



Developmental Neuropsychology

Publication details, including instructions for authors and
subscription information:

<http://www.tandfonline.com/loi/hdvn20>

Letter Naming and Letter Writing Reversals in Children With Dyslexia: Momentary Inefficiency in the Phonological and Orthographic Loops of Working Memory

Allison D. Brooks ^a , Virginia W. Berninger ^b & Robert D. Abbott ^b

^a Eunice Kennedy Shriver Center on Human Development &
Disability, University of Washington, Seattle, Washington, USA

^b Educational Psychology, University of Washington, Seattle,
Washington, USA

Version of record first published: 06 Oct 2011.

To cite this article: Allison D. Brooks, Virginia W. Berninger & Robert D. Abbott (2011): Letter Naming and Letter Writing Reversals in Children With Dyslexia: Momentary Inefficiency in the Phonological and Orthographic Loops of Working Memory, *Developmental Neuropsychology*, 36:7, 847-868

To link to this article: <http://dx.doi.org/10.1080/87565641.2011.606401>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.tandfonline.com/page/terms-and-conditions>

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Letter Naming and Letter Writing Reversals in Children With Dyslexia: Momentary Inefficiency in the Phonological and Orthographic Loops of Working Memory

Allison D. Brooks

Eunice Kennedy Shriver Center on Human Development & Disability, University of Washington, Seattle, Washington

Virginia W. Berninger and Robert D. Abbott

Educational Psychology, University of Washington, Seattle, Washington

Given mounting evidence for working memory impairments in dyslexia, letter reversals during rapid automatic letter naming (phonological loop) or rapid automatic letter writing (orthographic loop) may reflect momentary inefficiency of working memory. Few of the children, with or without dyslexia, in a multi-generational family genetics study, produced reversals, but those with dyslexia produced more than those without dyslexia. Working-memory component predictors (word storing and processing units, phonological and orthographic loops, and executive functions) in regressions differentiated children with dyslexia (average age 11) who did and did not make reversals, predicted the number of reversals on specific letter naming or letter writing tasks, and explained unique variance in reading and writing outcomes. Although reversals are not a hallmark defining feature of dyslexia, children who produce reversals may benefit from instruction designed to develop specific working memory components and their efficient coordination in time.

A sizable body of research has established evidence for a phonological core deficit in dyslexia (Morris et al., 1998) and for a reading fluency deficit in dyslexia (Breznitz, 2006). Moreover, a persisting spelling deficit occurs in dyslexia (Berninger, Nielsen, Abbott, Wijnsman, & Raskind, 2008a). Structural equation modeling supported a phonological core deficit in a working-memory architecture for both the reading and spelling deficits of dyslexia (Berninger, Abbott, Thomson, et al., 2006). This model is consistent with earlier evidence for both phonological and working memory impairment in dyslexia (Swanson & Siegel, 2001) and results of cross-cultural twin studies that verbal working memory and phonological deficits in the preschoolers predict future dyslexia during the school years (e.g., Byrne et al., 2002). This working memory architecture with a phonological core is best understood in the context of recent developments in working memory research.

Grants P50 33812 and HD 25858 from the National Institute of Child Health and Human Development (NICHD) supported this research.

Correspondence should be addressed to Allison D. Brooks, FAS-DPN, Center on Human Development & Disability, CD-260, Box 357920, University of Washington, Seattle, WA 98195. E-mail: brooksa@u.washington.edu or Virginia W. Berninger at vwb@u.washington.edu

Baddeley and colleagues (e.g., Hitch & Baddeley, 1976) originally proposed a model of working memory that consisted of a phonological or visual–spatial storage unit, an articulatory loop for maintaining information in the temporary storage unit, and a central executive. According to Baddeley (2002), the research stimulated by that early model led to an evolution of the model. Working memory is now thought to have other kinds of storage, including an *episodic buffer for storing and processing novel stimuli* encountered in the environment.

The *articulatory loop* is now thought to be a *time-sensitive phonological loop* (Kail, 1984). This phonological loop performs a variety of functions related to language learning (Baddeley, Gathercole, & Papagno, 1998), but individuals may vary in the speed or reliable accuracy of its functions for cross-code integration in working memory. Examples of phonological loop's cross-code functions include the following:

- a. coordinating analysis of the sound patterns in heard words in a phonological storage unit with oral-motor articulation codes for saying words, as in an aural pseudoword (nonword) repetition task or phoneme reversal task (Wagner, Torgesen, & Rashotte, 1999);
- b. coordinating familiar letters in an orthographic storage unit with oral-motor articulation codes for naming letters (rapid automatic naming of letters, RAN-letters) (Wolf, Bally, & Morris, 1986) or naming written words (oral reading of real words); and
- c. naming letters in unfamiliar written words in the episodic buffer for newly encountered stimuli (oral reading of pseudowords).

Thus, phonological loop guides the learning of new oral or written words through overt naming and its speed of function places constraints on how easily reading is acquired. Momentary breakdowns in efficiency of cross-code integration of phonological loop function could be upsetting to children learning to read. Reversals on a RAN letters task (miscalling *b* as *d* or *p* as *q*) may reflect such a momentary breakdown.

Moreover, mounting evidence shows working memory is not regulated by a single supervisory attention mechanism as originally thought (see Baddeley, 2002). Miyake and colleagues (2000) identified three separable executive functions in verbal working memory: inhibition, mental set shifting, and self-monitoring with updating. These executive functions may contribute to coordination in time of phonological codes with other codes (Baddeley et al., 1998), including motoric codes for output through mouth or hand. Another one is sustaining attention over time (Amtmann, Abbott, & Berninger, 2007). The results of the multi-generational family genetics study showed that a panel of lower-level executive functions was involved in regulating working memory: inhibition required to focus attention, as assessed with a Stroop task; flexibility required to switch attention, as assessed with rapid automatic switching (RAS) task (Wolf, 1986); sustaining attention over time, as assessed by RAN or RAS over rows (Amtmann et al., 2007); and self-monitoring, as assessed by repetitions on a verbal fluency task (for review of evidence, see Berninger, Abbott, Thomson, et al., 2006).

Thus, initial results of a multi-generational family genetics study supported these components in the working memory architecture—phonological and orthographic units for word storage and processing, a time-sensitive phonological loop, and panel of executive functions for supervisory attention—each of which has core phonological processes (Berninger, Abbott, Thomson, et al., 2006). The findings for two kinds of word storage and processing units are consistent with a growing body of research pointing to the importance of orthographic coding (storage and processing of written words and their constituent letters) (e.g., Badian, 1995; Sawyer, Kim, &

Lipa-Wade, 2000) in addition to phonological coding (storage and processing of spoken words and their constituent sounds). Functional brain imaging has confirmed that visual perception of nonlinguistic stimuli, which occurs in the occipital lobe, is not the same as orthographic processing of letters in written words, which requires integration of visual and language processes, that is, visible language, and occurs to a large extent in fusiform gyrus in posterior left inferior temporal lobe (Berninger & Richards, 2002; Richards et al., 2009a, 2009c). Frontal regions involved in executive functions may be temporally connected with fusiform, thus regulating orthographic functions (Richards & Berninger, 2002, 2008).

Research is also supporting the linking of orthographic codes alone (or orthographic codes corresponding to phonological codes) to the serial finger movements in letter formation and production (e.g., for review of evidence, see Berninger, 2009). This linkage of orthographic codes and finger writing codes occurs through a *time-sensitive orthographic loop* from a written word and its constituent letters or a letter alone and the sequential finger movements of hand that produce serial component strokes of written letters and letter sequences in words (Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008b). Impaired orthographic loop function, which is assessed through automatic legible letter writing in alphabetic order during the first 15 seconds of an alphabet writing task, underlies the writing problems of individuals with dyslexia (Berninger, Nielsen, et al., 2008b). This finding was consistent with orthographic coding and sequential finger planning contributing to letter writing and fluent text composing in normally developing writers (for review, see Berninger, 2009). For evidence of orthographic loop in a study of the advantage of forming letters in handwriting over touching letters on a keyboard in 2nd, 4th, and 6th graders (ages 7 to 11), see Berninger, Abbott, Augsburger, and Garcia (2009). Several brain imaging studies of children with and without dysgraphia at the end of a 5-year longitudinal study provided additional evidence for an orthographic loop in working memory for integrating internal orthographic codes with hand for producing letters (Richards, Berninger, Fayol, 2009; Richards et al., 2009b, 2011).

