Published in final edited form as:

Int J Sch Educ Psychol. 2019 ; 7(Suppl 1): 182–200. doi:10.1080/21683603.2018.1458357.

Behavioral and brain evidence for language by ear, mouth, eye, and hand and motor skills in literacy learning

Virginia W. Berninger^a, Todd L. Richards^b, Kathleen H. Nielsen^a, Michael W. Dunn^c,
Marshall H. Raskind^d, Robert D. Abbott^e

^aEducational Psychology, University of Washington, Seattle, Washington, USA

^bIntegrated Brain Imaging Center, Department of Radiology, University of Washington, Seattle, Washington, USA

^cSpecial Education, Washington State University, Vancouver, Washington, USA

^dEducational Consulting, Bainbridge Island, Washington, USA

^eEducational Measurement and Statistics, University of Washington, Seattle, Washington, USA

Abstract

Two studies were conducted of students with and without persisting Specific Learning Disabilities (SLDs-WL) in Grades 4 to 9 (M = 11 years, 11 months) that supported the hypotheses that CELF 4 parent ratings for listening (language by ear), speaking (language by mouth), reading (language by eye), and writing (language by hand) were correlated with both (a) normed, standardized behavioral measures of listening, speaking, reading, and writing achievement (Study 1, 94 boys and 61 girls); and (b) fMRI connectivity or DTI white matter integrity involving brain regions for primary motor functions or motor planning and control, or motor timing in a subsample of right handers who did not wear metal (Study 2, 28 boys and 16 girls). Results of these assessment studies, which have implications for planning instruction for three SLDs-WL (dysgraphia, dyslexia, and oral and written language learning disability [OWL LD]), show that more than multisensory instruction is relevant. Language by ear, by mouth, by eye, and by hand, as well as motor planning, control, and output skills and motor timing should also be considered. Research is also reviewed that supports other processes beyond multisensory input alone that should also be considered for students with SLDs-WL

Keywords

language by ear; language by mouth; language by eye; language by hand; literacy learning

The International Dyslexia Association (IDA) recommends multisensory instruction for teaching students with dyslexia. Such training emphasizes these sensory processes: auditory (processing sounds in heard words), visual (looking at written words), and kinesthetic (feedback from holding and moving fingers). The aim of the current research was to

investigate other processes that may also be relevant to literacy learning in students with dyslexia and other specific learning disabilities (SLDs) such as dysgraphia and oral and written language learning disability (OWL LD, also referred to as specific language impairment [SLI]). This article begins with the rationale and the hypotheses tested for Study 1, which examines four language systems hypothesized to be involved in literacy learning. It continues with the rationale and the hypotheses tested for Study 2, which examines the relationships between those language systems and motor functions in the brain for output during literacy learning.

Study 1: Behavioral assessment of language systems

Despite the widely used expression “Reading and Language,” reading is one of the four language systems that support literacy learning: aural language by ear (listening), oral language by mouth (speaking), written language by eye (reading), and language by hand (writing). Each of the multiple language systems is multileveled in that it draws on multiple building blocks of cascading size, ranging from subword to word to syntax to text.

Relatively more literacy research has focused on reading language by eye than on writing (language through the hand) or aural language (language through the ears) or oral language (language through the mouth). For example, in the United States there has been no National Panel on Teaching Writing as there was for Reading (National Institute of Child Health and Human Development, 2000). It is often assumed that aural language and oral language are learned during the preschool years, while reading and writing are learned during the school years. Yet aural and oral language continue to develop during the school years and both reading and writing draw on aural and oral language. For example, students have to process instructional talk, participate in class discussions, read orally, and sometimes think aloud when planning for composing. In addition, although it is assumed that learning to read will enable students to then write, the research in contrast supports a writing path to reading. That is, learning to write benefits learning to read. For example, word reading improved as a result of teaching students strategies for forming letters stroke by stroke, holding the formed letter in the “mind’s eye” in memory, and writing the letter from memory (Berninger, 2009). Brain research has shown that letter production facilitates letter perception in words (James, Jao, & Berninger, 2015).

Depending on which level of language is impaired, three SLDs can interfere with acquisition of written language: Reading and/or Writing (SLDs-WL) (a) Dysgraphia is an SLD with primary impairment at the subword level (letter production). (b) Dyslexia is an SLD with primary impairment at the word level both in the reading direction (decoding written words into spoken words) and spelling direction (encoding spoken words into written words; Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008). (c) OWL LD emerges during the preschool years when it is associated with oral language (delays in first words and word combinations and syntax); it may persist during the school years when it is associated with impaired oral and written syntax (Silliman & Berninger, 2011). Interdisciplinary research has been translated into tests in English for differential diagnosis of dysgraphia, dyslexia, and OWL LD (Berninger, 2007a) and dyscalculia (Berninger, 2007b). Language skills such as naming and writing numerals and the syntax of numbers (place value) can also interfere

with math calculation. To diagnose an SLD-WL it must also be shown that the five domains of development (cognitive, language, sensory and motor, social emotional, and attention/executive function) fall within the lower limits of the normal range to rule out a developmental disability (Berninger, 2015, chapters 7, 8, and 9).

Importantly, not all SLDs are reading disabilities— some involve only writing, some involve reading and writing, and yet others involve listening and oral expression as well as reading or writing. Note that each of these three SLDs-WL involves impaired writing skills but at different levels of language (subword, word, or syntax). Thus, there is a reason for specific learning disabilities being plural! The Mayo epidemiological studies show that overall, one in five school-age children and youth have an SLD-WL (Colligan & Katusic, 2015).

Prior research showed a relationship between parental observations and literacy achievement at school (AlstonAbel & Berninger, 2017). Parents have the advantage of observing their child's learning and development within and outside the home in a variety of both school and non- school-related activities. Thus, for Study 1 the hypothesis was tested that there would be significant correlations between parent ratings for Listening, Speaking, Reading, and Writing on the CELF 4 Checklist and normed achievement test measures for listening, speaking, reading, and writing achievement.

Study 2: Relationships of brain's motor functions and pathways with language systems

Also analyzed were the relationships between the CELF 4 parent ratings for Listening, Speaking, Reading, and Writing and brain imaging results related to its motor functions. The rationale was that not only sensory input (language by ear and language by eye) but also motor output (language by mouth and language by hand) are related to literacy learning.

Research evidence for the importance of the motor mode in reading has existed, but has been not well integrated into understanding dyslexia or other SLDs-WL or typical literacy learning. Oro-motor skills underlie speech (Green, Moore, Higashikawa, & Steeve, 2000) used in oral language and reading; and grapho (hand)-motor skills underlie gesture (Cook, Mitchell, & Goldin-Meadow, 2008) in oral language development, learning, and use beginning in the preschool years. During the school years, motor functions related to mouth and hand functions are involved in many aspects of literacy learning as children pronounce words, read text aloud, and discuss orally through their mouth what they have read. Producing words orally may also enhance listening skills, facilitating attention to features in the heard talk. Likewise, children produce letters through their hands to spell written words and compose sentences and text about what they read or hear. Also motor functions are involved in the eye movements as they read written words in the context of sentences, either orally or silently (Yagle et al., 2017).

During the school years, students with SLDs-WL may not be assessed at school for co-occurring motor problems even though neuropsychological research has shown that they are relevant both to learning to read and learning to write. For typical kindergarten and first graders, achievement in reading and other language skills was predicted by neuromotor

skills assessed by neurologists, such as dyskinesias in response to stress gaits or mirror movements in response to finger lifting, finger spreading, and timed motor maneuvers (Wolff, Gunnoe, & Cohen, 1983) or mirror movements, speed of timed motor repetitions and other timed motor maneuvers, and static balance (Wolff, Gunnoe, & Cohen, 1985). However, children with reading disabilities were more likely to have difficulty with bimanual coordination of motor movements across hands than unimanual movement or with oromotor coordination across syllables than single syllables alone (Wolff, Cohen, & Drake, 1984). These findings support the importance of temporal coordination of motor acts for literacy learning (Wolf, Bowers, & Biddle, 2000), consistent with brain research documenting the contribution of the cerebellum to that motor timing (Nicolson, Daum, Schugens, Fawcett, & Schultz, 2002).

On the one hand, brain research has shown the contribution of finger sequencing to learning to form letters stroke by stroke, to sequencing letters in spelling words, and to sequencing words in composing syntax (Richards et al., 2009). Finger sequencing requires executive functions for coordinating movement in time (Berninger, 2009). On the other hand, research has also shown that patterns of movement for well-practiced letters that treat individual letters as a single automatic unit rather than a series of component strokes are important in handwriting (Teulings, Thomassen, & van Galen, 1983). Accordingly, both the executive functions for coordinating sequencing and the automatization of procedures for sequential production are involved in the motor output for language by hand.

Thus, the hypothesis tested in Study 2 was that the brain measures related to motor functions and pathways would be correlated with CELF 4 parent ratings for each of the four language systems—listening, speaking, reading, and writing. Support for this hypothesis would demonstrate the importance of motor and language and not just multisensory processes in literacy learning. Based on Richards et al. (2015), both fMRI connectivity and DTI were used.

Study 1

Methods

Participants

Ascertainment over a four-year period.: Flyers distributed to local schools announced an opportunity to take part in a university study for children in Grades 4 to 9 who have a history of continuing reading and writing difficulties despite earlier intervention or who have never had any struggles in learning to read and write. An initial screening interview was conducted over the phone for the purpose of determining if the reading or writing difficulties were probably related to SLDs in otherwise typically developing individuals without acquired disorders or medical conditions rather than to developmental disabilities, brain injury, or other conditions that may be associated with motor or language disabilities more severe than specific learning disabilities in written language (SLDs-WL). For those who appeared by history to have an SLD or to be a typical language learner and the parent granted informed consent and the child granted assent per the approved Institutional Review Board protocol

where the research was conducted, comprehensive, evidence-based differential diagnosis assessment was conducted at the university.

Assignment to diagnostic groups.: For a diagnosis of dysgraphia, the student had to score below $-2/3$ SD (lower limit of the average range) on at least two handwriting measures and have a reported history of current and past struggles with handwriting. For a diagnosis of dyslexia, the student had to score below the mean and a standard deviation below Verbal Comprehension Index (to rule out aural and oral language difficulties) on at least two reading and spelling measures and have a reported history of current and past struggles with reading and spelling. For a diagnosis of OWL LD, the student had to score below $-2/3$ SD on at least two measures of listening or reading comprehension or oral or written sentence construction. All students had to have a Verbal Comprehension Index of at least 80 (lower limit of low average range). ADHD was not an exclusionary criterion, but few had ADHD except some with dysgraphia. For additional information on procedures, which used normed tests, developmental and educational histories, and parents ratings on evidencebased scales, see Berninger, Richards, and Abbott (2015), Sanders, Abbott, and Berninger (2017), and Lyman, Sanders, Abbott, and Berninger (2017).

