Delis Kaplan Color Word Form Inhibition (D-KEFS) Delis, Kaplan, & Kramer, 2001) is based on the classic Stroop task. The child is asked to read orally a color word in black and then name the ink color for a written word in which the color of the ink conflicts with the color name of the word (e.g., red written in green ink). The difference in time for reading the words in black and naming the color of the ink that conflicts with the name of the color word is an index of ability to inhibit irrelevant information and focus on relevant information. Raw scores were converted to scaled scores for age ($M = 10$, $SD = 3$). Reliability reported in the test manual is .62.

Rapid Automatic Switching (RAS) was given as an indicator of switching attention as the category of visual stimuli to be named alternates between letters and numbers. The prepublication version of the RAS from Wolf's Tufts University research group and raw scores were used because no age or grade norms were available at the time of data collection[1]. Test-retest reliability for an intervention study with younger students in the research sample was .81.

Verbal Fluency Letters subtest of the Delis–Kaplan Executive Function System (D-KEFS) (Delis, Kaplan, & Kramer, 2001). The task is to supply as many words as possible that begin with a designated letter. Repetitions, for which scaled scores, but no reliability is available, were scored and interpreted as an index of self-monitoring during sustained searching, finding, and retrieving written words. Repetition of the same word indicates that the individual is not self-monitoring what was already said.

## Measures for Reading and Writing Outcomes [1]

**Oral reading of real words—accuracy and rate—**The Word Identification subtest of the Woodcock Reading Mastery Test–Revised (Woodcock, 1987) was used to assess accuracy of oral reading of single words on a list without any sentence context clues. Raw scores were converted to standard scores for age ($M = 100$, $SD = 15$). According to the test manual, average reliability is .97. The TOWRE Sight Word Efficiency: Form A (Torgesen, Wagner, & Rashotte, 1999) requires speeded oral reading of a list of single real words, with a 45-sec limit. Raw scores were converted to standard scores for age ($M = 100$, $SD = 10$). According to the test manual, the average reliability is .91.

**Oral reading of pseudowords—accuracy and rate—**The Word Attack subtest of the Woodcock Reading Mastery Test–Revised (WRMT-R) (Woodcock, 1987) was used to

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assess accuracy of reading pseudowords (made-up nonsense words with real English sounds but no meaning) on a list, that is, phonological decoding. Raw scores were converted to standard scores for age ($M$ = 100, $SD$ = 15). According to the test manual, average reliability is .87. The Test of Phonemic Decoding Efficiency (Torgesen et al., 1999) was used to assess rate of phonological decoding of pronounceable pseudowords without meaning with a 45-sec limit. Raw scores were converted to standard scores for age ($M$ = 100, $SD$ = 15). According to the test manual, average reliability is .90.

**Reading comprehension—**The Passage Comprehension subtest of the Woodcock–Johnson Psycho-Educational Battery–Revised (Woodcock, & Johnson, 1990), which uses a cloze procedure, was given. The task is to read a passage and supply the missing word that makes sense in the context of the text. The WJ-R Passage Comprehension subtest has a reliability coefficient of .90.

**Dictated spelling—**The Wechsler Individual Achievement Test, Second Edition (WIAT II) Spelling subtest (Wechsler, 2001) and The Wide Range Achievement Tests, Third Edition (WRAT-3) Spelling subtest (Wilkinson, 1993) were used to assess spelling ability. The examiner pronounces a word, uses it in a sentence, and then pronounces the word again. The task on both tests is to spell the dictated real word in writing. Scores for number of correctly spelled words were converted to standard scores for age ($M$ = 100, $SD$ = 15). For WIAT-II Spelling the reliability reported in the test manual is .94 and for WRAT-3 Spelling subtest the reliability reported in the test manual is 96.