Moreover, evidence is mounting for a morphological word storage and oprocessing unit in working memory (for review, see Garcia, Abbott, & Berninger, 2010) and executive functions for coordinating interrelationships among the phonological, orthographic, and morphological relationships (e.g., Berninger, Raskind, Richards, Abbott, & Stock, 2008; Richards et al., 2006). Moreover, when a syntax storage and processing unit is added for accumulating words in working memory, this verbal working memory architecture may be the language learning mechanism that supports oral and written language learning (Berninger et al., 2010). Also, in keeping with Swanson, Howard, and Saez's (2006) demonstration that different components of working memory contribute to different aspects of reading disabilities, depending on which components are impaired, this model can be used for differential diagnosis of dysgraphia, dyslexia, and oral and written language learning disability (OWL LD also referred to as selective language impairment, SLD) (Berninger, 2007, 2008; Berninger, O'Donnell, & Holdnack, 2008; Berninger, Raskind, et al., 2008). These diagnoses should be made only in individuals whose developmental profile is consistently within the normal range across the five domains of development (cognitive, language, motor, social-emotional, and attention/executive function) despite selective impairments in components of verbal working memory supporting language learning and use (Silliman & Berninger, 2011). Variation in specific learning disabilities is consistent with the neuroanatomical findings of Leonard and colleagues showing heterogeneity of the brain bases of specific reading disabilities (see article by Leonard et al. in this special issue).

REFRAMING RESEARCH ON REVERSALS

Research has shown that reversals are neither the hallmark cause nor defining feature of dyslexia nor the result of a visual perceptual dysfunction (e.g., Vellutino, 1979). Likewise, reversals do not appear to be related to inability to attend to the left-right visual orientation cues of letters alone (Simner, 1984). In a family genetics study, Brooks (2003) confirmed Vellutino's findings that reversals are not related to visual perception dysfunction. Because researchers showed that typically developing children also make reversals in the early stages of learning to read and write and the overall incidence of reversals is typically very low in children with dyslexia, the importance of reversals in dyslexia for educational practice has been minimized.

Nevertheless, reversals may be one important clue in understanding symptoms of dyslexia as expressed in some individuals and when reversals do occur they may have treatment-relevant diagnostic significance. For example, Liberman and Shankweiler and colleagues called attention to the fact that letter reversals may reflect phonemic rather than visual confusions (e.g., Liberman, Shankweiler, Orlando, Harris, & Berti, 1971; Shankweiler & Liberman, 1972, 1978). Note that *b* and *d* rhyme as well as differ in orientation along the vertical axis for visual representation. This observation raises the possibility that the reversal results from a breakdown in the integration of letters and phonemes rather than from letter processing alone. However, in either case the reversal may reflect a momentary breakdown or inefficiency of the phonological loop function because the incorrect letter is named during cross-coding of letters and names.

Vogel (1973) pointed out that poor short-term memory for letters may underlie reversals. Since that earlier insight, researchers have begun to distinguish between short-term memory (initial brief coding of incoming stimuli from the external environment) and working memory—temporal storage and processing until goal-oriented task completed (see Goldman-Rakic, 1992). Frith and Vogel (1980) proposed a theory of the grammar of two-dimensional space that influences beginning reading and draws on *internal* scanning of letter forms in the mind's eye as well as positioning of letters in *external* space. This theory raises another intriguing possibility that reversals result from a breakdown in the integration of internal letter codes in internal working memory with motoric output to the external environment via hand as when writing. However, the theory also suggests that a breakdown could occur in the integration of internal codes letter codes in memory and motoric output to the external environment either via mouth as when phonological loop names letters or via the hand as when the orthographic loop writes letters. Both hand and mouth are motor output end organs of brain.

Historically, research on reversals has focused on reversals that occur while writing letters. The first author in her dissertation research (Brooks, 2003) proposed that reversals during oral naming may also reveal instructionally relevant information about processing inefficiencies of children with dyslexia who make reversals. Of interest was whether reversals might occur in oral naming as well as written letter production. For example, rapid automatic naming of letters is one of the best predictors of response to reading instruction (Compton, 2000) and reading development (Manis, Seidenberg, & Doi, 1999). Thus, reversals, both by mouth and hand, may reflect momentary breakdowns in working memory while reading, as reflected in RAN reversals, or momentary breakdowns in working memory while handwriting, as reflected in alphabet letter writing reversals.

Although research has dismissed the importance of reversals in dyslexia, clinical and teaching experience shows that reversals continue to be of concern to students with dyslexia who make them. Also, their teachers ask how to teach reading and writing in a way to overcome reversals

in students who make reversals beyond age 9 when normally developing readers and writers stop making occasional reversals. Despite their low incidence, reversals are salient in the literacy experiences of some individuals with dyslexia, both before and after they become compensated readers and writers. Kahneman and Tversky (1972) showed that from a mathematical perspective low incidence events may be perceptually salient to the perceiver.

THEORY-DRIVEN HYPOTHESES AND TESTED PREDICTIONS

Thus, the first author generated seven hypotheses, each with testable predictions, about reversals. These hypotheses and related predictions were grounded in previous theoretical advances by Swanson (1999) and Wolf (e.g., in her solo and collaborative studies described in Wolf, 2001). The goal was to understand the theoretical and practical significance of a low incidence behavioral sign, which has personal salience for affected individuals and may have theoretical significance for understanding why some individuals with dyslexia continue to persist in making occasional reversals from time to time but not constantly.

The theory underlying each of the seven testable hypotheses was that reversals reflect momentary breakdowns in one or more of the working memory loops when individuals with dyslexia name letters through their mouth (phonological loop) or write letters through their hand (orthographic loop). The momentary breakdowns reflect the vulnerability these individuals experience in whether the loops of their working memory for integrating internal codes with motor output channels function reliably and predictably. Even occasional breakdowns during oral reading or writing can be psychologically salient and upsetting to those so affected.

To begin with, we tested the first hypothesis that reversals of letter orientation would occur on both the phonological loop tasks (oral naming of letters on RAN or RAS) and orthographic loop tasks (writing alphabet letters from memory). Next we tested the second hypothesis that the incidence of reversal-errors would be low in all children, but higher in children with than children without dyslexia, thus accounting for the psychological salience of reversals for some children. We also tested the related third hypothesis that not all children with dyslexia would make reversals. The fourth hypothesis was that the working memory components would differentiate children who did and did not make reversals. The fifth hypothesis was that the working memory components predict who did and did not make reversals. The sixth hypothesis was that the working memory components predicted number of reversals on specific letter naming or letter writing tasks. The seventh hypothesis that indicators of verbal working memory components would explain unique variance in specific reading and writing outcomes for children with dyslexia who made reversals and thus have practical educational significance for them. Of interest was whether collectively the results provided converging evidence for reversals reflecting momentary breakdowns in working memory that impair its efficiency.

METHOD

Participants

Participants for this study of reversals were ascertained and if informed consent was obtained then assessed within a one-year period during a larger 11-year family genetics project of dyslexia.

Probands, who are the children who qualify their nuclear family members for participation in a family genetics study, and their extended family members (biological parents and siblings and extended family—aunts and uncles and cousins, grandparents, and even great grand parents) completed a battery of tests. For determining if children or adults met research criteria for dyslexia, we used the current definition of dyslexia recommended by the International Dyslexia Association (Lyon, Shaywitz, & Shaywitz, 2003). Dyslexia was defined as an unexpected difficulty of neurobiological origin in accuracy and/or rate of oral reading of single words or passages, decoding unknown words, or spelling. Dyslexia is both a reading and writing disorder in that affected individuals invariably have difficulty in learning to spell and spelling is often their persisting difficulty (Berninger, Nielsen, et al., 2008).

To be responsive to reviewers at a site visit who wanted to ensure that we did not include children whose reading problems were attributable to other neurogenetic disorders, only children whose Verbal Comprehension Factor was at least 90 ($-2/3$ standard deviations below the mean) or higher on the WISC-3 (Wechsler, 1991), which includes top 75% of population in oral language comprehension), were included as probands who qualified their multi-generational families for participation. Also one or more of the following reading or writing skills had to be below the population mean (and on average were about 1 to 1 1/3 *SDs* below the population mean on reading and writing achievement measures):

- WRMT-R (Woodcock Reading Mastery Test-Revised) Word Identification or Word Attack (Woodcock, 1987),
- TOWRE (Test of Word Reading Efficiency) Sight Word Reading Efficiency (real word reading rate) or Phonemic Reading Efficiency (pseudoword reading rate) (Torgesen, Wagner, & Rashotte, 1999),
- GORT 3 (Gray Oral Reading Test-Third Edition) Oral Reading Accuracy or Rate (Wiederholt & Bryant, 1992), and/or
- WRAT-3 (Wide Range Achievement Test, Third Edition) Spelling (Wilkinson, 1993) or WIAT II (Wechsler Individual Achievement Test-Second Edition) Spelling (The Psychological Corporation, 2001).