Sample characteristics.: Students were identified who never had any struggles in learning oral or written language (control group, $N = 42$) or who had persisting SLDs-WL during middle childhood and early adolescence (dysgraphia [$N = 29$], dyslexia [$N = 65$], and OWL LD [$N = 19$]).

Altogether 155 children (ages 9 to 15, $M = 11$ years, 11 months; 94 boys, 61 girls) completed the assessment; and their parents (mostly mothers but in rare exceptions fathers) with legal authority for educational decision making completed the CELF 4 Parent Ratings. Parentreported ethnicity for their children included European American 70.3%, mixed ethnicity 19.5%, Asian-American 3.2%, Hispanic 1.9%, African American 1.3%, non-European Caucasian 1.3%, and Other/Nonspecified 2.5%. Highest level of completed education reported by parents ranged from less than high school (mothers 0.7%, fathers 2.2%) to high school (mothers 2.8%, fathers 2.9%) to more than high school but less than college degree (mothers 5.6%, fathers 10.8%) to college degree (mothers 43.8%, fathers 43.9%) to more than college degree (mothers 47.2%, fathers 40.3%).

Measures

CELF 4 parent ratings.: The authors of the CELF 4 assessment (Semel, Wiig, & Secord, 2003) also developed an observational scale to supplement the standardized, normed language assessment measures. Parents are asked to read 40 statements that describe problems in listening, speaking, reading, and writing and then use a 4-point scale to rate the relative frequency with which such problems are observed in their own child. These ratings for each of the 40 items were then correlated with both standardized, normed measures of listening, speaking, reading, and writing and with fMRI functional connectivity of statistically significant magnitude that involved brain regions known to be involved in motor functions.

Normed measures of language by ear, by mouth, by eye, and by hand.: Table 1 (section I) displays means and standard deviations for the control group and each SLD group. Note that OWL LD, which may be missed if it is assumed that all reading disabilities are dyslexia, was the most impaired in all language skills, including but not restricted to reading.

Aural language by ear (listening).: The Woodcock Psychoeducational Cognitive Battery, third edition (WJ III), Oral Comprehension (Woodcock, McGrew, & Mather, 2001a; test–retest reliability .88) was given. It is a cloze task that requires supplying a word orally during pause in unfolding aural text. It yields a standard score ($M = 100$, $SD = 15$).

Oral language by mouth (oral expression).: The Clinical Evaluation of Language Function, fourth edition, Formulated Sentences (CELF 4; Semel et al., 2003; test–retest reliability .62 to .71) was given. It requires, for each of multiple items, constructing an oral sentence from three provided words. It yields scaled scores ($M = 10$ and $SD = 3$).

Visible written language by eye (reading).: To assess accuracy of oral real-word and pseudoword reading, also given were the Woodcock Psychoeducational Achievement Battery, third edition (WJ III; Woodcock, McGrew, & Mather, 2001b), Word Identification (test–retest reliability .95), for which the child is asked to pronounce a list of written real words without context clues, and WJ III, Word Attack (test–retest reliabilities .73 to .81), for which the child is asked to pronounce a list of written pseudowords. To assess the rate of oral real-word and pseudoword reading on a list (accuracy within 45 s), also given were the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999), Sight Word Efficiency Test for real words on list (test–retest reliability .91), and Pseudoword Efficiency Test (test–retest reliability .90) for pseudowords on a list. Also given was WJ III (Woodcock et al., 2001b) Passage Comprehension (test–retest reliability .85), a reading comprehension analogue of the oral cloze task, for which the task is to supply orally a missing word in the blank that fits the accumulating context of the sentence and preceding text. For all five reading measures, the raw scores are converted to standard scores ($M = 100$, $SD = 15$).

Producing written language by hand (writing).: On the Alphabet Writing Task, an experimenter-designed test, children are asked to handwrite in manuscript (unjoined letters) the lowercase letters of the alphabet from memory as quickly as possible in alphabetic order, but to make sure others can identify the letters. The raw score is the number of letters that are legible and in correct order during first 15 seconds. The raw score is converted to a z-score ($M = 0$, $SD = 1$), based on research norms for grade (interrater reliability .97; Berninger, 2009). On the Detailed Assessment of Speed of Handwriting (DASH) Best and Fast (Barnett, Henderson, Scheib, & Schulz, 2007), the task is to copy a sentence with all the letters of the alphabet under contrasting instructions: one's best handwriting or one's fast writing (interrater reliability .99). Students can choose to use their usual writing—manuscript (unconnected) or cursive (connected) or a combination. Note that even though the task is to copy letters in word and syntax context, the scaled score ($M = 10$, $SD = 3$), is based on legibility for single letters within the time limits. In the current study, two testers reviewed all the scored handwritten measures to reach consensus on scoring. The Wechsler

Individual Achievement Test, third edition (WIAT 3) Spelling (Pearson, 2009; test–retest reliability .92) was also given. The task is to spell in writing dictated real words, pronounced alone, then in a sentence, and then alone. The score is a standard score ($M = 100$, $SD = 15$). Two measures were given to assess sentence composing. For WIAT 3 Sentence Combining (test–retest reliability .81; Pearson, 2009), the task is to combine two provided sentences into one well-written sentence that contains all the ideas in the two separate sentences. For the WJ III Writing Fluency (Woodcock et al., 2001b; test–retest reliability .88), the task is to compose a written sentence for each set of three provided words, which are to be used without changing them in any way. There is a 7-min time limit. For all spelling and composing measures, the score is a standard score ($M = 100$, $SD = 15$).

Results and discussion

Correlations between CELF 4 parent ratings and achievement measures are reported in Table 2 (Listening), Table 3 (Oral Expression), Table 4 (Reading), and Table 5 (Writing). Parent ratings on the 40-item observation scale were related to multiple standardized, normed measures of the same four language skills. For the most part the significant correlations were negative—lower scores on the normed measure were associated with parents reporting higher observed frequencies of the problems occurring. These results support the first hypothesis that the CELF 4 parent ratings for language are related to normed measures of language. However, for each of the four language systems the patterns of correlations varied across the typical and SLDs-WL groups (dysgraphia, dyslexia, and OWL LD) confirming the diverse language learning strengths and weaknesses during upper elementary and middle school. These findings show that educators have the challenging job of teaching literacy skills to diverse language learners, even if they are all native English speakers. Thus, it is probably unrealistic to expect all students to meet the same criteria for U.S. common core standards at the same time in their educational journey. Flexible approaches like outlined in Chapter 4 (early childhood), Chapter 5 (middle childhood), and Chapter 6 (adolescence) in Berninger (2015) are probably more realistic as well as evidence-based. That is, although each student should be achieving higher at the end of a grade than at the beginning of a grade, level of functioning at the beginning of a grade will differ across skills relevant to oral and written language learning and rates of achieving criteria at specific levels of proficiency are likely to vary. The reasons for the variability are likely due in large part to biological variables shown in considerable interdisciplinary research to be related to individual differences in language learning (e.g., Berninger, 2015, chapters 7, 8, 9, 10, 12).

Study 2

Method

Participants—Right-handed participants in Study 1 who did not wear metal that could not be removed during scanning (e.g., braces on teeth) were invited to participate in Study 2, a brain imaging study, after completing the diagnostic assessment. Altogether, 44 parents provided informed consents and their children provided assent to participate in the subsequent brain imaging study: 9 in the control group (5 females, 4 males), 14 in the dysgraphia group (3 females, 11 males), 16 in the dyslexia group (5 females, 11 males), and 5 in the OWL LD group (3 females, 2 males). See Table 1 (section II) for the results of the

normed tests of language for these 44 participants. Given the smaller sample size, the correlations between CELF 4 parent ratings and brain imaging results involving motor regions of the brain were computed based on the total sample of 44 and not separately for each diagnostic group.

Brain imaging—data acquisition and analyses

MRI Data acquisition.: Functional magnetic resonance imaging (fMRI) connectivity scans were obtained on a Philips 3 T Achieva scanner (release 3.2.2 with the 32-channel head coil). All scans were acquired at the Diagnostic Imaging Sciences Center in collaboration with the Integrated Brain Imaging Center and had Institutional Review Board approval. Each participant was screened for MRI safety before entering the scanner. Physiological monitoring was performed using the Philips pulse oximeter placed on the left-hand index finger for cardiac recording; and respiration was recorded using the Philips bellows system where the air-filled bellows pad was placed on the abdomen. Head immobilization was aided by using an inflatable head-stabilization system (Crania, Elekta). See the Appendix for details about the scanning and analyses of the brain data.

fMRI Reading Tasks during Scanning.: An fMRI connectivity design was used instead of a block design that makes comparisons across repeating conditions. Connectivity scores were derived from each of the four seed points shown in human connectome brain research to be part of the rich club (left precuneus; Van den Heuvel & Sporns, 2011) or in meta-analyses of brain research to activate on tasks involving single written words (left occipital temporal gyrus, left supramarginal gyrus, and left inferior frontal gyrus [Broca's area]; Purcell, Turkeltaub, Eden, & Rapp, 2011). The fMRI lexical decision task was programmed, timed, and coordinated with the scanner triggers using E-prime and in-house LabView software. The task was chosen because prior research (Berninger et al., 2015) had shown that all the SLDs-WL groups tend to be impaired in this skill, which is related to both word spelling and reading (also see Ehri, 1992). The task was taught and practiced outside the scanner before performing it during scanning. A score of 90% correct on this training task outside the scanner was required to ensure ability to perform the task prior to entering the scanner and having one's brain imaged. Participants also practiced lying still before entering the scanner and were instructed to lie still throughout the scanning. During the functional scans, they were first instructed to look at a fixation cross (no reading task; 180 time points; resting condition) but then to perform the lexical judgment task, which was presented with self-paced advancing of stimuli for 2 min; 960 timepoints). The participant is instructed to press yes if a written word on the screen is a correctly spelled real word, but press no if the written word on the screen is not a correctly spelled word, even though when pronounced it sounds like a real word. An example of a yes item is "bus." An example of a no item is "eer," which is a homonym pronounced the same as a real word but not the correct spelling for a real word.