**Word choice—**Word Choice test is an adaptation of Olson et al. (Olson, Datta, Gayan, & DeFries, 1999; Olson, Forsberg, Wise, & Rack, 1994), in which students selected the correctly spelled word among three phonological equivalents (pseudohomonyms, which when pronounced sound the same as the correctly spelled real word). Unlike the dictated spelling measures, handwriting is not required to reproduce the correct spelling. Research norms for raw scores were used.[1]

### Data Analyses

To address the first research question, the summary descriptive statistics were examined for each of the predictor phenotypes and each of the reading and writing outcome phenotypes (see Table 1). To address the second research question, Pearson product moment correlations were computed between each of the predictor and outcome phenotypes. A summary table with all the values is available upon request from the first or second author. For those that were statistically significant at $p \leq .05$, the predictor was entered into the corresponding multiple regression (see Table 2). To address, the third research question, those correlated predictors that explained unique variance in a reading or writing outcome beyond shared variance with the other correlated predictors have a superscript for the measure used to measure them (see Table 2). To address the fourth research question, separate ANOVAs were performed for each measure in Table 3 to compare the group of adolescent and young adults meeting the research criteria for dyslexia and the control group of adolescent and young adults not meeting the research criteria for dyslexia. Of interest was whether the groups, both identified in a sample of participants at risk for dyslexia based on multi-generational family history, showed significant differences in means for Verbal Comprehension Index, each working memory predictor, and each reading or writing outcome during adolescence and young adulthood.

## Results

### First Research Question

**Verbal comprehension and word reading and spelling achievement—**Means and standard deviations for each of the measures in the total sample of adolescents and young adults are summarized first in Table 1 for Verbal Comprehension and each of the reading and writing outcomes because these measures were used in identifying the probands who qualified the families. Verbal Comprehension Index and Passage (Reading) Comprehension fell on average above the mean and within the upper limits of the average range. All the word-level reading scores for accuracy and rate of oral reading of real words and pseudowords fell on average slightly below the mean but within the average range. All three spelling measures (two for spelling dictated words in handwriting and one for choosing the correctly spelled word among foils which when pronounced sound like real words) were on average in the average range but surprisingly above the population mean. Reading comprehension and oral language syntax were on average in the average range but above the population mean. Thus, family history of dyslexia alone will not identify the adolescents and young adults with dyslexia.

**Working memory phenotypes—**For the whole sample, all working memory phenotypes, which are summarized next in Table 1, fell on average in the average range, but either above the population mean (orthographic coding, orthographic loop—rapid automatic letter writing, phonological loop—rapid automatic letter naming, switching attention—rapid automatic switching in naming letters or numerals) or below the population mean (focused attention and self-monitoring—repetitions during sustained word finding). Oral syntax construction and morphological coding fell on average above the population mean but in the average range. However, phonological coding on nonword repetition was, on average, in the low average range and the lowest of all the measures, consistent with the genetic basis of phonological coding in dyslexia (Wijsman et al., 2000). Some phenotypes such as phonological coding may identify signs of dyslexia in individuals whose reading and writing achievement may mask the working memory struggles they face when reading and writing on written assignments or exams or tasks in the world of work. These working memory struggles constitute an invisible disability inside the mind unlike visible disabilities related to impaired sensory functions (vision or hearing) or gross or fine motor functions (e.g., use of limbs or hands or speech). However, these working memory phenotypes may be heterogeneous and not identifiable just on basis of group means in research. Rather individual differences in the working memory phenotypes associated with dyslexia need to be identified through assessment rather than though family history alone.

### Second Research Question

A table with all correlations between all phenotype measures (working memory components and reading and writing outcomes) is available from the first or second author. However,



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working memory phenotypes that were statistically correlated with reading and writing outcomes at $p \leq .05$ or less are summarized in Table 2 for each of the relevant specific reading or writing outcomes. The number of significant correlations that explain some but not all the variance in the reading and writing outcomes provides further evidence of the heterogeneity of the working memory phenotypes.