Children who met the same criteria for automatic letter writing below were also included so that we could evaluate comorbidity of dysgraphia with dyslexia.

- Automatic Alphabet Writing¹ (Berninger & Rutberg, 1992).

Children were included if they met these written language achievement criteria and their written language achievement was below the mean and was also at least 15 points below their Verbal Comprehension factor (oral language comprehension). Children with psychiatric disability or developmental history indicating maternal substance abuse or brain injury or disease were excluded as probands.

Attention deficit hyperactivity disorder (ADHD) was not a reason for exclusion, but with these ascertainment criteria, the comorbidity of dyslexia and ADHD (meeting sufficient indicators of impairment in self-regulation of attention and behavior to qualify for the full diagnosis) was low in this sample (about 4%). However, almost all children were impaired in one or more executive

¹This task is a prepublication version of the PAL Alphabet Writing Task (Berninger, 2001), which was revised in 2007 (Berninger, 2007).

functions for supervisory attention, which fall along a continuum; and impaired self-regulation of attention was related to their orthographic word storage and processing and phonological loop function in the larger sample (Thomson et al., 2005). In keeping with the recommendations of the reviewers, had we set the cut-off for Verbal Comprehension lower (e.g., $-1 \frac{1}{3} SD$) the comorbidity with ADHD and attention/behavioral problems associated with other neurogenetic disorders would probably have been higher.

Samples for testing hypothesis-generated predictions. For purposes of evaluating incidence of reversals related to the first three predictions, the child sample (ages 6–18, $N = 182$) in the current study included 76 probands with dyslexia (average age, 11 years, 6 months), 30 unaffected children (12 years, 5 months), and non-proband affected children (average age 12 years, 3 months). Automatic alphabet letter writing were available for 76 and RAN/RAS were available for 66 (see Table 1 note). For purposes of testing the fourth and fifth predictions, the reversal group included 40 children and the non-reversal group included 25 children for whom all the working memory component measures were available. Only the 40 children with dyslexia in the reversal group were included in the regressions to test the sixth and seventh predictions.

Defining and Assessing Reversals

Defining reversal errors on letter naming (phonological loop). Number of reversal errors was counted for each participant on the prepublication Rapid Automatic Naming Task (RAN letters or numbers) (Wolf et al., 1986) and Rapid Automatized Switching Task (RAS) (alternating Letters and Numbers) (Wolf, 1986) of the Wolf and Denckla (2004) RAN/RAS Test. These speeded tasks require oral naming of rows of only letters or digits (RAN) or a mixture of digits and letters (RAS). Test–retest reliability over a nine-month intervention was .65 for RAN and .81 for RAS (Berninger, Abbott, Thomson, & Raskind, 2001).

Defining reversal errors on letter writing (orthographic loop). Number of reversal errors was counted for each participant on each of the following measures: an Alphabet Writing Task¹ (Berninger & Rutberg, 1992, interrater reliability of .97, Berninger et al., 1997), the WRAT–3

TABLE 1
Incidence Question: Frequency and Percentage of Participants Making At Least One Reversal Error in One Letter Naming Task, Three Letter Writing Tasks, or Any of the Four Tasks^a

	<i>Number (and Percentage) of Participants Who Made Reversal Errors</i>					
	<i>N</i>	<i>Naming Task</i>	<i>Alphabet Writing Task</i>	<i>Dictated Spelling Tasks</i>	<i>Written Composition Task</i>	<i>Any of 4 Tasks</i>
Children						
Probands Affected	76	44/66 ^a (66.7%)	22 (28.9%)	23 (30%)	32 (42%)	59 (77.6%)
Nonproband Affected	76	34 (44.7%)	13 (17.1%)	16 (21%)	23 (30.3%)	44 (57.9%)
Nonproband Unaffected	30	10 (33.3%)	6 (20%)	4 (13%)	5 (16.7%)	15 (50%)

^aNote that of the 76 children with dyslexia, all had all the writing tasks available to inspect for letter writing reversals but only 66 of these children had the letter naming task scored in a way that permitted inspection for letter naming reversals.

Spelling Test (reliability coefficient of .96), the WIAT-II Spelling Test (reliability coefficient of .94), and the WIAT-II Written Expression subtest (reliability coefficient of .86). For the Alphabet task, participants wrote the alphabet from memory, as quickly and accurately as possible, using printed lower-case letters. The WRAT-3 and WIAT-II Spelling Tests required subjects to write letters and/or words from dictation, without time requirements. The WIAT-II Written Expression subtest required subjects to produce multiple types of written output, including words, sentences, paragraphs, and compositions; there was a time limit but most finish before that limit. For writing output tasks, the alphabet task was the only one for which participants were instructed to use only print and only lower-case letters, but typically children printed on the other writing task as well.

Procedure for determining incidence of reversal errors. A rater blind to affected status counted the number of reversal errors. *Reversal error* refers to the dislocation of a single letter or number on the horizontal or vertical axis or a combination of these. For example, displacement on the vertical axis results in a mirror-image reflection (e.g., b-d or p-q) whereas displacement on the horizontal axis yields an up-down inversion (b-p), and a combination may yield an error such as b-q, including a displacement of a letter tail (e.g., g/q). Consistent with Terepocki, Kruk, and Willows (2002), self-corrected letter reversals on both naming and writing tasks were counted as reversal errors. For naming output, reversal errors can only occur in letters or numbers in which the reversal is itself another number or letter (b, d, p, q, 9, 6, now referred to as “reversible-real” letters). After reversal errors were coded and scored for all participants, the percentage of participants who made reversals was calculated for the children, according to whether they were probands (affected children who qualified their families for participation), other children in the sample who met the same criteria for dyslexia as the probands, or unaffected children who did not meet the criteria for dyslexia.

Defining and Comparing Reversal and Nonreversal Groups

To form groups of children that did and did not make reversals, children were selected if they were between the ages of 9 years and 13 years, 11 months, and were in a grade between 4 and 8 at the time of testing, that is, past the age when reversals typically disappear. Only those children who made at least two reversal errors were selected for the reversal group ($n = 40$) whereas those who made no reversal errors (with no missing data) were included in the nonreversal group ($n = 25$).

The reversal and nonreversal groups did not differ on age, gender, or Verbal IQ. At the time of testing, the reversal group had a mean age of 11 years, 6 months ($SD = 15.35$) and the nonreversal group had a mean age of 11 years, 9 months ($SD = 15.14$). The reversal group (29 boys, 11 girls) had an average VIQ of 109.90 ($SD = 12.48$) and the nonreversal group (15 boys and 10 girls) had an average Verbal IQ of 109.72 ($SD = 10.18$). Ethnicity of the reversal group was 92.5% Caucasian, 2.5% African American, and 5% other (e.g. a combination). Ethnicity of the nonreversal group was 88% Caucasian, 4% Asian American, 4% African American, and 4% other.

Assessing Verbal Working Memory Components

The following measures were used to assess each of the verbal working memory components so that comparisons could be made between those with dyslexia who did and did not make reversals,

predict who did and did not make reversals, and predict number of reversals on letter naming and letter writing tasks.

Storage and processing of phonological words. The Woodcock Johnson–Revised (WJ–R; Woodcock & Johnson, 1990) Numbers Reversed subtest and the Comprehensive Test of Phonological Processing (CTOPP; Wagner et al., 1999) Phoneme Reversal subtest required storage and retrieval of spoken numerals or nonwords, respectively. The WJ–R Numbers Reversed subtest required participants to recall a sequence of digits in reverse order. The CTOPP Phoneme Reversal subtest (test–retest reliability coefficient = .79) required subjects to reverse the order of sounds in a made-up word to make a real word.

Storage and processing of orthographic words. On PAL Receptive Coding subtest (Berninger, 2001) (reliability coefficients range from .61 to .76 for grades 1 through 6), a whole word was exposed to the participant for a one-second duration, followed by exposure of a second stimulus, which was a whole word, a letter, or a letter cluster (two to three letters). The examinee had to decide if previous words contained all the letters, the single letter, or the letter cluster. These receptive tasks require coding of written words into working memory and subsequent analysis of letters in working memory.