Acquisition of the brain scans—Scanning included the following MRI series: (a) 3-plane scout view with gradient echo pulse sequence: TR/TE 9.8/ 4.6 ms; field of view $250 \times 250 \times 50$ mm; acquisition time 30.3 s; (b) reference scan (used in parallel imaging) with gradient echo pulse sequence: TR/TE 4.0/0.75 ms; Field of View $530 \times 530 \times 300$ mm;

acquisition time 44.4 s; (c) fMRI scan with echo-planar gradient echo pulse sequence (single shot): TR/TE 2000/25 ms; Field of view $240 \times 240 \times 99$ mm; slice orientation transverse, acquisition voxel size $3.0 \times 3.08 \times 3.0$ mm; acquisition matrix $80 \times 80 \times 33$; slice thickness 3.0, SENSE factor in the AP direction 2.3; epi factor 37; bandwidth in the EPI frequency direction 1933 Hz, SoftTone factor 3.5, sound pressure 6.1 dB, 180 dynamic scans; 5 dummy scans; fold over direction AP, 396 dynamic scans; (d) B0 field map imaging with gradient echo pulse sequence and 2 echoes; TR/TE 11/ 6.3 ms; delta TE 1.0 ms; slice orientation transverse, field of view $240 \times 240 \times 129$ mm; voxel size $1.5 \times 1.5 \times 3.0$ mm; acquisition matrix $160 \times 160 \times 43$, output image magnitude and phase, acquisition time 2:29 min/s; (e) MPRAGE structural scan: TR/TE 7.7/3.5 ms, Field of view $256 \times 256 \times 176$ mm, slice orientation sagittal, voxel size $1 \times 1 \times 1$ mm, inversion pulse delay 1,100 ms, Sense factor 2 in the AP direction, acquisition time 5:33 min/s.

Diffusion tensor imaging analysis—DTI data were processed with DTIPrep/GTRACT software to ensure quality control and generate the tensors (<http://www.nitrc.org/projects/dtiprep/>). Then custom software (GFORTAN) was used to calculate the DTI parameters (fractional anisotropy, axial diffusivity, radial diffusivity, relative anisotropy, mean diffusivity) from the tensors. FSL software (tract-based spatial statistics, TBSS) was used to co-register and prepare the DTI data for group analysis using a higher-level design matrix to perform a voxel-byvoxel group map comparison between groups. FSL's Randomise software, which robustly corrects for multiple comparisons with permutation methods in <http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/TBSS/UserGuide> (see “Threshold-Free Cluster Enhancement” TFCE option), was used to generate the group maps, which were co-registered to the FSL standard white matter atlas called FHU. A regional analysis was performed within each significant cluster using FSL's cerebellum atlas for cerebellar regions. Fractional anisotropy (FA) is used as an index of white matter integrity, that is, relative amount of myelination. Relative anisotropy (RA) refers to relative connectivity strength of water molecules in white factor tracts in one direction. Fractional anisotropy (FA) describes the degree to which the diffusion is anisotropic. Radial diffusivity (RD) in directions perpendicular to the principal axis of diffusion has been associated with the degree of myelination and number of branching, exiting fibers, whereas axial diffusivity (AD) along and parallel to the principal axis (axial diffusivity) has been associated with the axon diameter. Mean diffusivity (MD) is the average diffusivity, whether radial or axial. See Song et al. (2002), and Song et al. (2005).

fMRI connectivity map—An fMRI connectivity map for reading was generated for each individual using four seed points in the (a) left precuneus cortex PCC (MNI $-6, -58.28$ mm, Jülich atlas label GM_Superior_parietal_lobule_7a_L), (b) in the left occipital temporal cortex OTC (MNI $-50, -60, -16$ mm, between Jülich atlas labels GM_Visual_cortex_V4_L and WM_OptiC_radiation_L), (c) in the left supramarginal gyrus SMG (MNI $-52, -32.34$ mm, Jülich atlas label GM_Inferior_parietal_lobule_PF_L), and (d) in the left inferior frontal gyrus, IFG (MNI -52.20 34 mm, Jülich atlas label GM_Broca's_area_BA44_L).

Functional images were corrected for motion using FSL MCFLIRT (Jenkinson et al., 2002), and then high-pass filtered at $\sigma = 20.83$. Motion was also monitored in real time during

scanning by observing the real-time reconstruction display of each fMRI volume on the scanner console. Motion scores (as given in the MCFLIRT report) were computed for each participant and average motion score (mean absolute displacement) for each of the groups: control 1.31 ± 1.37 mm, dysgraphic 1.50 ± 1.23 mm, dyslexic 1.47 ± 1.03 mm, and OWL LD 1.32 ± 0.638 mm. Spikes were identified and removed using the default parameters in AFNI's 3dDespike. Slice-timing correction was applied with FSL's slice-timer and spatial smoothing was performed using a 3D Gaussian kernel with FWHM = 4.0 mm. Time series motion parameters and the mean signal for eroded (1 mm in 3D) masks of the lateral ventricles and white matter (derived from running FreeSurfer's reconall on the T1-weighted image) were analyzed. Co-registration of functional images to the T1 image was performed using boundary-based registration based on a white matter segmentation of the T1 image through `epi_reg` in FSL. The MPAGE structural scan was segmented using FreeSurfer software; white matter regressors were used to remove unwanted physiological components.

Data analyses—For Group analyses, Oxford's fMRIB software library (FSL) randomize, which performs permutations and threshold-free cluster enhancement, was used to control for multiple comparisons. The threshold-free cluster enhancement method controls for the family-wise error rate so that if p-values less than 0.05 are accepted, the chance of one more false positive occurring over all space is no more than 5%. The group statistical images were further controlled for false positives by setting a high threshold of 6.0 for the *t*-score *t*-stat images produced by FSL's software randomize. A global design matrix was used as part of the GLM model in software randomized to make the group statistical maps as described by FSL guidelines for higher group-level analysis as shown by this weblink (http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/glm#Single-Group_Average_28One-Sample_T-Test.29). Group maps for fMRI functional connectivity were generated for the four different seed points described earlier in the left precuneus cortex PCC, in the left occipital temporal cortex OTC, in the left supramarginal gyrus SMG, and in the left inferior frontal gyrus, IFG Broca's area for the fMRI task. fMRI time-series were averaged within regions of interest (ROIs) formed from a 15-mm sphere centered at each seed. The averaged time-series at each ROI was correlated with every voxel throughout the brain to produce functional connectivity correlation maps, converted to *z* statistics using the Fisher transformation. These group maps show where in the brain there was significant fMRI functional connectivity from the seed point with the brain regions of interest because of their known involvement in motor functions—primary motor area BA 4a and 4p, premotor motor area BA 6, and corticospinal tract-and DTI structural connectivity for cerebellum.

A regional analysis was used with custom software (written in FORTRAN), which was able to identify and quantify the brain regions significantly connected to the seed point. The Jülich histological (cyto-and myeloarchitectonic) atlas (Eickhoff et al., 2006, Eickhoff et al., 2007) is part of this software. The Jülich atlas does contain the inferior parietal lobule and its sub-parts which overlap with the angular gyrus.

Results and discussion

Correlations between CELF 4 parent ratings and motor regions of brain

Significant correlations with fMRI connectivity with primary motor area (BA4a or BA4 p):

As shown in Tables 6 (listening) and 7 (speaking), for the primary motor area, a brain region associated with processing and transmitting motor output for acting on the environment, correlations between brain connectivity with it and CELF 4 parent-ratings and brain connectivity were significant for a number of aural or oral language skills: (a) *Listening—has trouble looking at people when talking or listening* from Left Occipital Temporal seed and from Left Inferior Frontal seed (Broca's) with Right Primary Motor Area BA4a; (b) *Speaking—trouble staying on subject when talking* from Left Supramarginal Seed with Right Primary Motor Area BA4p; (c) *Talks in short, choppy sentences* from Left Supramarginal Seed with Left Primary Motor Area, BA4p; (d) *Speaking—trouble completing sentences when talking* from Left Precuneus seed and from Left Supramarginal Gyrus seed with Left Primary Motor Area BA4a; from Left Supramarginal Gyrus seed with bilateral Primary Motor Area BA 4p; from Left Supramarginal Gyrus seed with Right Primary Motor Area 4p; and from Left Occipital Temporal seed with Left Primary Motor Area BA4p. For parent rating of speaking, there was connectivity with a primary motor region from each seed for written words and some connectivity with bilateral primary motor regions! However, correlations were also significant for connectivity with other brain regions involved in motor functions and the parent ratings for listening but not speaking: for *Listening—has trouble paying attention* from Left Inferior Frontal (Broca's) seed with bilateral corticospinal tract; and for *Listening—trouble remembering things people say* from Left Inferior Frontal (Broca's seed) with bilateral corticospinal tract. The corticospinal tract connects cortical functions for higher-level cognitive and language skills with the spine for acting on the world.

As shown in Tables 8 (Reading) and 9 (Writing), for the primary motor area, a brain region associated with processing and transmitting motor output for acting on the environment, correlations between connectivity with it and CELF 4 parent-ratings were significant for a number of written language skills. For reading, correlations were significant for the following: *Reading—has trouble sounding out words when reading* from Left Precuneus seed with right primary motor BA4a; *Reading—has trouble understanding what was read* from Left Precuneus seed with Right Primary Motor Area BA4a and Right Primary Motor Area BA4 p; *Reading—has trouble explaining what was read* from Left Precuneus seed with Left Primary Motor Area BA4a; *Reading—has trouble identifying the main idea* from Left Precuneus seed with Right Primary Motor Area BA4a and from Right Precuneus seed with Right Primary Motor Area, BA4p; and *Reading—has trouble remembering details* from Left Precuneus seed with Left Primary Motor Area BA4a and bilateral Primary Motor Area BA 4p.

However, what was remarkable and not anticipated was the number of significant correlations between the parent ratings for reading and motor-related brain regions other than primary motor area such as premotor area BA 6 involved in motor planning and control; corticospinal tract involved in integrating cortical cognitive and language function with motor output; and DTI indicators of white matter integrity in cerebellum that affect the

structural connections involved in temporal coordination of motor and language functions. These are summarized next. Correlations were significant for the following: *Reading—has trouble sounding out words when reading*, for DTI white matter integrity of Right Fractional Anisotropy and Left Axial Diffusivity in Cerebellum; *Reading—has trouble understanding what read* for functional connectivity from Left Precuneus seed with Right Premotor Area and DTI white matter integrity of Left Axial Diffusivity, Left Radial Diffusivity, and Left Mean Diffusivity in cerebellum; *Reading—has trouble understanding what is read* from Left Precuneus Seed with Bilateral Premotor Area seed BA 6, and DTI white matter integrity of Left Axial Diffusivity, Left Radial Diffusivity, and Left Mean Diffusivity in Cerebellum; *Reading—has trouble explaining what read* for DTI white matter integrity of Left Axial Diffusivity in Cerebellum; *Reading—has trouble following written directions* for DTI white matter integrity of Left Axial Diffusivity in Cerebellum; *Reading—has trouble following written directions* for DTI white matter integrity of Left Axial Diffusivity in Cerebellum; *Reading—has trouble remembering details* for DTI white matter integrity of Left Axial Diffusivity, Left Radial Diffusivity, and Left Mean Diffusivity in Cerebellum.