## Third Research Question

Table 2 summarizes the results of the multiple regressions used to identify which correlated predictors contributed uniquely over and beyond shared variance with other correlated predictors to each of the reading and writing outcomes. As shown in Table 2, with simultaneous correlated predictors of verbal comprehension, phonological coding, orthographic coding, morphological coding, phonological loop, orthographic loop, and switching attention, only orthographic coding explained unique variance in accuracy of orally reading real words. With simultaneous correlated predictors of phonological coding, orthographic coding, morphological coding, phonological loop, focused attention and switching attention only phonological coding explained unique variance in accuracy of orally reading pseudowords. With simultaneous correlated predictors of verbal comprehension, orthographic coding, morphological coding, phonological loop, orthographic loop, and switching attention, only phonological loop explained unique variance in rate of orally reading real words. With simultaneous correlated predictors of verbal comprehension, phonological coding, orthographic coding, morphological coding, phonological loop, focused attention, and switching attention, only switching attention explained unique variance in rate of orally reading of pseudowords.

With the simultaneous correlated predictors of verbal comprehension, phonological coding, orthographic coding, morphological coding, phonological loop, and orthographic loop as simultaneous predictors, only phonological coding, orthographic coding, and orthographic loop explained unique variance in the first measure of dictated spelling. With the same simultaneous correlated predictors, only orthographic coding, morphological coding, phonological loop, and orthographic loop explained unique variance in the second measure of dictated spelling. Common to both measures of dictated spelling was the unique contribution of orthographic coding and orthographic loop. Only morphological coding was significantly correlated with word choice and explained unique variance in word choice (choosing correctly spelled words); word-choice is considered a measure of word-specific spelling that underlies both silent word reading and written spelling of words. With the simultaneous correlated predictors of verbal comprehension, orthographic coding, morphological coding, and syntactic coding, only verbal comprehension and syntactic coding explained unique variance in reading comprehension. Overall, these findings in Table 2 provide additional evidence of the heterogeneity of phenotype expression in adolescents and young adults in families with multi-generational history of dyslexia.

## Fourth Research Question

Of the 81 adolescents and young adults in the family sample at risk for dyslexia, 31 (38%) met the same evidence-based criteria for dyslexia as did the younger children who qualified the family for participation, but 50 (62%) did not. As shown in Table 3, those who met the

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research criteria for dyslexia scored, on average, significantly higher in Verbal Comprehension (above average range) than those who did not meet criteria for dyslexia (average range and above the population mean). This finding reinforces that dyslexia is a *specific* learning disability affecting word reading and spelling (written language); individuals may have relative strengths in using oral language to explain thinking and may even score higher in this ability than those without dyslexia.

As also shown in Table 3, main effects for differences between groups with and without dyslexia were significant for word-level measures of accuracy and rate of orally reading real words on lists and pseudowords and of spelling (two dictated written spelling and one choice of correct spelling). No significant differences were found between groups with and without dyslexia on measures of oral language, or reading comprehension requiring syntax level production or processing. The differences between groups with and without dyslexia in the adolescents and young adults were consistent with the definition of dyslexia used with younger children during early and middle childhood and observed in their parents. That is, dyslexia—impaired accuracy and rate of oral reading of real words and pseudowords and written spelling—can be identified in adolescents and young adults.

Although measures of these word reading and spelling had been used in assigning adolescents and young adults to diagnostic groups, measures of working memory phenotypes had not. As shown in Table 3, the working memory phenotypes that differentiated adolescents and young adults with and without dyslexia in the current study included phonological coding (CTOPP nonword repetition), orthographic coding (Expressive Coding—whole words, single letters, and letter groups), phonological loop (RAN for letters), focused attention (Inhibition on D-KEFS Color Word Form Inhibition), switching attention (RAS for letters and numbers), and morphological coding (Comes From). In all cases, those with dyslexia scored more poorly, showing that these working memory phenotype impairments associated with dyslexia occur at the adolescent and young adult developmental levels. No significant differences were observed on orthographic loop (rapid automatic letter writing) or self-monitoring (repetitions during word finding) in this sample of adolescents and young adults. Of special interest, only the group with dyslexia scored in the low average range on phonological coding, showing that even in adolescents and young adults this phenotype may be impaired, consistent with what had been found for the younger children and the older adults (see Introduction). However, examination of the working memory phenotypes in individual profiles for group with dyslexia showed intra-individual and inter-individual heterogeneity, as was also the case with the younger children and older adults (see Introduction).