PAL Word Choice subtest (reliability coefficients range from .66 to .89 for grades 1 through 6), which was a modification of Olson, Forsberg, Wise, and Rack (1994), presented examinees with groups of three words, one of which is spelled correctly and two that were spelled incorrectly but their pronunciations were phonological equivalents of a real word. Participants were asked to circle the real (correctly spelled) word in each group, as quickly as possible. This measure required access to long-term memory storage of precise word spellings for specific word pronunciations and meanings.

Central executive for supervisory attention. This construct was assessed with attention ratings and a rapid automatic switching (RAS) task. Attention scores were derived from a rating scale in which parents rated their children. Confirmatory factor analysis showed that this scale yielded reliable indicators of two components of attention—focused attention and goal-directed attention (Thomson et al., 2005). Ratings on specific items (indicators) related to each of the factors were used to assign each child or adult separate attention scores for focused attention and goal-directed attention, each of which has a genetic basis (Hsu, Wijsman, Berninger, Thomson, & Raskind, 2002).

Other central executive functions. The Delis-Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001) Color-Word Interference Test has test-retest reliability coefficients that range from .62 to .76. The Inhibition subtest is a Stroop measure of the time required to name rapidly the ink color of color words written in a different color of ink; this score reflects the ability to suppress irrelevant information (name of color word) and attend to relevant information (color of ink). It also yields an Inhibition/Switching score across the color-word forms in the task. The Verbal Fluency subtest from the *D-KEFS* has a letter fluency test (test–retest reliability coefficients ranging from .36 to .80) that required rapid generation within a time limit of spoken words that start with a particular letter/sound. Repetition errors on this task may signal problems in self-monitoring memory retrieval processes and updating working memory.

Motor planning measures. Two motor tasks were included that draw on both motor output skills and executive functions for planning for motor output. Oral-motor planning was assessed using a timed task that required repetition of the oral sequence PaTaKa on the Time-by-Count Test Measurement of Diadochokinetic Syllable Rate (Fletcher, 1978) for which no test–retest reliability was reported. The PAL (Berninger, 2001) timed Finger Succession subtest (test–retest reliability coefficients range from .87 to .89), an adaptation of Denckla (1973) and Wolff, Gunnoe, and Cohen (1983), which required touching the thumb to each finger in sequence while hands were held in air out of sight, was used to assess grapho-motor planning.

Predicting the Reading and Writing Skills in Reversal Group on the Basis of Working Memory Components

Measures of each of the following reading and writing outcomes were used to test the prediction that measures of working memory components would explain unique variance in the reading and writing outcomes in those with dyslexia who made reversals.

Accuracy of single real word reading and phonological decoding. The Woodcock Reading Mastery Test–Revised WRMT–R Word Identification (average reliability coefficient = .97) was used to assess accuracy of oral reading of single words. The WRMT–R Word Attack (average reliability coefficient = .87) was used to assess accuracy of phonological decoding, that is, oral reading of pseudowords, which are pronounced like real words but have no meaning.

Rate of single real word reading and phonological decoding. The Test of Word Reading Efficiency TOWRE (Torgesen et al., 1999) Sight Word Efficiency: Form A (test–retest reliability of .91), which required speeded oral reading of a list of single real words, with a 45-second time limit, was used to assess rate of real word reading. TOWRE Phonemic Decoding Efficiency: Form A (test–retest reliability of .98), which required speeded oral reading of a list of pseudowords, with a 45-second time limit, was used to assess rate of phonological decoding.

Handwriting. An alphabet task¹ required the examinee to print lowercase manuscript letters from memory in alphabetic order. Scoring took into account legibility and correct order of production within the first 15 seconds, total legibility, and total time. Interrater reliability for this task was .97 (Berninger et al., 1997).

Spelling. The Wechsler Individual Achievement Test–II (WIAT–II; The Psychological Corporation, 2002; reliability coefficient of .94) and the Wide Range Achievement Test–3 (WRAT–3; Wilkinson, 1993; reliability coefficient of .96) were used to assess spelling of dictated single words.

Written expression. The WIAT II Written Expression subtest (reliability coefficient of .86) was used to assess word fluency, sentence construction, and paragraph or essay composition.

RESULTS

Incidence of Reversals

Results in Table 1 are relevant to the first two predictions. In support of the first prediction, reversals were observed on letter naming as well as letter writing tasks. In support of the second prediction, although the overall incidence of reversals was low, when opportunity to reverse was possible, children with dyslexia, whether they were probands or not, had a higher incidence of reversals than did those without dyslexia. The one exception was affected and unaffected nonprobands on alphabet writing. See Table 1 for percentage on each of four tasks and totals across tasks. Overall, 77.6% of the probands with dyslexia and 57.7% of the non-probands with dyslexia and half the children without dyslexia made at least one reversal error on one or more of the tasks. Overall, significantly more children with dyslexia made reversal errors than did children without dyslexia, as confirmed by Fisher's Exact Test ($FI = 7.46$), $p < .005$. However, consistent with the third prediction, not all children made reversals.

Relationships of Working Memory Components to Reversals

Differentiating reversal and non-reversal groups on basis of working memory components. Results in Table 2 are relevant to the fourth prediction. Although the overall incidence of reversals was relatively low, the child reversal group had significantly lower scores than the non-reversal group on four measures of working memory components: The *Repetitions error score* on the D-KEFS Verbal Fluency task is an index of self-monitoring and updating working memory.

TABLE 2
Differences Between the Nonreversal and Reversal Groups on Working Memory Measures in Grades 4 to 8 ($n = 25$ in Nonreversal Group and $n = 40$ in Reversal Group)

Task	Mean	SD	SE	<i>t</i>	<i>df</i>	<i>p</i> (2-tailed)
Executive functions						
(D-KEFS repetition errors)						
Nonreversal group	8.20	2.35	.47	2.930	63	.005
Reversal group	6.43	2.40	.38			
Phonological coding						
(WJ-R numbers reversed)						
Nonreversal group	98.68	18.32	3.66	2.325	63	.023
Reversal group	88.55	16.29	2.58			
Phonological coding						
(CTOPP phoneme reversal)						
Nonreversal group	8.79	2.43	.50	2.130	61	.037
Reversal group	7.54	2.16	.35			
Orthographic coding						
(PAL word choice)						
Nonreversal group	.08	.46	.10	4.159	49	.001
Reversal group	-1.12	1.21	.21			

CTOPP = Comprehensive Test of Phonological Processing; D-KEFS = Delis-Kaplan Executive Function System; PAL = Process Assessment of the Learner; WJ-R = Woodcock Johnson-Revised.

TABLE 3
 Predicting Reversal or Nonreversal Group Membership Based on Single Working Memory Predictors^a
 (See Text for Significant Predictors in Multiple Regression.)

<i>Significant Single Predictors^a</i>	<i>Adjusted R²</i>	<i>Standardized Coefficient β</i>	<i>t</i>	<i>p</i>
PAL word choice	.246	-.511	-4.16	.001
DK-EFS Color word form inhibition/switching	.060	-.274	-2.25	.028
DK-EFS verbal fluency repetitions	.106	-.346	-2.93	.005
CTOPP Phoneme reversals	.054	-.263	-2.13	.037
WJ-R numbers reversed	.064	-.281	-2.325	.023

^aRegressions were not significant for PAL Receptive Coding, age in months, handedness, prorated Verbal IQ, inattention ratings, goal-related attention ratings, DK-EFS Color Word Form Inhibition, Verbal Fluency, Category Switching Switches, and Set Loss Errors, or attention deficit hyperactivity disorder (ADHD)—inattention, hyperactivity, or mixed diagnoses. CTOPP = Comprehensive Test of Phonological Processing; D-KEFS = Delis-Kaplan Executive Function System; PAL = Process Assessment of the Learner; WJ-R = Woodcock Johnson-Revised.

The Woodcock-Johnson-Revised (WJ-R) Numbers Reversed and CTOPP Phoneme Reversal subtests are indices of phonological coding (storage and processing of spoken words). PAL Word Choice is an index of orthographic coding (storage and processing of written words). The reversal and nonreversal groups with dyslexia differed in an executive function and phonological and orthographic storage and processing in working memory. The children with dyslexia who make occasional reversals may be the ones with multiple impaired working memory components, thus contributing to their occasional breakdowns in working memory efficiency.