Compared to reading, fewer correlations were observed between the CELF 4 Parent Ratings of Writing and Motor Regions of the Brain. For *Writing—has trouble putting words in right order when writing sentences*, three involved primary motor areas; fMRI connectivity from Left Occipital Temporal Seed with bilateral Primary Motor Area BA4a and Left Primary Motor Area BA4p; one involved the Left Premotor Area from the Inferior Frontal Gyrus (Broca's Area) seed; and two involved the Bilateral Cortical Spinal Tract from the Left Occipital Temporal seed. Only the one for *Writing—has trouble writing down thoughts* involved DTI White Matter Integrity of Left Axial Diffusivity in Cerebellum. Clearly, the relationships between language and motor functions are involved in writing but not just primary motor regions.

Overall the tested hypothesis for Study 2 was supported. CELF 4 Parent Ratings of each of the language systems were correlated with motor regions of the brain. Not only sensory input but also motor output (primary motor regions) and planning and control for output (secondary association regions) and motor timing (cerebellum) are involved in aural, oral, visible, and written language learning.

General discussion

Moving beyond only explicit phonological and multisensory instruction

Multiple modes of language.: CELF 4 Parent Ratings of all four Language Systems were correlated with normed measures of all four Language Systems (Study 1) and motor regions of the brain (Study 2). Thus, both sensory systems (language by ear—auditory, and language by eye—visual) and motor systems—language by mouth—oro-motor, and language by hand—graphomotor) are involved in literacy learning. Correlations were not restricted to phonological skills in language by ear or mouth. All levels of the multiple language systems matter in some way in literacy learning. The current study also documents the contributions of both behavioral language assessment and brain research (not only fMRI connectivity but also DTI imaging of motor pathways, e.g., Zhang et al., 2015) to understanding the motor functions in language learning. Thus, emphasis in literacy assessment and instruction should

be on multiple modes of language learning rather than restricted to multisensory (Berninger & Wolf, 2016).

The significant correlations between the CELF 4 parent ratings and brain regions involved many motor areas and pathways in the brain: (a) fMRI connectivity with primary motor areas, premotor areas, and corticospinal regions on a word-specific spelling task, and (b) DTI indicators of white matter integrity, which affect structural connectivity in cerebellum. The findings for cerebellum associated with temporal coordination of motor functions involved in language provide additional confirmatory evidence for the longstanding programmatic research of both Nicolson and colleagues (e.g., Nicolson et al., 2002) and Wolf and colleagues (e.g., Wolf et al., 2000). At the same time, writing is not just a motor skill, as is often mistakenly assumed—it is also a written language skill whose many processes need to be temporally coordinated. At a time that advances are being made in handwriting assessment (e.g., Matias, Teulings, Silva, & Melo, 2017) and instruction (e.g., Wawrzyniak, Teulings, Korbecki, Cichy, & Rokita, 2017), it is important to assess and teach both the language and motor bases of writing skills and the executive functions for coordinating them.

Overall, the findings validated the inclusion of CELF 4 parent ratings along with normed achievement measures for assessing listening, speaking, reading, and writing in assessing literacy learning during middle childhood and early adolescence in students with and without SLDs-WL. Educational professionals should reach out to parents and seek their observations and input regarding their child's language learning to create positive rather than adversarial relationships (AlstonAbel & Berninger, 2017).

Limitations and future directions.: This study was conducted in one English-speaking country. Additional research on use of parent ratings of language skills in developing readers and writers is needed in multiple languages and cultures. Progress is being made in developing evidence-based instruction and assessment of response to instruction for students with and without SLDs-WL (e.g., Berninger & Dunn, 2012; Swanson, Harris, & Graham, 2013; Treiman & Kessler, 2014; Troia, 2009), but much work remains in translating this research into educational practice and educating the educators about the processes underlying the writing brain and related language systems. Future research should evaluate whether the current findings replicate when other brain imaging methods and tasks and other measures of listening, speaking, reading, and writing are used and other grade levels, languages, and cultures are studied.

Implications for instruction.: Although the current study involved assessment, it raises issues that may inform instruction based on language and motor skills and not just multiple sensory skills. In addition, there are undoubtedly other skills beyond even language, motor, and sensory processes that should be considered in planning and implementing literacy instruction for both students with and without SLDs-WL.

Cognitive engagement.: Effective ways to facilitate cognitive engagement include adding to explicit literacy instruction hands-on, problem-solving activities such as computer coding (see Thompson et al., 2017) or science experiments (e.g., Berninger, 2000; Berninger et al.,

2008; Winn et al., 2006). Providing science experiments for hands-on cognitive engagement in other studies was effective in improving both reading and writing in students with SLDs-WL and normalizing brain function (for review see Berninger & Richards, 2010). Writing and other hands-on manual activities, for example in the science domain, engage the cognitive portal of mind (thought world; Fayol, Alamargot, & Berninger, 2012), as the prominent roles of the arm and hand touching the head housing the brain in Rodin's sculpture "The Thinker" and of clasped hands and fingers of Rodin's sculpture "The Secret" serve as a reminder.

Interest.: Students who lack interest in what is being taught typically may not pay attention to the content of the teacher's oral instruction, the content of assigned reading material, or the topic of the written assignment, and thus learn from them. Interest affects not only paying attention but also engaging in learning and wanting to learn (motivation; Renninger & Hidi, 2016). The example that follows from an after-school intervention program illustrates how interest may be related to the cognitive domain (familiarity with content and background knowledge) and emotional domain (negative versus positive affect about that topic) as well as engagement in reading lessons. A mother told the research team that the current session would be her fifth-grade daughter's last one because her daughter did not find the lessons interesting. However, at the end of that session the girl announced with a big smile on her face that she could not wait to come back next week and read what comes next. She explained that today she started reading about exploring the oceans of the world, which was very interesting to her because she wanted to be a deep-sea diver and explore ocean life when she finished her education. That was not boring to her like the lessons before when she read about the history of math in human civilization. Indeed, analyses of the growth curves for this student showed a flat effect for growth across the first six lessons about the history of math, but a dramatic escalating slope for improvement across the last six lessons about oceans and world geography and cultures.

Asking students to write an essay on "My Interests In and Out of School" is one way teachers can learn to know individual students' interests and then incorporate them in instruction. Sensory input can also influence interest and facilitate paying attention during literacy learning. Use of animation (movement generates interest that leads to paying attention) to present visual stimuli in motion helps students pay attention to the relevant letter components and letter sequences in computerized handwriting instruction (e.g., Tanimoto, Thompson, Berninger, Nagy, & Abbott, 2015).

Multiple levels of language close in time.: It is also critical that instruction be aimed at all levels of language close in time (e.g., subword, word, syntax, and text) so connections are created among them to integrate them temporally (Berninger & Richards, 2010). See Richards, Nagy, Abbott, and Berninger (2016a) for evidence that the multiple levels of language are involved in the reading brain, all of which must work together in concert for an individual to read and write skillfully (see Richards et al., 2016b). For research evidence at the behavioral level from multiple research groups showing that each of the four language systems (language by ear, by mouth, by eye, and by hand) is multileveled (subword, word, syntax, and text), see Berninger (2015, chapters 7, 8, and 9 and companion websites). For

translating this research evidence into developmentally appropriate instruction and linking instruction with assessment before and after instruction, see Berninger (2015, chapters 4, 5, and 6 and companion websites with instructional resources, many of which could be adapted for other languages and cultures).

At the subword level, research across languages and cultures supports teaching students to become hybrid writers able to use multiple tools for letter production (for review of research see Berninger, 2012, 2013). Research showed that students benefit from two years of manuscript handwriting instruction (Grades 1 to 2 in the United States) embedded in structured language instruction (Wolf, Berninger, & Abbott, 2017) and also cursive handwriting instruction (in Grades 3 or 4 and above), which benefits word spelling and rate of composing in upper elementary and transition to middle school (Alstad et al., 2015). Computer tools should be used not only for accommodations but also for written work in the classroom. Students in the upper elementary and middle school grades benefit from explicit instruction in using multiple technology tools for interfacing with computers (Thompson et al., 2016) and explicit instruction in touch typing (Richards et al., 2016b).

At the word level, English is a morphophonemic orthography (Venezky, 1970, 1999). Thus, learning to spell and read words requires explicit instruction in phonological, orthographic, and morphological awareness (see Nagy, Berninger, & Abbott, 2006; Nagy, Berninger, Abbott, Vaughan, & Vermeulen, 2003). Phonological awareness is necessary, but phonological awareness instruction alone did not lead to brain normalization after intervention for the dyslexia group; combined phonological and morphological awareness did. In a subsequent study, adding orthographic awareness instruction (and its links to morphology and phonology) resulted in brain normalization after instructional intervention, but morphological awareness instruction without orthographic awareness did not (see Berninger & Richards, 2010 for review of the studies). For instructional activities and resources for teaching phonological, orthographic, and morphological awareness and their application to word spelling and phonological decoding and word reading, see Berninger (2015, chapters 4, 5, and 6 and companion websites for resources and readings). For French morphophonemic orthography, see Abbott et al. (2016).

At the sentence level, two instructional activities helped students with syntax impairments affecting reading and writing to improve their sentence writing: rearranging sets of scrambled words into a correct word order that complies with English syntax; and creating sentences from a set of content words (nouns, verbs, adjectives, and adverbs) and a set of function words (prepositions, conjunctions, pronouns, and articles; e.g., Berninger & O'Malley May, 2011; Tanimoto et al., 2015). At the text level, teaching planning, translating, reviewing, and revising narrative and expository genres was effective (see Berninger et al., 2008).

Multiple motor domains.: Multiple-motor domains (talking through mouth and writing through hand) are necessary for integrating both sensory input and motor output with language in learning to read, write, and do math (see Birsch, 2017; Wolf et al., 2017).

Social emotional issues and self-efficacy.: Chronic struggles in learning to read, write, and do math may create social emotional issues including poor self-concept (Gans, Kenny, & Ghany, 2003), poor self-efficacy (belief in one's own abilities; Abbott et al., 2017), anxiety (Nielsen et al., 2017, March), and depression (Maag & Reid, 2006). Prior success or lack thereof in academic achievement plays a major role in developing the cognitive beliefs about one's ability to learn and thus selfconcept and self-identity. For example, students with persisting struggles in learning may develop a sense of not being able to learn (Bandura, 1986; Pajares & Valiante, 2006) and thus develop a sense of learned helplessness, that is, that nothing they do will matter for their learning outcomes and thus they become unmotivated to learn. Shernoff, Csikszentmihayli, Schneider, and Shernoff (2003) showed that students are more likely to engage in and become interested in learning and experience success when they can participate in activities rather than only passively listen to instruction or read instructional materials. Moreover, if students do not develop a sense of self-efficacy that they can be a reader or writer, they may avoid writing and reading (Hen & Goroshit, 2014) and thus fall further behind. Indeed, research has shown that combining training in both strategies for composing and for motivating one's self to write and develop self-efficacy as a writer can improve quality of writing and attitude toward writing in fifth- and sixth-grade students with learning disabilities compared to a control group without learning disabilities (Garcia & de Caso, 2004, 2006). Students also benefit emotionally from engaging in play with language through riddles and jokes, for example, choosing and reading them, discussing why they are funny, and writing their own. Humor can be uplifting in developing positive self-efficacy.