## Discussion

### Applications to Assessment of Adolescents and Young Adults with Dyslexia

Gregg and Nelson (2012) conducted a meta-analysis of how assessment information was used to justify extended time as an accommodation for high school and college students with SLDs. They found considerable variation in practices, frequent failure to justify accommodations based on assessment evidence, and nearly exclusive use of only intellectual functioning and academic achievement measures. Mapou and the American Academy of

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Clinical Neuropsychology (2009) made a compelling case that a lack of consensus in defining SLDs, especially for adolescents and young adults, is problematic; likewise, basing accommodations for young adults on research conducted with children, without evidence for doing so, is not justified. Moreover, although SLDs are the most common disabilities reported among college students, accommodations are often denied if the SLD was not identified during the school age years. The American Disabilities Act recognizes SLDs as one kind of disability, but does not provide specific operational procedures for defining SLDs. Evidence-based diagnosis of SLDs is not the same as eligibility criteria for special education services K to 12, which vary widely from state to state and even within state in implementation. So if dyslexia was not diagnosed earlier in schooling, young adults do not qualify for accommodations even if as adolescents and adults they meet research criteria for dyslexia on evidence-based assessment. Such assessment practices do not seem fair or sensible or consistent with the spirit of the Americans with Disabilities legislation.

The current study provides evidence relevant to improving assessment of adolescents and young adults. Family history of dyslexia alone does not predict adolescent and young adult outcomes. Adolescents and young adults from families with multigenerational history of dyslexia benefit from individual assessment to determine their profile of relative strengths in working memory components and reading and writing skills as well as current Verbal Comprehension Index. The relationships between the working memory predictors and reading and writing outcomes showed unique findings for different reading and writing outcomes; and inter-individual and intra-individual differences were observed in participant profiles across phenotypes. Results show that for adolescents and young adults, the phenotypes are heterogeneous. Findings support including all the reading and writing achievement and working memory phenotype measures used in the current study in an assessment battery for adolescents and young adults with family history of reading and writing problems.

For those who meet criteria for dyslexia, the word reading and spelling and working memory phenotypes on which they show impairments can be used to recommend accommodations individually tailored to the assessed individual. The current research results show that it is unlikely that one size fits all for accommodations in adolescents and young adults with dyslexia. For example, if an adolescent or young adult is impaired in rate of oral reading of real words or silent reading of real words (not assessed in the current study) or rapid automatic naming (RAN), then additional time on tests requiring reading is probably warranted. Or, if the adolescent or young adult is impaired in the orthographic loop for handwriting legibility and automaticity, then use of a scribe or technology for recording oral lectures for later transcription by the student is probably warranted. Alternatively, if spelling is also significantly impaired in addition to handwriting, then accommodation alone may not be sufficient. Spell checks flag possible spellings, but the computer user has to recognize and select the correct spelling, which is difficult for some with dyslexia. If both handwriting automaticity and spelling are impaired, then probably not only accommodations but also explicit instruction in touch typing with computer keyboard and spelling is needed.

However, others at risk based on family history may not show signs of dyslexia. Yet others may have history and current findings documenting reading comprehension problems rather

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than word reading and spelling problems (e.g., Miller et al., 2013). Collectively, the results support use of multiple measures in an evidence-based assessment battery for dyslexia or other specific learning disabilities in adolescents and young adults who may exhibit some diversity in their current learning profiles. See Berninger and Richards (2015) and Wolf and Berninger (2015) for recent research showing that dyslexia is not the only specific learning disability. For example, some may have dysgraphia (impaired handwriting) only, or both dyslexia and dysgraphia, or oral and written language learning disability (OWL LD) impairing listening and reading comprehension and oral and written language expression.