Predicting reversal or non-reversal group membership from working memory components. Results in Table 3 are relevant to the fifth prediction. When only single measures were considered in separate analyses, five measures differentiated who did and did not make reversals. One was an indicator of orthographic coding (PAL Word Choice). Two were indicators of phonological coding (CTOPP Phonemes Reversal and WJ-R Numbers Reversed). Two were indicators of executive functions (D-KEFS Inhibition/Switching and Verbal Fluency Repetitions). Thus, results for the fifth tested prediction provide converging evidence for the results of the fourth tested prediction.

However, when all significant single predictors were entered simultaneously into the multiple regression, only an executive function (D-KEFS Inhibition/Switching) uniquely differentiated the group that did and the group that did not make reversals: Adjusted R^2 was .317, standardized coefficient β was -.310, $t = -2.27$, $p = .028$. However, eliminating *CTOPP phoneme reversal* that had the lowest p -value of the five significant single predictors, resulted in an adjusted $R^2 = .339$, $F(4, 49) = 7.28$, $p < .001$, and two unique predictors—orthographic coding and an executive function, respectively, which differentiated those who do and do not make reversals: PAL Word Choice ($\beta = -.293$, $t = -2.10$, $p = .04$), and DK-EFS Color Word Form Inhibition/Switching, ($\beta = -.303$, $t = -2.35$, $p = .023$). Thus, the converging evidence for the fourth and fifth predictions has to be qualified in that executive functions and orthographic word storage and processing were related to reversals—but a different executive function—flexibility in switching attention rather than self-monitoring of working memory and only when the phonological measure was omitted.

Predicting number of reversals on specific letter naming or letter writing tasks from working memory components. Results in Tables 4 to 6 are relevant to the sixth rediction. Only one single measure—oral motor planning—uniquely predicted the number of reversals during rapid letter naming (see Table 4); note that these two tasks share oral motor output through the mouth. To further explore the significance of oral motor planning for making reversals during rapid automatic naming of letters, which is relevant to construct validity (Shadish et al., 2002), a multiple regression based on this predictor and another indicator of RAN performance besides letter reversals (total time) was conducted. The multiple regression results showed that RAN total time did not contribute uniquely (standardized coefficient $\beta = .271$, $t = 2.19$, $p = .033$) and only PA TA KA contributed uniquely with Total Adjusted $R^2 = .117$. Thus, the serial organization of the phonological loop output rather than its speed per se may be contributing to the occasional reversals.

As shown in Table 5, three single measures uniquely explained the number of reversals in the first 15 seconds of writing the letters in the alphabet from memory: PAL Expressive Coding, which is an indicator of the orthographic loop (Berninger et al., 2008), the number of legible letters in correct alphabet order in the first 15 seconds, which is also an indicator of orthographic loop (Berninger et al., 2008), and repetitions during the Verbal Fluency task, which is an indicator of self monitoring and updating working memory (see Table 5).

However, when all significant single predictors were entered simultaneously into a multiple regression that accounted for significant variance in the number of reversals made during the

TABLE 4
Predicting Letter Reversals in Rapid Naming of Letters^a

Significant Single Predictors	Adjusted R^2	F	df	p	Standardized Coefficient β	t	p
PA TA KA	.085	6.58	1,60	.013	.317	2.57	.013

^aRegressions were not significant for DK-EFS Inhibition, Inhibition/Switching, or Verbal Fluency Repetitions, CTOPP phoneme reversal, or CTOPP nonword repetition. CTOPP = Comprehensive Test of Phonological Processing; D-KEFS = Delis-Kaplan Executive Function System.

TABLE 5
Predicting Letter Writing Reversals on Alphabet Writing^a (See Text for Dictated Spelling)

Significant Single Predictors	Adjusted R^2	Standardized Coefficient β	t	p
PAL expressive coding	.188	-.448	-3.92	.001
Alph 15 (automaticity in first 15 seconds) ^a	.100	-.338	-2.85	.006
DK-EFS verbal fluency repetitions	.106	-.346	-2.93	.005

^aRegressions were not significant for total accuracy or total time on alphabet task, PAL receptive coding, inattention ratings, goal attention ratings. DK-EFS Inhibition, Inhibition/Switching, and Category Switching/Switching, CTOPP phoneme reversal, WJ-R Numbers Revised, RAN letters, and PAL Finger Succession dominant. CTOPP = Comprehensive Test of Phonological Processing; D-KEFS = Delis-Kaplan Executive Function System; PAL = Process Assessment of the Learner; WJ-R = Woodcock Johnson-Revised.

TABLE 6
Predicting Letter Writing Reversals on Written Expression^a (See Text for Dictated Spelling)

Significant Single Predictors	Adjusted R^2	Standardized Coefficient β	t	p
WRAT-3 spelling	.067	-.286	-2.35	.022
PAL word choice	.076	-.308	-2.24	.030
CTOPP Phoneme reversals	.051	-.257	-2.06	.044
PAL expressive coding	.144	-.380	-3.18	.002

^aRegressions were not significant for Alph 15, alphabet task total accuracy or total time, WIAT II Spelling, PAL receptive coding, inattention or goal ratings, DK-EFS inhibition, inhibition/switching, or verbal fluency repetitions, WJ-R numbers reversed, WIAT II Written Expression standard score, CTOPP nonword repetition, RAN letter, or PAL finger succession dominant hand.

CTOPP = Comprehensive Test of Phonological Processing; D-KEFS = Delis-Kaplan Executive Function System; PAL = Process Assessment of the Learner; RAN = rapid automatic naming; WIAT II = Wechsler Individual Achievement Test—Second Edition; WJ-R = Woodcock Johnson-Revised; WRAT-3 = Wide Range Achievement Test, Third Edition.

alphabet task (adjusted $R^2 = .297$, $p = .001$), each still contributed uniquely to the outcome: PAL Expressive Coding (standardized coefficient $\beta = -.335$, $t = -2.96$, $p = .004$); automatic letter writing in the first 15 seconds (standardized coefficient $\beta = -.278$, $t = -2.59$, $p = .012$); and D-KEFS Verbal Fluency Repetitions (standardized coefficient $\beta = -.248$, $t = -2.207$, $p = .031$). Thus, integration of orthographic coding and letter formation through hand and executive functions are contributing uniquely to letter writing reversals.

No measures were significantly related to the number of reversals on dictated spelling. That was probably because on these measures there was little variation among children in the number of reversals produced.

As shown in Table 6, four single measures were each statistically related to the number of letter reversals during written expression: dictated spelling and word choice, indicators of orthographic coding; CTOPP phoneme reversal, an indicator of phonological coding; and PAL Expressive Coding, an indicator of the orthographic loop. However, when all significant single predictors were entered simultaneously, the multiple regression accounted for significant variance in written composition (adjusted $R^2 = .111$, $p = .013$) but none of these four variables contributed uniquely. However, PAL expressive coding had the largest standardized beta weight and lowest p -value and CTOPP phoneme reversal was a suppressor variable (correlation and beta weight had opposite signs). When the regression was repeated with just these two variables, PAL expressive coding contributed uniquely: adjusted $R^2 = .111$, standardized coefficient $\beta = -.306$, $t = -2.15$, $p = .036$. This result suggested that the orthographic loop contributed uniquely to the reversal errors on written composition.

However, when the nature of the task—naming or writing—and of the writing task—handwriting, spelling, or composing—was taken into account, the nature of which working memory component contributed uniquely tended to change. This pattern of results is consistent with a model in which the whole working memory architecture may be vulnerable in children who make reversals and which component shows momentary breakdowns is dependent on task at hand.

Predicting Reading and Writing Outcomes in Reversal Group

Results in Table 7 are relevant to the seventh prediction. A series of stepwise multiple regressions was conducted to determine which of two working memory components—coding (word

TABLE 7
Multiple Regression for Significant Working Memory Predictors of Reading and Writing Skills in 40 Children With Dyslexia in the Reversal Group (Coding = Word Storage and Processing)

<i>Independent Measure(s)</i>	<i>R² for the Multiple Regression</i>	<i>Dependent Measure</i>	<i>Standardized Coefficient β</i>	<i>t</i>	<i>p</i>
WRMT-R word identification (accurate reading of real words)	.526	Orthographic Coding ^a	.439	3.275	.003
		Phonological Coding ^b	.479	3.569	.001
WRMT-R word attack (accurate reading of pseudowords)	.478	Orthographic Coding ^a	.208	1.479	.150
		Phonological Coding ^b	.610	4.327	.001
TOWRE sight word efficiency (rate of reading real words)	.471	Orthographic Coding ^a	.384	2.519	.019
		Phonological Coding ^b	.355	2.321	.029
		Executive Function ^c	.368	2.511	.019
TOWRE Phonemic Reading Efficiency (rate of reading pseudowords)	.592	Phonological Coding ^b	.704	6.513	.001
		Executive Function ^c	.356	3.294	.002
WIAT II Spelling	.454	Orthographic Coding ^a	.541	3.782	.001
		Executive Function ^c	.335	2.343	.026
		WIAT II Spelling Accuracy (see Note) ^d	.463	2.127	.044

^aPAL word choice

^bCTOPP phoneme reversal

^cD-KEFS inhibition

^dThree other predictors did not contribute uniquely (phonological coding, orthographic coding, or phonological decoding—accuracy of reading pseudowords) probably because all of these contributed to the spelling that contributed uniquely to the written composition.