Hope.: Hope has potential for transforming negative self-efficacy into positive self-efficacy via affective response as students receive instruction from others during social interaction—typically an adult teacher (social emotional domain). Lackaye and Margalit (2008) demonstrated that hope was predicted from students' self-efficacy beliefs. Idan and Margalit (2014) applied structural equation modeling to confirm the mediating role of hope between academic self-efficacy and achievement. Many students who participated in interventions at the university research lab initially exhibited in varied ways doubts in their beliefs that they could learn to read and write successfully. One way to facilitate their hope was through hope stories of individuals who overcame initial early struggles and eventually made major contributions to society. For a recent example of how HOPE was added to explicit literacy instruction and hands on engagement see Thompson et al. (2017).

Attention and executive functions.: Attention and executive functions are relevant to learning from teacher talk during oral instruction (Berninger, Abbott, Cook, and Nagy, 2017) as well as the learner's self-regulation of the learning process (e.g., Richards et al., 2017). Examination of the content of compositions in a cross-sectional study grades 1 to 9 (see Berninger, 2009) showed that students in general education wrote more about relationships with other students, the teacher, or family issues. Students still think about social relationships when they are at school (social domain of development) and may not pay attention to academic instruction in the classroom. Teachers can capitalize on this interest in social relationships by providing opportunities for the students to take turns in sharing what they have composed in writing by reading it orally to a group of two or three of their

“writing buddies” just as published authors read their works at public gatherings (e.g., Berninger & Chanquoy, 2012; Berninger, Dunn, Lin, & Shimada, 2004).

There are multiple reasons students may not be able to pay attention while reading. One reason is that students may not pay attention to what they are reading is that they do not have the reading skills to comprehend the read text (language by eye domain) and need explicit reading comprehension instruction. Another reason is insufficient background knowledge to comprehend the content (cognitive domain). That is why teachers often introduce reading lessons by discussing with students the background knowledge needed for the text to be read in that lesson. Texts that have both written sentences and pictorial illustration of content also facilitate attention to written language and engagement in the reading process. However, as ability to complete the reading activities successfully improved, students were less likely to tune out and more able to complete the reading and reading-writing activities without the frequent reminders to pay attention (Tanimoto et al., 2015).

Yet other students may appear not to be interested in writing, but their ability to write, not their lack of interest in writing, is contributing to their poor attention to the writing task at hand. A boy with OWL LD who participated in a writing-readers workshop consistently produced poems instead of conventional written compositions in academic register with syntactically complete sentence construction. His preference for poetry is consistent with recent research documenting the generativity of written expression in multiple genres, including poetry, well beyond the simple distinction between narrative and expository in students with and without SLDs in writing (e.g., Wallis, Richards, Boord, Abbott, & Berninger, 2017). He received an award at school for his creative talent in poetry writing. Also, consistent with the programmatic research of Dunn and colleagues showing the benefits of drawing and art apps for idea generating and planning before writing, translating during writing or revising (Dunn, 2011, 2012a, 2012b; Dunn & Finley, 2008, 2010; Dunn & Miller, 2016; and Dunn, Tudor, Scattergood, & Closson, 2010), this boy also spontaneously illustrated his writing with art. The research team reassured this middle-school student that books need illustrators as well as authors and the world needs poets!

Both extrinsic other-regulation, for example, teachers providing explicit instruction in self-regulated writing strategies, and intrinsic regulation by the self, that is, the developing writer, contribute to development of writing skill (cf. Deci & Ryan, 1985). Research has also shown that extrinsic instruction delivered by “virtual” teachers rather than human teachers can be effective (Raskind, Margalit, & Higgins, 2006), but relatively little research has focused on the effects of “virtual” teachers on learners’ self-efficacy and transforming one’s beliefs from a previous one of learned helplessness due to chronic struggles in learning to empowerment that one can learn successfully. Less research has focused on the role of the self in selfregulation of learning to write rather than the teacher in learning self-regulation strategies. Dunn and colleagues are currently investigating the clues to the self and the self-regulation strategies of the writer that occur in children’s writing that are not preceded by teacher instruction (submitted).

Conclusions

The goal of assessment is often to plan instruction. For this purpose, subword and word-level phonological skills (e.g., Lyon, Shaywitz, & Shaywitz, 2003) are relevant, but so are other language skills: (a) aural and oral skills at the syntax and text levels for language by mouth, and (b) subword, word, syntax, and text level skills for language by eye and by hand. Just as in algebra, there are multiple variables in the equation. As shown by the current results, for both students with and without SLDs-WL, multileveled language by ear, mouth, eye, and hand skills and multimotor skills are evidencebased, as well as multisensory skills, for assessment to plan for instruction.

Acknowledgments

Dr. Richards thanks Kevin Yagle, Paul Robinson, and Peter Boord who helped with the MRI analysis.

Funding

The current study was supported by grant P50HD071764 from the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) at the National Institutes of Health (NIH) USA to the University of Washington Learning Disabilities Research Center.

Biography

Virginia W. Berninger, PhD, Psychology, Johns Hopkins University, is Professor Emerita, Educational Psychology, University of Washington. Her research interests are twofold: (a) interdisciplinary foundational knowledge for learning and instruction that draws upon cognitive, linguistic, social, developmental, and brain science, genetics and epigenetics, and (a) translation science that draws on both the foundational knowledge and practitioner experience/expertise to develop scientifically supported clinical assessment and classroom instruction that optimize learning and development of ALL students. She has conducted studies with interdisciplinary teams that span normal variation in typical learners, specific learning disabilities, developmental and acquired severe physical and communication disabilities, and demonstrations that students from low income families and diverse racial/cultural groups can succeed in public schools.

Todd L. Richards, PhD, Biophysics with emphasis on Neuroscience, University of California, Berkeley, is Professor of Radiology, University of Washington and a core member of the Integrated Brain Imaging Center (IBIC) at the University of Washington. He is interested in neuroimaging studies involving acquisition and analysis of MRI/ MRS data from infant and young children, including infants at risk for developing autism spectrum disorder, premature infants, and children with learning disabilities. He is also interested in utilizing advanced MR imaging techniques such diffusion tensor imaging (DTI) (including fractional anisotropy, DTI tractography, DTI co-registration with structural image, DTI quality control), voxel-based morphometry, cortical thickness, structural brain volume analysis, statistical analysis (including design matrix, design contrast definition, general linear model, mixed-effects models, paired analysis models, repeated analysis of variance models) and anatomical individual analysis extracted from statistical maps. For over 30 years his research has been supported by NIH-funded grants and from 1995–2006 and 2011

to 2016 he headed the brain imaging studies in the University of Washington Multidisciplinary Learning Disabilities Center.

Kathleen H. Nielsen, PhD, Educational Psychology, University of Georgia, was the staff psychologist for the Assessment and Intervention Studies in the Center for Oral and Written Language Learners (OWLS) within the NICHD-funded University of Washington Multidisciplinary Learning Disabilities Center. Her research interests include diagnosis of and intervention for reading and written language disabilities and brain-behavior correlates involved in these diagnoses and brain responses to intervention.

Michael W. Dunn, PhD, Indiana University Bloomington, is an Associate Professor of Special Education and Literacy, Washington State University, Vancouver, WA. His research focuses on students who struggle with writing and those who are identified as having a learning disability—often within a response to intervention (RTI) or multi-tiered system of supports (MTSS) framework. Integrating technology components into intervention designs is often a key aspect of his research. He was a consultant to the University of Washington, Seattle, WA Multidisciplinary Learning Disabilities Center.

Marshall H. Raskind, PhD, Education with specialization in learning disabilities, Claremont Graduate School, is an educational researcher and consultant living on Bainbridge Island, Washington who has collaborated with the University of Washington Multidisciplinary Learning Disabilities Center. His research interests are in learning disabilities with a focus on technological interventions, lifespan development, and factors predictive of positive adult outcomes.

Robert D. Abbott, PhD, Psychology with specialization in Quantitative Psychology, University of Washington is Professor Emeritus, Quantitative Methods and Statistics, University of Washington. His interests include longitudinal data analyses and multi-level modeling which he has applied to interdisciplinary research cross-campus at the University of Washington including Educational Psychology and Social Work. He headed the statistical analyses for the NICHD-funded research on typical writing and reading development, reading and writing instructional intervention, and Literacy Trek Longitudinal Studies 1989–2008 and Multidisciplinary Learning Disabilities Center 1995–2006 and 2011–2016.

References

- Abbott R, Fayol M, Zorman M, Casalis S, Nagy W, & Berninger V (2016). Relationships of French and English morphophonemic orthographies to word reading, spelling, and reading comprehension during early and middle childhood. *Canadian Journal of School Psychology*, 31(4), 305–321. doi:10.1177/0829573516640336 NIHMS 759762 Released to PMC. [PubMed: 27818573]
- Abbott R, Mickail T, Richards T, Renninger A, Hidi S, Beers S, Berninger V (2017, 7). Understanding interest and self-efficacy in the reading and writing of students with persisting specific learning disabilities during middle childhood and early adolescence. *International Journal of Educational Methodology*, 31, 41–64. doi:10.12973/ijem.3.1.41
- Alstad Z, Sanders E, Abbott R, Barnett A, Hendersen S, Connelly V, Berninger V (2015). Modes of alphabet letter production during middle childhood and adolescence: Interrelationships with each other and other writing skills. *Journal of Writing Research*, 6(3), 199–231. doi:10.17239/jowr-2015.06.03.1 [PubMed: 25984288]