## Applications to Instruction for Adolescents and Young Adults with Dyslexia

For adolescents and young adults with dyslexia and other SLDs, more attention should be devoted to going beyond assessment for accommodations only to assessment for instruction. Unknown is the degree to which educational programs in elementary or middle school may have contributed to the academic achievement outcomes differentiating the two groups identified as either showing or not showing signs of dyslexia in the secondary grades or postsecondary years. However, twin studies have shown that reading disabilities may persist despite specialized instruction across the grades (e.g., Samuelson et al., 2008). Thus, adolescents and young adults with dyslexia may benefit from instruction geared to their current educational needs. For example, some individuals in the current study had impaired focused or switching attention or self-monitoring during sustained word finding. These individuals may benefit from explicit instruction in executive functions, which help them to focus, switch, and sustain attention to stay on task, self-monitor, override immediate demands in favor of longer-term goals, plan and organize activities, and persist to complete a task (see Dawson & Guare, 2004). Additionally, these executive skills are crucial to self-regulating affect, including monitoring one's emotions, in order to work more efficiently and effectively and interact with others in school learning environments.

Adolescents and young adults with dyslexia may also benefit from specialized instruction in reading and/or writing. Such instruction is increasingly offered in some high schools to promote access to postsecondary education, and in writing or literacy centers on college campuses to help with the writing requirement of postsecondary curriculum. For evidence-based, effective multi-component reading instruction for high school students, see Lovett, Lacerenza, Palma, and Frijters (2012). For evidence-based word study intervention for incoming college students who had scored poorly on the Verbal SAT and improved their spelling skills compared to a control group, see Atkinson et al. (2014). For the role of morphological awareness instruction in becoming a compensated dyslexic as an adult, see Law, Wouters, and Ghesquière (2015). For benefits of cross-age tutoring by college students with dyslexia for younger students at risk for dyslexia and the nature of effective instruction across age levels, see Juel (1996). For evidence-based writing instruction for high school students, see Cook and Bennett (2014). For evidence-based writing instruction for undergraduates in general, see MacArthur, Philippakos, and Ianetta (2014).

Creating developmental milestones in reading and writing for students with dyslexia from secondary to postsecondary levels might facilitate translation of assessment results to both accommodations and instruction. McNulty (2003) developed a checklist for dyslexia during

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various stages in life: Whereas childhood symptoms include problems with learning the alphabet, letter names, phonics, adolescent symptoms include slow reading speed, poor performance on timed tests, and difficulty with completing homework. Adult symptoms include difficulties with spontaneous spelling, slow reading or writing speed, and unusual reading or spelling errors.

## Limitations and Future Research Directions

Importantly, in interpreting the findings for phonological coding of words in working memory, genetics research has not explored recent psycholinguistic research on prosody (stress patterns in spoken words), but could do so in the future. Prosody is more important than segmental phonology in adolescent word reading (Anastasiou & Protopapas, 2014); and prosody contributes more than automatic word identification to silent reading comprehension (Paige, Rasinski, Magpuri-Lavelle, & Smith, 2014). The current study is limited by its focus on a single reading disability—dyslexia—in a sample with documented family history. Other etiologies for persisting learning problems or other kinds of specific learning disabilities were not considered. For example, Beidas, Khateb, and Breznitz (2013) studied compensated dyslexics and discovered that adult Hebrew readers with dyslexia exhibited better executive functions than the skilled readers. However, they assessed higher-order executive functions rather than the lower-order supervisory attention of working memory as in the current study (see Berninger, Swanson, & Griffin, 2014, for distinction between higher-order and lower-order executive functions). Such higher order executive functions may help compensate for weaknesses in lower order supervisory attention functions. Sabatini, Sawaki, Shore, and Scarborough (2010) studied 476 adults with low literacy achievement and found that word-level word identification and text-level comprehension accounted for their reading achievement. Latent profile analysis of economically and academically at-risk young adults enrolled in career or technical education programs showed that average and low achievers in literacy differed in their word reading skills and processing speed, but not their language comprehension or working memory skills (Mellard, Woods, & Lee, 2014). Birch and Chase (2004) compared compensated and noncompensated college students with dyslexia on visual and language processing deficits. Thus, evidence-based models for assessing literacy related phenotypes in adolescents and young adults should take into account the various kinds of learning problems that occur, including but not restricted to dyslexia. Assessment batteries will need to include multiple measures tailored to the case at hand.