CTOPP = Comprehensive Test of Phonological Processing; D-KEFS = Delis-Kaplan Executive Function System; PAL = Process Assessment of the Learner; TOWRE = Test of Word Reading Efficiency; WIAT II = Wechsler Individual Achievement Test—Second Edition; WRMT-R = Woodcock Reading Mastery Test—Revised.

storage and processing) and executive functions, entered as simultaneous predictors, explained unique variance in reading and writing outcomes in children with dyslexia who made reversals. RAN, an indicator of phonological loop (Amtman et al., 2007), and rapid automatic letter writing 15 seconds, an indicator of orthographic loop (Berninger, Nielsen, et al., 2008), were not included because the reversal group was identified on the basis of letter naming reversals and letter writing reversals on those tasks. All of the multiple regressions in Table 7 accounted for significant variance at $p =$ or $< .001$, except for the written expression outcome, which was significant at $p = .005$. For real word reading accuracy, both orthographic and phonological coding (storage and processing) contributed uniquely. For pseudoword reading accuracy, only phonological coding contributed uniquely. For rate of real word reading, not only orthographic and phonological coding but also an executive function (inhibition) contributed uniquely. Likewise, for rate of pseudoword reading, not only phonological coding but also an executive function (inhibition) contributed uniquely. For spelling, both orthographic coding and an executive function (inhibition) contributed uniquely. For children's composition, only spelling accuracy contributed uniquely. Thus, weaknesses in working memory components may interfere with reading or writing skills of children with dyslexia who make reversals.²

DISCUSSION

Synthesizing the Findings

Results confirmed the first three predictions. Children with dyslexia made reversals on a letter naming task and on letter writing for review, see tasks. They also produced a higher proportion of reversal errors than did children without dyslexia, but not all children with dyslexia made reversals.

The incidence of reversal errors in children is higher in this study than in previously reported studies of reversals and observed in preliminary studies with normal and at-risk individuals (Brooks, 2003). One possible explanation for the higher incidence is that the number of tasks analyzed per participant for reversal errors was greater in this study than in previous studies; we included a written composition task that yielded a much higher volume of written language production than in any other reported study of reversals, providing more opportunities for finding reversal errors during independent writing when children with dyslexia have to self-regulate their written composing process. However, even though the incidence was higher than in prior studies, overall it was still relatively low, consistent with reversals being an indicator of an occasional breakdown rather than constant problem. Baseline rates of reversals across development (grades 1 to 6) are now available so that it is possible to determine if an individual student makes more reversals than grade peers even though overall few children make reversals.²

At the same time a substantial number of the 122 children with dyslexia in the Berninger Abbott, Thomson, et al. (2006) phenotyping study were impaired on RAN total time scores and thus the timing of the phonological loop function for cross-code integration, which is not the same as impaired phonological awareness for reflecting on sound units stored in heard or spoken

²PAL II (Berninger, 2007) has baseline rates for making letter writing reversals (and sustaining oral naming across rows of RAN and RAS) and other kinds of non-reversal errors, based on national norming samples during standardization.

words in working memory (Wolf & Bowers, 1999). Reversals on the RAN task, which are less frequent, probably reflect a different process in the time-sensitive phonological loop function of working memory than do RAN times.

The current findings that reversals may be made during oral naming of letters and not just writing letters converges with Roald Dahl's insight (Dahl, 1991)³ that individuals with dyslexia, even adults, may be vulnerable to problems in sequencing motor output—through the mouth—as well as the hand. Under stressful conditions of a new job, which may overwhelm working memory capability, a new pastor, the Vicar of Nibbleswick, who had overcome earlier problems with dyslexia to complete his formal education, began to make reversals in speech. Although Roald Dahl playfully suggested that the Vicar overcame his reversals of sounds in speech by walking backwards, it is the case that the brain pathways that supports walking overlaps in large part with the brain pathways in the word form areas involved in reading and spelling, which are impaired in dyslexia (see Wood, Flowers, & Grigenko, 2001). Even when children or adults with a history of dyslexia appear to have overcome their oral reading and writing problems they may be vulnerable to working memory inefficiencies, especially under conditions that overwhelm their working memory efficiency in coordinating its multiple components.

The research approach that tested four theory-driven, related hypotheses generated converging evidence for working memory components contributing to reversals (fourth, fifth, and sixth predictions), but exactly which working memory components contribute was related to the nature of the task—oral reading or writing or kind of writing task (sixth prediction). Even though relatively few individuals with dyslexia make reversals, for those who do, the working memory components appear to be related to their reading and writing achievement (seventh prediction) and, as many participants self-reported, may at times cause them psychological stress.

Specific results depended to some extent on whether groups who did and did not make reversals were compared on mean level of performance on working memory components or which working memory predictors entered in multiple regression (a) differentiated those who do and do not make reversals, (b) predicted number of errors on specific letter naming or letter writing tasks, or (c) predicted reading and writing achievement. Thus, the results support generalizations to vulnerabilities in working memory architecture rather than invariant relationships between working memory components and the loops of working memory explaining letter reversals through mouth or hand. Nevertheless converging evidence was observed across tested predictions that phonological or orthographic storage and processing and executive functions (inhibition, switching attention, or self-monitoring) may contribute to the vulnerabilities in phonological or orthographic loop functions and result in letter reversals.

Future research might investigate whether the neuroanatomical variables associated with oral processing speed may be related to phonological loop function vulnerabilities and those associated with visual processing speed may be related to orthographic loop function vulnerabilities (see article by Leonard et al. in this special issue). Also, future research might investigate whether the Fox 2 gene variations may contribute to phonological loop or orthographic loop functions both of which require serial motor planning (see Peter et al., 2011).

³Dahl (1991) donated the proceeds of the *Vicar of Nibbleswick*, his last book, to the British Dyslexia Society.

Limitations

Sample size of reversal and non-reversal groups was too small to conduct confirmatory factor analysis or structural equation modeling. Nevertheless, consistent with findings from those studies that employed confirmatory factor analyses and structural equation modeling from larger samples in the same family genetics study, results support the conclusions that (a) working memory architecture is a useful theoretical framework from which to understand various aspects of dyslexia (Berninger, Abbott, Thomson, et al., 2006), including the tendency of some (not all) students with dyslexia to make reversals (current study); and (b) an orthographic loop is involved in learning to write letters and compose (Berninger, Nielsen, et al., 2008; Richards et al., 2009a, 2009b, 2009c).

Educational and Clinical Significance

Consistent with Bunting, Conway, and Heitz (2004), reversals may occur because of breakdowns in supervisory attention, that is, executive functions in working memory. Consistently, one executive function—inhibition—contributed to reading and writing outcomes in children with dyslexia who made reversals. This result supports the important role of executive functions in self-regulation of attention (focus on what is relevant and ignore what is not relevant) during literacy learning, which may be momentarily impaired in some individuals with dyslexia (Altemeier, Abbott, & Berninger, 2008). Although reversals are not the hallmark defining feature of dyslexia, they do occur in some individuals with dyslexia. Rather than minimizing or denying the significance of reversals for individuals with dyslexia who persist in making reversals beyond age 9, the current research findings support an approach in which professionals acknowledge the reversals and explain to those who make them that they are only occasional, momentary, temporary breakdowns or inefficiencies, and do not mean that they are not smart or cannot be good readers and writers.

Moreover, with special teaching techniques such momentary breakdowns may be preventable. Teaching strategies such as numbered arrow cues to create letter forms and holding letter forms in the mind's eye for increasing durations to automatize letter writing (Berninger et al., 1997) was effective in overcoming reversals (Brooks, 2003; Berninger, Rutberg, et al., 2006, Study 3). Normalizing reversals, that is, recognizing that some good readers and writers occasionally make reversals too at least early in written language acquisition, may provide some relief to those who may make occasional letter reversals later in written language acquisition. However, more research is needed on this issue.