- Alston-Abel N, & Berninger V (2017). Relationships between home literacy practices and school achievement: Implications for school-home collaboration and consultation practices. *Journal of Educational and Psychological Consultation*, 1–26. doi:10.1080/10474412.2017.1323222
- Bandura A (1986). The explanatory and predictive score of self-efficacy theory. *Journal of Clinical and Social Psychology*, 4, 359–373. doi:10.1521/jscp.1986.4.3.359
- Barnett A, Henderson L, Scheib B, & Schulz C (2007). *Detailed Assessment of Speed of Handwriting (DASH) copy best and fast*. London, England: Pearson.
- Berninger V (2000). Dyslexia an invisible, treatable disorder: The story of Einstein's Ninja Turtles. *Learning Disability Quarterly*, 23, 175–195. doi:10.2307/1511163
- Berninger V (2007a). *Process assessment of the learner* (2nd ed.). San Antonio, TX: The Psychological Corporation. Now Pearson Diagnostic for Reading and Writing (PALII RW) www.PAL-II.com
- Berninger V (2007b). *Process assessment of the learner diagnostic for math* (PAL II-M). San Antonio, TX: Psychological Corporation. Now Pearson www.PAL-II.com
- Berninger V (2009). Highlights of programmatic, interdisciplinary research on writing. *Learning Disabilities. Research and Practice*, 24, 68–79. NIHMS 124304 PM C2717633 doi:10.1111/j.1540-5826.2009.00281.x
- Berninger V (2012, May-Jun). Strengthening the mind's eye: The case for continued handwriting instruction in the 21st century. *Principal*, 28–31. Retrieved from <http://www.naesp.org/sites/default/files/MJ12%20Berninger.pdf>
- Berninger V (2013, 3). Educating students in the computer age to be multilingual by hand. Invited Commentary on “The Handwriting Debate” NASBE Policy Debate (2012, September) for National Association of State Boards of Education (NASBE), Arlington, VA <http://www.nasbe.org/wp-content/uploads/Commentary-Handwriting-keyboarding-andbrain-development1.pdf>
- Berninger V, Abbott R, Cook C, & Nagy W (2017). Relationships of attention and executive functions to oral language, reading, and writing skills and systems in middle childhood and early adolescence. *Journal Of Learning Disabilities*, 50, 434–449. doi:10.1177/0022219415617167 [PubMed: 26746315]
- Berninger V, & Chanquoy L (2012). What writing is and how it changes across early and middle childhood development: A multidisciplinary perspective In Grigorenko E, Mambrino E, & Preiss D (Eds.), *Writing: A mosaic of perspectives and views* (Ch. 5, pp. 65–84). New York, NY: Psychology Press.
- Berninger V, Dunn A, Lin S, & Shimada S (2004). School evolution: Scientist-practitioner educators creating optimal learning environments for ALL students. *Journal of Learning Disabilities*, 37, 500–508. doi:10.1177/00222194040370060401 [PubMed: 15586468]
- Berninger V, & Dunn M (2012). Brain and behavioral response to intervention for specific reading, writing, and math disabilities: What works for whom? In Wong B & Butler D (Ed.), *Learning about LD* (4th ed., pp. 59–89). Elsevier, Toronto: Academic Press.
- Berninger V, Nielsen K, Abbott R, Wijsman E, & Raskind W (2008). Writing problems in developmental dyslexia: Under-recognized and under-treated. *Journal of School Psychology*, 46, 1–21. doi:10.1016/j.jsp.2006.11.008 [PubMed: 18438452]
- Berninger V, & O'Malley May M (2011). Evidence-based diagnosis and treatment for specific learning disabilities involving impairments in written and/or oral language. *Journal of Learning Disabilities*, 44, 167–183. doi:10.1177/0022219410391189 [PubMed: 21383108]
- Berninger V, Richards T, & Abbott R (2015). Differential diagnosis of dysgraphia, dyslexia, and OWL LD: Behavioral and neuroimaging evidence. *Reading and Writing. An Interdisciplinary Journal*, 28, 1119–1153. [online publication April 21, 2015] doi:10.1007/s11145-015-9565-0
- Berninger V, Winn W, Stock P, Abbott R, Eschen K, Lin C, Garcia N, Anderson-Youngstrom M, Murphy H, Lovitt D, Trivedi P, Jones J, Amtmann D, & Nagy W (2008). Tier 3 specialized writing instruction for students with dyslexia. *Reading and Writing: An Interdisciplinary Journal*, 21, 95–129. doi:10.1007/s11145-007-9066-x
- Berninger V, & Wolf B (2016). *Dyslexia, dysgraphia, OWL LD, and dyscalculia: Lessons from teaching and science* (2nd ed.). Baltimore, MD: Paul H. Brookes. [Also e-book]

- Berninger VW (2015). Interdisciplinary frameworks for schools: Best professional practices for serving the needs of all students. Washington, DC: American Psychological Association. doi:10.1037/14437-002
- Birsch JR (Ed.). (2017). Multisensory teaching of basic language skills (4th ed.). Baltimore, MD: Paul H. Brookes.
- Colligan R, & Katusic S (2015). Overview of epidemiological studies of incidence of learning disabilities with annotated research references from the Mayo Clinic, Rochester, MN In Interdisciplinary Frameworks for schools: Best professional practices for serving the needs of all students. Washington, DC: APA.
- Cook SW, Mitchell Z, & Goldin-Meadow S (2008). Gesturing makes learning last. *Cognition*, 106, 1047–1058. doi:10.1016/j.cognition.2007.04.010 [PubMed: 17560971]
- Deci EL, & Ryan RM (1985). *Intrinsic motivation and self-determination in human behavior*. New York, NY: Plenum.
- Dunn M (2011). Ask, reflect, text: Illustrating story plans with art. *Journal of Research in Childhood Education*, 25(4), 376–389. doi:10.1080/02568543.2011.606758
- Dunn M, & Finley S (2008). Thirsty thinkers: A workshop for artists and writers. *Journal of Reading Education*, 33, 28–36.
- Dunn M, & Miller D (2016). Improving story writing: Integrating the story mnemonic strategy with iPad apps for art and keyboarding. *International Journal for Research in Learning Disabilities*, 3, 11–28.
- Dunn MW (2012a). Illustrating story plans: Does a mnemonic strategy including art media render more elaborated text? *Journal of Visual Literacy*, 31(1), 93–123. doi:10.1080/23796529.2012.11674696
- Dunn MW (2012b). Facilitating children's translation of ideas into written language through combining art activities and self-regulated strategy instruction for writing In Fayol M, Alamargot D, & Berninger V (Eds.), *Translation of thought to written text while composing: Advancing theory, knowledge, methods, and applications* (pp. 275–285). New York, NY: Psychology Press.
- Dunn MW, & Finley S (2010). Exploring children's thoughts about writing: Offering storytelling, visual arts, and keyboarding to promote narrative story writing. *Multicultural Education*, 18(1), 33–42.
- Dunn MW, Tudor D, Scattergood C, & Closson S (2010). Ask, reflect, text: ART as a narrative story-writing strategy. *Childhood Education*, 87(2), 98–105. doi:10.1080/00094056.2011.10521453
- Ehri L (1992). Reconceptualizing the development of sight word reading and its relationship to recoding In Gough PB, Ehri LC, & Treiman R (Eds.), *Reading acquisition* (pp. 107–143). Hillsdale, NJ: Lawrence Erlbaum.
- Eickhoff SB, Heim S, Zilles K, & Amunts K (2006). Testing anatomically specified hypotheses in functional imaging using cytoarchitectonic maps. *NeuroImage*, 32 (2), 570–582. doi:10.1016/j.neuroimage.2006.04.204 [PubMed: 16781166]
- Eickhoff SB, Paus T, Caspers S, Grosbras M-H, Evans AC, Zilles K, & Amunts K (2007). Assignment of functional activations to probabilistic cytoarchitectonic areas revisited. *NeuroImage*, 36(3), 511–521. doi:10.1016/j.neuroimage.2007.03.060 [PubMed: 17499520]
- Fayol M, Alamargot D, & Berninger V (Eds.). (2012). *Translation of thought to written text while composing: Advancing theory, knowledge, methods, and applications*. New York, NY: Psychology Press/Taylor Francis Group.
- Gans AM, Kenny MC, & Ghany DL (2003). Comparing the self-concept of students with and without learning disabilities. *Journal of Learning Disabilities*, 36, 287–295. doi:10.1177/002221940303600307 [PubMed: 15515648]
- Garcia J, & de Caso A (2004). Effects of a motivational intervention for improving the writing of children with learning disabilities. *Learning Disabilities Quarterly*, 27, 141–159. doi:10.2307/1593665
- Garcia J, & de Caso A (2006). Changes in writing self-efficacy and writing products and processes through specific training in the self-efficacy beliefs of students with learning disabilities. *Learning Disabilities: A Contemporary Journal*, 4, 1–27.

- Green J, Moore C, Higashikawa M, & Steeve R (2000). The physiologic development of speech motor control lip and jaw coordination. *Journal of Speech, Language, and Hearing Research*, 43, 239–255. doi:10.1044/jslhr.4301.239
- Hen M, & Goroshit M (2014). Academic procrastination, emotional intelligence, academic self-efficacy, and GPA: A comparison between students with and without learning disabilities. *Journal of Learning Disabilities*, 47, 116–124. doi:10.1177/0022219412439325 [PubMed: 22442254]
- Idan O, & Margalit M (2014). Socioemotional self-perception, family climate, and hopeful thinking among students with learning disabilities and typically achieving students from the same classes. *Journal of Learning Disabilities*, 47, 136–152. doi:10.1177/0022219412439608 [PubMed: 22442252]
- James K, Jao JR, & Berninger V (2015). The development of multi-leveled writing systems of the brain: Brain lessons for writing instruction In MacArthur C, Graham S, & Fitzgerald J (Eds.), *Handbook of writing research* (pp. 116–129). New York, NY: Guilford.
- Jenkinson M, Bannister P, Brady M, & Smith S (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images. *Neuroimage*, 17, 825–841. [PubMed: 12377157]
- Lackaye T, & Margalit M (2008). Self-efficacy, loneliness, effort, and hope: Developmental differences in the experiences of students with learning disabilities and their nonlearning disabled peers in two age groups. *Learning Disabilities: A Contemporary Journal*, 6, 1–20.
- Lyman R, Sanders E, Abbott R, & Berninger V (2017). Translating interdisciplinary research on language learning into identifying specific learning disabilities in verbally gifted and average children and youth. *Journal of Behavioral and Brain Research (JBBS)*, 7(6). [Special issue on Learning Disorders] doi:10.4236/jbbs.2017.76017
- Lyon GR, Shaywitz SE, & Shaywitz BA (2003). A definition of dyslexia. *Annals of Dyslexia*, 53, 1–14. doi:10.1007/s11881-003-0001-9
- Maag JW, & Reid R (2006). Depression among students with learning disabilities: Assessing the risk. *Journal of Learning Disabilities*, 39, 3–10. doi:10.1177/00222194060390010201 [PubMed: 16512079]
- Matias A-R, Teulings H-L, Silva L, & Melo F (2017). Measuring handwriting stability versus context variations. Presentation at the International Graphonomics Society IGS2017.
- Nagy W, Berninger V, & Abbott R (2006). Contributions of morphology beyond phonology to literacy outcomes of upper elementary and middle school students. *Journal of Educational Psychology*, 98, 134–147. doi:10.1037/00220663.98.1.134
- Nagy W, Berninger V, Abbott R, Vaughan K, & Vermeulen K (2003). Relationship of morphology and other language skills to literacy skills in at-risk second graders and at-risk fourth grade writers. *Journal of Educational Psychology*, 95, 730–742. doi:10.1037/00220663.95.4.730
- National Institute of Child Health and Human Development. (2000). Report of the National Reading Panel: Teaching children to read: An evidence-based assessment of the scientific research literature on reading and its implications for reading instruction. Retrieved January 8, 2002, from <http://nationalreadingpanel.org/publications.htm>
- Nicolson RL, Daum L, Schugens M, Fawcett A, & Schultz A (2002). Eyeblick conditioning indicates cerebellar abnormality in dyslexia. *Experimental Brain Research*, 143, 42–50. doi:10.1007/s00221-001-0969-5 [PubMed: 11907689]
- Nielsen K, Haberman K, Richards T, Abbott R, Mickail T, & Berninger V (2017, 3). Emotional and behavioral correlates of persisting specific learning disabilities in written language (SLDs-WL) during middle childhood and early adolescence. *Journal of Psychoeducational Assessment*. NIHMSID 852098. Retrieved from 10.1177/0734282917698056
- Pajares F, & Valiante G (2006). Self-efficacy beliefs and motivation in writing development In MacArthur CA, Graham S, & Fitzgerald J (Eds.), *Handbook of writing research* (pp. 158–170). New York, NY: Guilford Press.
- Pearson. (2009). Wechsler individual achievement test. (3rd ed.). San Antonio, TX: Pearson.
- Purcell J, Turkeltaub PE, Eden GF, & Rapp B (2011). Examining the central and peripheral processes of written word production through meta-analysis. *Frontiers in Psychology*, 2, 1–16. doi:10.3389/fpsyg.2011.00239 [PubMed: 21713130]