Other limitations of the current study include lack of consideration of social emotional and affective factors in adolescents and young adults with SLDs, inclusion of only adolescents and adults at risk by multi-generational family history, and investigation of only assessment findings. However, other research has addressed these issues (e.g., Gerber, Ginsberg, & Reift, 1992; Stack-Cutler, Parrila, Jokisaari, & Nurmi, 2013), which merit further research. Future research should also focus on other handicapping conditions affecting reading and writing in adolescents and young adults such as attention deficit disorder (Zuckerman, Lee, Odom, Solomon & Sills, 2013), mild head injuries (Beers, Goldstein, & Katz, 1994), and concussions (Alosco, Fedor, & Gunstad, 2014; Collins et al., 1999; Griffin, 2015; Covassin, Elbin, McAllister, & Whalen, 2014; Hunt, McCamey, & Beisner, 2010; Solomon & Haase,

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2008). Future research should also address linking assessment to instruction for a variety of conditions affecting learning in adolescents and young adults.

Research is also needed on reading and writing issues for adolescents and young adults who grew up or are living in poverty (e.g., Berliner, 2012, 2013; Duncan & Mumane, 2011; Morphy, Graham, & Rigby-Wills, 2013; Reardon, in press). Now with the growing emphasis on access to higher education for students who come from low income backgrounds, research should consider both the nutritional and social nurturing needs these students may continue to have during adolescence and young adulthood (Jensen, 2009; Luby et al., 2013).

## Conclusions

Evidence-based assessment during the secondary and postsecondary grades has different purposes than preventing reading and writing problems in the early grades, planning appropriate educational programming for persisting written language problems during the upper elementary and middle school grades, or qualifying individuals for special education. For example, it is often yoked to meeting standards and graduation requirements, gaining entrance to postsecondary education, or passing professional credentialing exams. Accommodations issues often focus on more time for taking a test. For those who are students, accommodations for instruction (e.g., a note taker during lectures or use of technology tools) may be an issue. In some cases, the need for accommodations in the work place after transition from schooling becomes an issue. Yet, we lack a systematic body of evidence for appropriate assessment for accommodations, instruction, assessment-accommodation links, or assessment-instruction links for a variety of biological disabilities and environmental risk factors. Family genetics studies focused on heterogeneity of phenotypes during adolescence and young adulthood have potential for contributing, along with other kinds of research, to this broader effort to support access to and success in postsecondary education and the work world for all adolescents and young adults.

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**Table 1**

Descriptive Statistics (Means and Standard Deviations for Each Phenotype Measure in Methods)

| Measure | M | SD |
|---|---|---|
| ***WAIS-III*** **Verbal Comprehension Index** | 107.38 | 11.78 |
| **Working Memory Predictors** | | |
| *Phonological Coding CTOPP Nonword Repetition* | 7.90 | 2.14 |
| *Orthographic Coding* UW Expressive Orthographic | 0.62 | 0.48 |
| *Morphological Coding UW Comes From* | 0.27 | 0.68 |
| Syntax Coding *CELF3 Formulated Sentences* | 10.84 | 2.72 |
| Phonological Loop *RAN Letters* | 0.04 | 0.99 |
| *Orthographic Loop Alphabet 15 seconds* | 0.09 | 0.74 |
| *Focused Attention D-KEFS Color Word Form Inhibition* | 9.26 | 2.81 |
| *Switching Attention RAS Letters and Numbers* | 0.15 | 1.08 |
| *Monitoring D-KEFS Repetitions Verbal Fluency Letters* | 9.58 | 2.75 |
| **Reading Outcomes** | | |
| *WRMT-R Letter and Word Identification* | 98.30 | 10.41 |
| *WRMT-R Word Attack* | 97.51 | 12.42 |
| *TOWRE Sight Word Efficiency* | 96.69 | 11.93 |
| *TOWRE Phonemic Decoding Efficiency* | 93.83 | 12.83 |
| *WJR Passage Comprehension* | 109.46 | 12.21 |
| **Spelling Outcomes** | | |
| *WIAT2 Spelling* | 103.48 | 12.34 |
| *WRAT-3 Spelling* | 100.41 | 11.19 |
| *UW Word Choice* | 0.52 | 0.17 |