It is worth noting that of the five studies in which we imaged brains of children with and without dyslexia, before and after instructional treatment for the dyslexia, we always found normalization on language tasks (previous differences between those with and without dyslexia were eliminated), but not on the *n-back* working memory task (Richards et al., 2009d). Only when the instructional strategies for phonological loop and orthographic loop were integrated close in time was normalization of functional connectivity from working memory regions observed (Richards & Berninger, 2008). Thus, both clinicians and teachers should pay close attention to (a) RAN and letter writing reversals, (b) slow total time for RAN or alphabet writing, and (c) steady slow or slow and slower across row times on RAN (or RAS) (Amtmann et al., 2007;

Berninger, 2007)². Any of these may indicate the *invisible disability* in dyslexia related to working memory loops and need for specialized teaching to improve phonological loop and orthographic loop and executive functions of working memory to to inhibit (focus), switch attention (be flexible), maintain attention (stay on task over time), and self-monitor (update working memory over time).

ACKNOWLEDGMENT

This article is based on the dissertation of the first author and a presentation by the first author at the International Dyslexia Association in November 2003 in San Diego in a symposium organized by Virginia Berninger and Maryanne Wolf: “Temporal Coordination of Orthographic, Phonological, and Morphological Word Forms and Other Levels of Language in Working Memory of the Reading Brain: Developmental and Instructional Perspectives on The Real Whole Language.”

REFERENCES

- Altmeier, L., Abbott, R., & Berninger, V. (2008). Executive functions for reading and writing in typical literacy development and dyslexia. *Journal of Clinical and Experimental Neuropsychology*, *30*, 588–606.
- Amtmann, D., Abbott, R., & Berninger, V. (2007). Mixture growth models for RAN and RAS row by row: Insight into the reading system at work over time. *Reading and Writing. An Interdisciplinary Journal*, *20*, 785–813.
- Baddeley, A. (2002). Is working memory still working? *European Psychologist*, *7*, 85–97.
- Baddeley, A., Gathercole, S., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, *105*, 158–173.
- Badian, N. (1995). Predicting reading ability over the long term: The changing roles of letter naming, phonological awareness, and orthographic processing. *Annals of Dyslexia*, *45*, 79–96.
- Berninger, V. (2007). *Process Assessment of the Learner II User's Guide (CD format) and the Diagnostic Test Battery for Reading and Writing*. San Antonio, TX: Pearson/PsyCorp.
- Berninger, V. (2008). Defining and differentiating dyslexia, dysgraphia, and language learning disability within a working memory model. In E. Silliman & M. Mody (Eds.), *Language impairment and reading disability-interactions among brain, behavior, and experience* (pp. 103–134). New York, NY: Guilford Press.
- Berninger, V. (2009). Highlights of programmatic, interdisciplinary research on writing. *Learning Disabilities. Research and Practice*, *24*, 68–79.
- Berninger, V., Abbott, R., Augsburger, A., & Garcia, N. (2009). Comparison of pen and keyboard transcription modes in children with and without learning disabilities affecting transcription. *Learning Disability Quarterly*, *32*, 123–141.
- Berninger, V., Abbott, R., Jones, J., Wolf, B., Gould, L., Anderson-Youngstrom, M., . . . Apel, K. (2006). Early development of language by hand: Composing-, reading-, listening-, and speaking- connections, three letter writing modes, and fast mapping in spelling. *Developmental Neuropsychology*, *29*, 61–92.
- Berninger, V., Abbott, R., Swanson, H. L., Lovitt, D., Trivedi, P., Lin, S. et al. (2010). Relationship of word- and sentence-level working memory to reading and writing in second, fourth, and sixth grade. *Language, Speech, and Hearing Services in Schools*, *41*, 179–193.
- Berninger, V., Abbott, R., Thomson, J., & Raskind, W. (2001). Language phenotype for reading and writing disability: A family approach. *Scientific Studies of Reading*, *5* 59–106.
- Berninger, V., Abbott, R., Thomson, J., Wagner, R., Swanson, H. L., Wijsman, E., et al. (2006). Modeling developmental phonological core deficits within a working-memory architecture in children and adults with developmental dyslexia. *Scientific Studies of Reading*, *10*, 165–198.

- Berninger, V., Nielsen, K., Abbott, R., Wijsman, E., & Raskind, W. (2008a). Writing problems in developmental dyslexia: Under-recognized and under-treated. *Journal of School Psychology, 46*, 1–21.
- Berninger, V., Nielsen, K., Abbott, R., Wijsman, E., & Raskind, W. (2008b). Gender differences in severity of writing and reading disabilities. *Journal of School Psychology, 46*, 151–172.
- Berninger, V., O'Donnell, L., & Holdnack, J. (2008). Research-supported differential diagnosis of specific learning disabilities and implications for instruction and response to instruction (RTI). In A. Prifitera, D. Saklofske, & L. Weiss (Eds.), *WISC-IV Clinical Assessment and Intervention, Second Edition* (pp. 69–744). San Diego, CA: Academic Press (Elsevier).
- Berninger, V., Raskind, W., Richards, T., Abbott, R., & Stock, P. (2008). A multidisciplinary approach to understanding developmental dyslexia within working-memory architecture: Genotypes, phenotypes, brain, and instruction. *Developmental Neuropsychology, 33*, 707–744.
- Berninger, V., & Richards, T. (2002). *Brain literacy for educators and psychologists*. San Diego, CA: Academic Press (Elsevier Imprint).
- Berninger, V., & Rutberg, J. (1992). Relationship of finger function to beginning writing: Application to diagnosis of writing disabilities. *Developmental Medicine & Child Neurology, 34*, 155–172.
- Berninger, V., Rutberg, J., Abbott, R., Garcia, N., Anderson-Youngstrom, M., Brooks, A., et al. (2006). Tier 1 and Tier 2 early intervention for handwriting and composing. *Journal of School Psychology, 44*, 3–30.
- Berninger, V. W. (2001). *The process assessment of the learner: Test battery for reading and writing*. San Antonio, TX: The Psychological Corporation.
- Berninger, V. W., Vaughan, K., Abbott, R. D., Brooks, A., Abbott, S. P., Rogan, L., Reed, E., & Graham, S. (1997). Early intervention for spelling problems: Teaching functional spelling units of varying size with a multiple-connections framework. *Journal of Educational Psychology, 90*, 587–605.
- Breznitz, Z. (2006). *Fluency in reading. Synchronization of processes*. Mahwah, NJ: Lawrence Erlbaum.
- Brooks, Allison D. (2003). Neuropsychological processes related to persisting reversal errors in dyslexia and dysgraphia. *Dissertation Abstracts International, 63*(11-A), p. 3850.
- Bunting, M., Conway, A., & Heitz, R. (2004). Individual differences in the fan effect and working memory capacity. *Journal of Memory and Language, 51*, 604–622.
- Byrne, B., Delaland, C., Fielding-Barnsley, R., Quain, P., Samuelsson, S., Høien, T., . . . Olson, R. (2002). Longitudinal twin study of early reading development in three countries: Preliminary results. *Annals of Dyslexia, 52*, 4–73.
- Compton, D. (2000). Modeling the relationship between growth in rapid naming speed and growth in decoding skill in first grade children. *Journal of Educational Psychology, 95*, 225–239.
- Dahl, R. (1991). *The Vicar of Nibbleswicke*. London, England: Random Century Group, Ltd., and Penguin Books.
- Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). *Delis-Kaplan executive function system*. San Antonio, TX: The Psychological Corporation.
- Denckla, M. (1973). Development of speed in repetitive and successive finger movements in normal children. *Developmental Medicine and Child Neurology, 15*, 635–645.
- Fletcher, S. G. (1978). *Time-by-Count Test Measurement of Diadochokinetic Syllable Rate*. Austin, TX: PRO-ED.
- Frith, U., & Vogel, J. (1980). *Some perceptual prerequisites for reading*. New York, DE: International Reading Association.
- Garcia, N., Abbott, R., & Berninger, V. (2010). Predicting poor, average, and superior spellers in grades 1 to 6 from phonological, orthographic, and morphological, spelling, or reading composites. *Written Language and Literacy, 13*, 61–99.
- Goldman-Rakic, P. (1992). Working memory and the mind. *Scientific American, 111*–117.
- Hitch, G. J., & Baddeley, A. (1976). Verbal reasoning and working memory. *Quarterly Journal of Experimental Psychology, 28*, 603–621.
- Hsu, L., Wijsman, E., Berninger, V., Thomson, J., & Raskind, W. (2002). Familial aggregation of dyslexia phenotypes: Paired correlated measures. *American Journal of Medical Genetics/Neuropsychiatric Section, 114*, 471–478.
- Kahneman, D., & Tversky, A. (1972). Subjective probability: A judgment of representativeness. *Cognitive Psychology, 3*, 430–454.
- Kail, R. (1984). *The development of memory in children*, 2nd ed. New York, NY: W. H. Freeman & Co.
- Lieberman, I. Y., Shankweiler, D., Orlando, C., Harris, K. S., & Berti, F. B. (1971). Letter confusions and reversals of sequence in the beginning reader: Implications for Orton's theory of developmental dyslexia. *Cortex, 7*, 127–142.
- Lyon, G. R., Shaywitz, S., & Shaywitz, B. (2003). A definition of dyslexia. *Annals of Dyslexia, 53*, 1–14.