- Raskind MH, Margalit M, & Higgins EL (2006). My LD: Children's voices on the Internet. *Learning Disability Quarterly*, 29, 253–268. doi:10.2307/30035553
- Renninger KA, & Hidi S (2016). *The power of interest for motivation and engagement*. New York, NY: Routledge.
- Richards T, Berninger V, Stock P, Altemeier L, Trivedi P, & Maravilla K (2009). fMRI sequential-finger movement activation differentiating good and poor writers. *Journal of Clinical and Experimental Neuropsychology*, 29, 1–17. doi:10.1080/13803390902780201
- Richards T, Nagy W, Abbott R, & Berninger V (2016a). Brain connectivity associated with cascading levels of language. *Journal of Systems and Integrative Neuroscience (JSIN)*, 2, 219–229. doi:10.15761/JSIN.1000139
- Richards T, Peeverly S, Wolf A, Abbott R, Tanimoto S, Thompson R, Berninger V (2016b). Idea units in notes and summaries for read texts by keyboard and pencil in middle childhood students with specific learning disabilities: Cognitive and brain findings. *Trends in Neuroscience and Education*, 5, 146–155. Retrieved from <http://www.journals.elsevier.com/trends-in-neuroscienceand-education/NIHMSID806920> [PubMed: 28133634]
- Richards TL, Abbott RD, Yagle K, Peterson D, Raskind W, & Berninger V (2017, 7 31). Self-government of brain's response to instruction informed by cingulo-opercular network for adaptive control and working memory components for language learning. *Journal of Systems and Integrative Neuroscience (JSIN)*, 3 (4), 1–12. Open Access Text (OAT). doi:10.15761/JSIN.1000173
- Richards TL, Grabowski T, Askren K, Boord P, Yagle K, Mestre Z, . . . Berninger V (2015). Contrasting brain patterns of writing-related DTI parameters, fMRI connectivity, and DTI-fMRI connectivity correlations in children with and without dysgraphia or dyslexia. *Neuroimage Clinical*, 8, 1–14. doi:10.1016/j.nicl.201503.018 [PubMed: 26110109]
- Sanders E, Abbott R, & Berninger V (2017). Sequential prediction of literacy achievement for specific learning disabilities contrasting in impaired levels of language in grades 4 to 9. *Journal of Learning Disabilities*. [Published online February 15, 2017] doi:10.1177/0022219417691048
- Semel E, Wiig EH, & Secord WA (2003). *Examiner's manual: Clinical evaluations of language fundamentals* (4th ed.). San Antonio, TX: Harcourt.
- Sherhoff D, Csikszentmihayli M, Schneider B, & Sherhoff E (2003). Student engagement in high school classrooms from the perspective of flow theory. *School Psychology Quarterly*, 18, 158–176.
- Silliman E, & Berninger V (2011). 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. Retrieved from http://journals.lww.com/topicsinlanguagedisorders/Fulltext/2011/01000/Cross_Disciplinary_Dialogue_about_the_Nature_of.3.aspx
- Song SK, Sun SW, Ramsbottom MJ, Chang C, Russell J, & Cross AH (2002). Demyelination revealed through MRI as increased radial (but unchanged axial) diffusion of water. *Neuroimage*, 17, 1429–1436. doi:10.1006/nimg.2002.1267 [PubMed: 12414282]
- Song S-K, Yoshino J, Le TQ, Lin S-J, Sun S-W, Cross AH, & Armstrong RC (2005). Demyelination increases radial diffusivity in corpus callosum of mouse brain. *Neuroimage*, 26, 132–140. doi:10.1016/j.neuroimage.2005.01.028 [PubMed: 15862213]
- Swanson HL, Harris K, & Graham S (Eds.). (2013). *Handbook of learning disabilities* (2nd ed.). (307–325). New York, NY: Guilford.
- Tanimoto S, Thompson R, Berninger V, Nagy W, & Abbott R (2015). Computerized writing and reading instruction for students in grades 4 to 9 with specific learning disabilities affecting written language. *Journal of Computer Assisted Learning*, 31, 671–689. doi:10.1111/jcal.12110 [PubMed: 26858470]
- Teulings HL, Thomassen A, & van Galen G (1983). Preparation of partly precued handwriting movements: The size of movement units in handwriting. *Acta Psychologica*, 34, 165–177. doi:10.1016/0001-6918(83)90031-8
- Thompson R, Tanimoto S, Abbott R, Nielsen K, Geselowitz K, Lyman R, Habermann K, Mickail T, Raskind M, Peeverly S Nagy W, & Berninger V (2016). Relationships between language input and letter output modes in writing notes and summaries for students in grades 4 to 9 with persisting

writing disabilities. *Assistive Technology Journal*. doi:10.1080/10400435.2016.1199066.
Retrieved from <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5291827>

- Thompson R, Tanimoto S, Lyman R, Geselowitz K, Begay K, Nielsen K, . . . Berninger V (2017, 9 17). Effective instruction for persisting dyslexia in upper grades: Adding hope stories and computer coding to explicit literacy instruction. *Education and Information Technology*. doi:10.1007/s10639-017-9647-5
- Torgesen J, Wagner R, & Rashotte C (1999). *Test of word reading efficiency*. Austin, TX: Pro-Ed.
- Treiman R, & Kessler B (2014). *How children learn to write words*. New York, NY: Oxford University Press.
- Troia G (Ed.). (2009). *Instruction and assessment for struggling writers. Evidence-based practices*. New York, NY: Guilford Press.
- Van den Heuvel M, & Sporns O (2011). Rich-club organization of the human connectome. *The Journal of Neuroscience*, 31, 15775–15786. doi:10.1523/JNEUROSCI.3539-11.2011 [PubMed: 22049421]
- Venezky R (1970). *The structure of English orthography*. The Hague, Netherlands: Mouton.
- Venezky R (1999). *The American way of spelling*. New York, NY: Guilford Press.
- Wallis P, Richards T, Boord P, Abbott R, & Berninger V (2017). Relationships between translation and transcription processes during fMRI connectivity scanning and coded translation and transcription in writing products after scanning in children with and without transcription disabilities. *Creative Education*, 8, 716–748. doi:10.4236/ce.2017.85055 [PubMed: 29600113]
- Wawrzyniak S, Teulings H-L, Korbecki M, Cichy I, & Rokita A (2017). Effects of physical education with EDUballs on first-grade school children's writing skills and handwriting kinematics. Presentation at the International Graphonomics Society IGS2017.
- Winn W, Berninger V, Richards T, Aylward E, Stock P, Lee Y, & Lovitt D (2006). Effects of nonverbal problem solving treatment on skills for externalizing visual representation in upper elementary grade students with and without dyslexia. *Journal Of Educational Computing Research*, 34, 395–418.
- Wolf B, Berninger V, & Abbott R (2017). Effective beginning handwriting instruction: Multimodal, consistent format for 2 years, and linked to spelling and composing. *Reading and Writing. An Interdisciplinary Journal*, 30(2), 299–317. doi:10.1007/s11145-016-9674-42016
- Wolf M, Bowers P, & Biddle K (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities*, 33, 387–407. doi:10.1177/002221940003300409 [PubMed: 15493099]
- Wolff PH, Cohen C, & Drake C (1984). Impaired motor timing control in specific reading retardation. *Neuropsychologia*, 22, 587–600. doi:10.1016/0028-3932(84)90023-X [PubMed: 6504299]
- Wolff PH, Gunnoe C, & Cohen C (1983). Associated movements and developmental age. *Developmental Medicine & Child Neurology*, 25, 417–429. doi:10.1111/j.1469-8749.1983.tb13786.x [PubMed: 6618020]
- Wolff PH, Gunnoe C, & Cohen C (1985). Associated movements and developmental age. *Developmental Medicine & Child Neurology*, 27, 344–354. doi:10.1111/j.1469-8749.1985.tb04546.x [PubMed: 4018429]
- Woodcock R, McGrew K, & Mather N (2001a). *Woodcock-Johnson III psychoeducational cognitive test battery*. Itasca, IL: Riverside.
- Woodcock R, McGrew K, & Mather N (2001b). *Woodcock-Johnson III achievement battery*. Itasca, IL: Riverside.
- Yagle K, Richards T, Askren K, Mestre Z, Beers S, Abbott R, . . . Berninger V (2017). Relationships between eye movements during sentence reading comprehension, word spelling and reading, and DTI and fMRI connectivity in students with and without dysgraphia or dyslexia. *Journal of Systems and Integrated Neuroscience*, 3(1), 1–11. NIHMS 846434. 10.15761/JSIN.1000150
- Zhang M, Lin Q, Lu J, Dongdong R, Zhao Z, Ma Q, . . . Li K (2015). Pontine infarction: Diffusion-tensor imaging of motor pathways—A longitudinal study. *Radiology*, 274, 841–850. doi:10.1148/radiol.14140373 [PubMed: 25356962]

Table 1.

Means (standard deviations) for diagnostic assessment battery by diagnostic group for behavioral and brain imaging study standard scores ($M = 100$, $SD = 15$), Scaled Scores ($M = 10$, $SD = 3$), z scores ($M = 0$, $SD = 1$).