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## Table 2

Multiple Regressions for Significant Working Memory Predictors of Specific Reading or Writing Outcomes. (See Table Notes for tests used and superscripts for significant unique predictors)

| Outcome | Adjusted $R^2$ | *F*(df) | *p* | Unique Predictors | *t* | *p* | β |
|---|---|---|---|---|---|---|---|
| **Oral Reading** | | | | | | | |
| Real Word Accuracy[a] | 0.35 | *F*(7,57)=5.34 | <.001 | Orthographic Coding[j] | 2.360 | .022 | .318 |
| | | | | Verbal Comprehension[h] | .680 | .499 | .086 |
| | | | | Phonological Coding | .917 | .364 | .106 |
| | | | | Morphological Coding | 1.040 | .301 | .130 |
| | | | | Phonological Loop | −1.150 | .257 | −.204 |
| | | | | Orthographic Loop | −.199 | .843 | −.023 |
| | | | | Switching Attention | −2.420 | .019 | −.370 |
| Pseudoword Accuracy[b] | 0.24 | *F*(7, 57)=3.57 | .003 | Phonological Coding[i] | 2.080 | .043 | .255 |
| | | | | Orthographic Coding | −.062 | .095 | −.009 |
| | | | | Morphological Coding | 1.790 | .221 | .080 |
| | | | | Phonological Loop | −2.240 | .080 | −.421 |
| | | | | Focused Attention | .684 | .086 | .497 |
| | | | | Switching Attention | .624 | .535 | .113 |
| Real Word Rate[c] | 0.36 | *F*(6,57)=6.41 | <.001 | Phonological Loop[m] | −3.370 | .001 | −.593 |
| | | | | Verbal Comprehension | 1.150 | .258 | .141 |
| | | | | Orthographic Coding | 0.035 | .972 | .005 |
| | | | | Morphological Coding | 1.680 | .100 | .206 |
| | | | | Orthographic Loop | .530 | .598 | .062 |
| | | | | Switching Attention | .615 | .541 | .105 |
| Pseudoword Rate[d] | 0.46 | *F*(7,58)=8.11 | <.001 | Switching Attention[p] | −2.420 | .019 | .370 |
| | | | | Verbal Comprehension | −.466 | .644 | −.052 |
| | | | | Phonological Coding | 1.830 | .074 | .189 |
| | | | | Orthographic Coding | 1.680 | .099 | .199 |
| | | | | Morphological Coding | 1.870 | .068 | .209 |
| | | | | Phonological Loop | −1.080 | .285 | −1.720 |
| | | | | Focused Attention | −.623 | .536 | −.370 |
| Reading Comprehension[e] | 0.54 | *F*(4,63)=19.14 | <.001 | Verbal Comprehension[h] | 7.060 | <.001 | .675 |
| | | | | Syntactic Coding[l] | 2.360 | .022 | .211 |
| | | | | Orthographic Coding | .340 | .735 | .031 |
| | | | | Morphological Coding | .200 | .842 | .019 |
| **Spelling Dictated Real Words**[f] | 0.52 | *F*(6,64)=12.67 | <.001 | Phonological Coding[i] | 2.620 | .011 | .239 |
| | | | | Orthographic Coding[j] | 5.520 | <.001 | .556 |
| | | | | Orthographic Loop[n] | 2.090 | .041 | .189 |
| | | | | Verbal Comprehension | −.489 | .626 | −.048 |

| Outcome | Adjusted $R^2$ | *F*(df) | *p* | Unique Predictors | *t* | *p* | β |
|---|---|---|---|---|---|---|---|
| | | | | Morphological Coding | 1.390 | .169 | .133 |
| | | | | Phonological Loop | .050 | .960 | .005 |
| **Spelling Dictated Real Words**[g] | 0.53 | *F*(8,57)= 9.14 | <.001 | Orthographic Coding[j] | 4.370 | <.001 | .498 |
| | | | | Morphological Coding[k] | 2.540 | .014 | .269 |
| | | | | Verbal Comprehension | −.849 | .399 | −.080 |
| | | | | Phonological Coding | 1.010 | .315 | .088 |
| | | | | Phonological Loop[m] | −2.056 | .044 | −.187 |
| | | | | Orthographic Loop[n] | 2.050 | .045 | .177 |
| **UW Word Choice**[r] | | | | Morphological Coding[k] | 2.040 | .045 | .246 |