- Manis, F., Seidenberg, M., & Doi, L. (1999). See Dick RAN: Rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading*, 3, 129–157.
- Miyake, A., Friedman, N., Emerson, M., Witzki, A., Howerter, A., & Wager, T. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, 41, 49–100.
- Morris, R., Morris, R., Stuebing, K., Fletcher, J., Shaywitz, S., Lyon, G. R., . . . Shaywitz, B. (1998). Subtypes of reading disability: Variability around a phonological core. *Journal of Educational Psychology*, 90, 347–373.
- Olson, R., Forsberg, H., Wise, B., & Rack, J. (1994). Measurement of word recognition, orthographic, and phonological skills. In G. R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities* (pp. 243–277). Baltimore, MD: Brooks.
- Peter, B., Raskind, W., Matsushita, M., Lisowski, M., Vu, T., Berninger, V., . . . Brkanac, Z. (2011). Replication of CNTNAP2 association with nonword repetition and support for FOXP2 association with timed reading and motor activities in a dyslexia family sample. *Journal of Neurodevelopmental Disorders*, 3, 39–49.
- Richards, T., Aylward, E., Raskind, W., Abbott, R., Field K., Parsons, A. et al. (2006). Converging evidence for triple word form theory in children with dyslexia. *Developmental Neuropsychology*, 30, 547–589.
- Richards, T., & Berninger, V. (2008). Abnormal fMRI connectivity in children with dyslexia during a phoneme task: Before but not after treatment. *Journal of Neurolinguistics*, 21, 294–304.
- Richards, T., Berninger, V., & Fayol, M. (2009a). fMRI activation differences between 11-year-old good and poor spellers’ access in working memory to temporary and long-term orthographic representations. *Journal of Neurolinguistics*, 22, 327–353.
- Richards, T., Berninger, V., Stock, P., Altemeier, L., Trivedi, P., & Maravilla, K. (2009b). fMRI sequential-finger movement activation differentiating good and poor writers. *Journal of Clinical and Experimental Neuropsychology*, 29, 1–17.
- Richards, T., Berninger, V., Stock, P., Altemeier, L., Trivedi, P., & Maravilla, K. (2011). Differences between good and poor child writers on fMRI contrasts for writing newly taught and highly practiced letter forms. *Reading and Writing*, 24(5), 493–516.
- Richards, T., Berninger, V., Winn, W., Swanson, H. L., Stock, P., Liang, O., & Abbott, R. (2009d). Differences in fMRI activation between children with and without spelling disability on 2-back/0-back working memory contrast. *Journal of Writing Research*, 1(2), 93–123. Open access peer reviewed journal available online: Download pdf at the JOWR-website
- Sawyer, D., Kim, J., & Lipa-Wade, S. (2000). Application of Frith’s developmental phase model to the process of identifying at-risk readers. In N. Badian (Ed.), *Prediction and prevention of reading failure* (pp. 87–103). Baltimore, MD: York Press.
- Shadish, W., Cook, T., & Campbell, D. (2002). *Experimental and quasi-experimental designs for generalized causal inference*. Boston, MA: Houghton Mifflin Company.
- Shankweiler, D. & Liberman, I. Y. (1972). Misreading: A search for causes. In J. F. Kavanagh and I. G. Mattingly (Eds.), *Language by ear and by eye; the relationships between speech and reading*. Cambridge, MA: MIT Press.
- Shankweiler, D. & Liberman, I. Y. (1978). Reading behavior in dyslexia: Is there a distinctive pattern? *Bulletin of the Orton Society*, 28, 114–123.
- Silliman, E., & Berninger, V. (2011, January to March). Cross-disciplinary dialogue about the nature of oral and written language problems in the context of developmental, academic, and phenotypic profiles. *Topics in Language Disorders*, 31, 6–23.
- Simner, Marvin L. (1984). The grammar of action and reversal errors in children’s printing. *Developmental Psychology*, 20, 136–142.
- Swanson, H. L. (1999). Reading comprehension and working memory in learning-disabled readers: Is the phonological loop more important than the executive system? *Journal of Experimental Child Psychology*, 72, 1–31.
- Swanson, H. L., Howard, C., & Saez, L. (2006). Do different components of working memory underlie different subgroups of reading disabilities? *Journal of Learning Disabilities*, 39, 252–269.
- Swanson, H. L., & Siegel, L. (2001). Learning disabilities as a working memory deficit. *Issues in Education*, 7, 1–48.
- Terepocki, M., Kruk, R. S., & Willows, D. M. (2002). The incidence and nature of letter orientation errors in reading disability. *Journal of Learning Disabilities*, 35, 214–233.
- The Psychological Corporation. (2001). *Wechsler Individual Achievement Test—Second Edition*. San Antonio, TX: Psychological Corporation.

- Thomson, J., Chennault, B., Abbott, R., Raskind, W., Richards, T., Aylward, E. et al. (2005). Converging evidence for attentional influences on the orthographic word form in child dyslexics. *Journal of Neurolinguistics*, 18, 93–126.
- Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of Word Reading Efficiency*. Austin, TX: PRO-ED.
- Vellutino, F. (1979). *Dyslexia: Theory and research*. Cambridge, MA: MIT Press.
- Vogel, J. (1973). *Children's short-term memory for the left-right orientation of visual forms* (Unpublished doctoral dissertation). Harvard University, Cambridge, MA.
- Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive Test of Phonological Awareness*. Austin, TX: PRO-ED.
- Wechsler, D. (1991). *Wechsler Intelligence Scale for Children—Third Edition*. San Antonio, TX: Psychological Corporation.
- Wiederholt, J. & Bryant, B. (1992). *Gray Oral Reading Test—Third Edition*. Odessa, FL: Psychological Assessment Resources.
- Wilkinson, G. (1993). *Wide Range Achievement Tests—Revised*. Wilmington, DE: Wide Range, Inc.
- Wolf, M. (1986). Rapid alternating stimulus naming in the developmental dyslexias. *Brain and Language*, 27, 360–379.
- Wolf, M. (Ed.). (2001). *Dyslexia, fluency, and the brain* (pp. 383–414). Extraordinary rain Series. Baltimore, MD: York Press.
- Wolf, M., Bally, H., & Morris, R. (1986). Automaticity, retrieval processes, and reading: A longitudinal study in average and impaired reading. *Child Development*, 57, 988–1000.
- Wolf, M., & Bowers, P. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology*, 91, 415–438.
- Wolf, M., & Denckla, M. (2004). *Test of rapid automatic naming*. Austin, TX: PRO-ED.
- Wolff, P., Gunnoe, C., & Cohen, C. (1983). Associated movements as a measure of developmental age. *Developmental Medicine and Child Neurology*, 25, 417–429.
- Wood, F., Flowers, L., & Grigenko, E. (2001). On the functional neuroanatomy of fluency or why walking is just as important to reading as talking is. In M. Wolf (Ed.), *Dyslexia, fluency and the brain* (pp. 235–244). Extraordinary Brain Series. Baltimore, MD: York Press.
- Woodcock, R. (1987). *Woodcock Reading Mastery Tests—Revised*. Circle Pines, MN: American Guidance Service.
- Woodcock, R., & Johnson, B. (1990). *Woodcock-Johnson Psycho-Educational Battery. Revised Tests of Achievement*. Chicago, IL: Riverside Publishing.