Notes:

D-KEFS Color Word Form Inhibition[o] (focused attention)

D-KEFS Verbal Fluency Repetitions[q] (self-monitoring sustained attention)

Also see introduction, methods, and results sections.

[a]Outcomes: WRMT-R Word Identification

[b]Word Attack

[c]TOWRE Sight word

[d]Phonemic Decoding Efficiency

[e]WJ-R Passage Comprehension

[f]WIAT2 Spelling

[g]WRAT 3 Spelling.

[h]Predictors: Verbal Comprehension Index (WAIS-II)

[i]CTOPP nonword repetition (phonological coding)

[j]UW Orthographic Coding

[k]Comes From (morphological coding)

[l]CELF3 Sentence Formulation (syntactic coding)

[m]Wolf RAN letters (phonological loop)

[n]alphabet 15 (Orthographic Loop)

[p]Wolf RAS numbers and letters (switching attention)

[r]UW Word Choice.



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### Table 3

One-Way Between Subjects Analyses of Variance (ANOVAs) Yielding Significant Main Effects for Group (Dyslexic or Non-Dyslexic) and Associated Means (M) and Standards Deviations (SDs), F-values, Degrees of Freedom (df), and p-values

| Measure | *F*(df)= *p* | Dyslexic M (*SD*) | Non-Dyslexic M (*SD*) |
|---|---|---|---|
| **Verbal Comprehension Index** | 9.66 (1, 80)** | 112.29 (10.26) | 104.34 (11.72) |
| **Working Memory Phenotypes** | | | |
| CTOPP nonword | 4.30 (1,78)* | 7.29(1.99) | 8.29 (2.16) |
| Orthographic Coding | 5.02 (1, 71)* | 0.48 (0.52) | 0.73 (0.43) |
| Comes From | 4.14 (1,77)* | 0.08 (0.80) | 0.39 (0.57) |
| CELF3 Form Sentences | 1.08 (1,74) | 10.45 (2.67) | 11.11 (2.76) |
| Wolf RAN Letters | 10.14 (1,79)* | 0.47 (1.30) | −0.22 (0.62) |
| Alphabet 15 | 0.93 (1,71) | −0.01(0.63) | 0.16(0.81) |
| D-KEFS Inhibition | 4.78 (1,75)* | 8.42 (2.92) | 9.80 (2.63) |
| Wolf RAS Letters and Numerals | 7.26 (1,67)** | 0.53 (1.27) | −0.15 (0.79) |
| D-KEFS Verbal Fluency | 3.25 (1,75) | 8.90 (3.03) | 10.04(2.48) |
| **Oral Reading** | | | |
| Word Identification | 15.31 (1, 79)*** | 93.03 (11.00) | 101.63 (8.57) |
| TOWRE Sight Word | 9.72 (1,80)** | 91.71 (12.87) | 99.78 (10.27) |
| Word Attack | 25.71 (1,80)*** | 89.74 (12.07) | 102.32 (10.04) |
| TOWRE Phonemic | 32.72 (1, 80)*** | 85.06(11.85) | 99.26 (10.20) |
| **Spelling** | | | |
| WIAT 2 Spelling | 12.16 (1, 76)*** | 97.90 (13.00) | 107.24 (10.42) |
| WRAT 3 Spelling | 14.35 (1, 76)*** | 94.87 (13.17) | 103.84 (8.18) |
| UW Word Choice | 0.24 (1,69) | 0.51 (0.19) | 0.53 (0.15) |

*Note.* On RAN and RAS, a negative score is better because it is faster.

See Table Note for RAN and RAS.

*p< or =.05

**p< or =.01

***p< or =.001.