	Controls	Dysgraphia	Dyslexia	OWL LD
I Behavioral Study				
WJ III Oral Comprehension	111.45 (11.36)	114.06 (10.69)	113.66 (8.85)	94.57 (13.14)
CELF 4 Formulated Sentences	11.98 (2.65)	10.31 (2.89)	11.36 (0.36)	6.14 (2.65)
UW Alphabet 15	-0.56 (0.78)	-1.58 (0.66)	-1.11 (0.80)	-1.40 (0.62)
DASH Copy Best	12.42 (2.59)	8.44 (3.20)	9.36 (3.41)	8.71 (3.74)
DASH Copy Fast	11.24 (2.53)	6.53 (2.84)	7.74 (3.26)	6.38 (3.85)
WIAT 3 Spelling	109.59 (13.71)	97.69 (19.29)	85.53 (10.80)	80.71 (12.22)
WIAT 3 Sentence Combining	113.05 (11.11)	100.83 (17.46)	98.49 (14.21)	87.94 (11.48)
WJ III Writing Fluency	108.47 (11.55)	96.94 (12.67)	96.48 (10.37)	79.10 (15.28)
WJ III Word Identification	109.69 (11.07)	108.71 (11.20)	96.40 (10.85)	88.40 (10.97)
WJ III Word Attack	105.17 (9.78)	105.29 (11.85)	93.91 (10.58)	90.14 (9.72)
TOWRE—Sight Word	109.88 (13.31)	109.26 (14.06)	93.16 (12.72)	87.10 (13.58)
TOWRE—Phonemic	109.45 (14.93)	106.32 (16.68)	88.34 (12.62)	80.52 (17.67)
WJ III Passage Comprehension	104.73 (9.15)	104.26 (11.10)	99.04 (11.89)	79.60 (11.70)
Brain Imaging Study				
WJ III Oral Comprehension	112.00 (6.00)	108.36 (8.39)	113.67 (10.71)	95.80 (8.11)
CELF 4 Formulated Sentences	12.78 (1.92)	9.57 (3.01)	12.27 (2.40)	6.20 (1.30)
UW Alphabet 15	-0.64 (1.23)	-1.60 (0.63)	-1.48 (0.73)	-1.06 (0.49)
DASH Copy Best	11.44 (3.24)	7.57 (2.93)	8.20 (3.08)	9.60 (5.50)
DASH Copy Fast	10.33 (2.29)	6.00 (2.69)	7.40 (3.16)	7.00 (5.05)
WIAT 3 Spelling	108.89 (14.34)	98.07 (16.78)	85.40 (9.11)	68.80 (10.69)
WIAT 3 Sentence Combining	111.56 (8.47)	102.36 (15.03)	99.87 (16.25)	98.00 (9.43)
WJ III Writing Fluency	108.22 (7.73)	99.08 (13.97)	94.07 (7.59)	80.80 (13.48)
WJ III Word Identification	113.11 (13.95)	109.46 (9.34)	95.80 (9.97)	84.60 (2.70)
WJ III Word Attack	105.22 (6.14)	106.08 (10.43)	95.40 (8.24)	84.00 (9.06)
TOWRE—Sight Word	113.11 (13.95)	110.23 (14.22)	96.60 (12.57)	82.80 (14.48)
TOWRE—Phonemic	112.56 (14.66)	106.15 (16.53)	86.00 (11.83)	75.20 (5.83)
WJ III Passage Comprehension	107.78 (10.32)	103.46 (10.93)	99.93 (10.32)	78.00 (8.98)

Table 2.

Pearson product moment correlations (r 's) between CELF 4 parent ratings for listening and behavioral measure of listening, speaking, reading, and writing achievement.

Listening Item	Typical	Dysgraphia	Dyslexia	OWL LD
Has Trouble Paying Attention	ns	ns	ns	
Alphabet Writing 15 sec				-.67**
Has Trouble Following Spoken	ns			ns
Directions				
TOWRE Phonemic		-.42*		
WJ III Writing Fluency			-.28*	
Has Trouble Remembering	ns	ns		
Things People Say				
WJ III Word Attack			-.30*	
WJ III Passage Comprehension			-.35**	
Alphabet Writing 15 sec				-.71***
Copy Best			-.32**	
Copy Fast			-.35**	
WIAT 3 Spelling			-.26*	
WJ III Writing Fluency			-.30*	
WIAT 3 Sentence Combining				-.55*
Has Trouble Understanding		ns	ns	
What People Are Saying				
WJ III Oral Comprehension	-.36*			
WJ III Word Attack				.50*
WJ III Passage Comprehension	-.39**			
Alphabet Writing 15 sec				-.58**
WIAT 3 Spelling	-.31*			
WIAT 3 Sentence Combining	-.43**			
Has to Ask People to Repeat	ns		ns	ns
What They Have Said				
WJ III Writing Fluency		.42*		
Has Trouble Understanding the Meaning of Words				
WJ III Oral Comprehension	-.40**	-.43*	-.43***	
WJ III Word Identification	-.33*			
TOWRE Sight		-.39*		-.60**
Alphabet Writing 15 sec	-.40**			
WIAT 3 Spelling				
WIAT 3 Sentence Combining			-.29*	

Listening Item	Typical	Dysgraphia	Dyslexia	OWL LD
WJ III Writing Fluency			-.26 [*]	
Has Trouble Understanding				ns
New Ideas				
WJ III Oral Comprehension	-.48 ^{**}	-.62 ^{***}	-.34 ^{**}	
CELF4 Formulated Sentences		-.45 ^{**}		
WJIII Word Identification				
TOWRE Sight		-.47 ^{**}		
WJ III Passage Comprehension	-.33 [*]	-.42 [*]		
WIAT 3 Word Spelling		-.51 ^{**}		
Has Trouble Looking at People	ns	ns	ns	ns
When Listening or Speaking				
Has Trouble Understanding	ns		ns	
Facial Expressions				
WJ III Oral Comprehension		-.42 [*]		
DASH Copy Fast				.47 [*]

Note.

^{*}
 $p < .05$

^{**}
 $p < .01$

^{***}
 $p < .001$.

ns = not statistically significant.

Table 3.

Pearson product moment correlations (r 's) between CELF4 parent ratings for speaking and behavioral measure of listening, speaking, reading, and writing achievement.

Speaking Item	Typical	Dysgraphia	Dyslexia	OWL LD
Has trouble answering questions people ask		ns		
Automatic Alphabet Writing 15 sec				-.51 *
WJ III Oral Comprehension	-.38 *			
DASH Copy Best			-.28 *	
WJ III Writing Fluency			-.25 *	
Has trouble answering questions as quickly as other students	ns	ns		
DASH Copy Best			-.36 **	
WIAT3 Spelling				.55 *
WIAT 3 Sentence Combining			-.26 *	
Has trouble for asking for help when needed	ns	ns		ns
WJ III Writing Fluency			-.27 *	
Has trouble asking questions	ns	ns	ns	ns
Has trouble using a variety of vocabulary words when talking		ns	ns	ns
WJ III Word Identification	.46 *			
WJ III Word Attack	-.38 *			
TOWRE Phonemic	-.32 *			
WIAT 3 Spelling	-.38 *			
Has trouble thinking of (finding) the right word to say		ns	ns	ns
CELF4 Formulated Sentences	-.36 *			
WIAT III Sentence Combining	-.38 *			
Has trouble expressing thoughts	ns	ns	ns	
WIAT 3 Spelling				.55 *
Has trouble describing things to People		ns		
Automatic Alphabetic Writing 15 sec				-.60 **
WJ III Oral Comprehension	-.32 *		-.26 *	
CELF 4 Formulated Sentences		ns		ns
Has trouble staying on a topic when talking		ns		ns
CELF 4 Formulated Sentences		ns		ns
Has trouble staying on a topic when talking		ns		ns
CELF 4 Formulated Sentences		ns		ns
Has trouble staying on a topic when talking		ns		ns
CELF 4 Formulated Sentences		ns		ns
Has trouble staying on a topic when talking		ns		ns
WJ III Oral Comprehension	-.38 *			
WIAT 3 Spelling	-.31 *			
WIAT III Sentence Combining	-.40 **		.27 *	

Speaking Item	Typical	Dysgraphia	Dyslexia	OWL LD
Has trouble getting to the point when talking		ns	ns	ns
Alphabet Writing 15 sec	-.36 *			
Has trouble putting the events in the right order when telling stories		ns	ns	
CELF 4 Formulated Sentences				.55 *
WJ III Writing Fluency	-.36 *			
Uses poor grammar when talking		ns		ns
WJ III Oral Comprehension	-.40 *		.31 *	
CELF4 Formulated Sentences	-.37 *			
WJ III Word Attack	-.34 *			
TOWRE Phonemic	-.38 *			
WJ III Passage Comprehension	-.33 *		-.29 *	
WIAT 3 Spelling	-.41 **			
WJ III Writing Fluency	-.39 *			
Has trouble using complete sentences when talking		ns	ns	ns
CELF4 Formulated Sentences	-.37 *			
TOWRE Phonemic	-.34 *			
WJ III Passage Comprehension	-.34 *			
WIAT 3 Spelling	-.37 *			
WIAT 3 Sentence Combining	-.34 *			
WJ III Writing Fluency	-.41 *			
Talks in short, choppy sentences		ns	ns	ns
CELF 4 Formulated Sentences	-.39 **			
WJ III Passage Comprehension	-.37 *			
Has trouble expanding an answer or providing details when talking	ns	ns	ns	ns
Has trouble having a conversation with someone		ns	ns	ns
WJ III Oral Comprehension	-.36 *			
Has trouble talking with a group of people	ns	ns		ns
WJ III Word Identification			.25 *	
Has trouble saying something another way when someone doesn't understand	ns	ns	ns	
Automatic Alphabet Writing 15 seconds				-.55 *
WIAT 3 Sentence Combining				-.53 *
Gets upset when people don't understand	ns	ns	ns	
Automatic Alphabet Writing 15 seconds				-.50 *

* $p < .05$

** $p < .01$

*** $p < .001$

ns = not statistically significant.

Table 4.

Pearson product moment correlations (r 's) between CELF 4 parent ratings for reading and behavioral measure of listening, speaking, reading, and writing achievement.

Reading Item	Typical	Dysgraphia	Dyslexia	OWL LD
Has Trouble Sounding Out		ns		
Words When Reading				
WIAT3 Spelling	-.40 **		-.26 *	-.48 *
WIAT3 Sentence Combining	-.40 **			
WJ III Writing Fluency			-.34 **	
WJ III Word Identification			-.53 ***	-.50 *
TOWRE Sight			-.32 **	-.58 *
WJ III Word Attack			-.29 *	
TOWRE Phonemic			-.39 **	
WJ III Passage Comprehension			-.30 *	
Has Trouble Understanding				ns
What Is Read				
WJ III Oral Comprehension	-.56 ***	-.40 *		
WIAT 3 Spelling	-.49 ***	-.40 *		
WIAT 3 Sentence Combining	-.43 **			
WJ III Word Identification	-.44 **	-.52 **	-.36 **	
TOWRE Sight	-.36 *			
WJ III Word Attack	-.37 *	-.38 *		
TOWRE Phonemic	-.39 *	-.40 *	-.32 **	
WJ III Passage Comprehension	-.35 *		-.38 **	
Has Trouble Explaining What Was Read				
WJ III Oral Comprehension	-.43 **		-.25 *	
DASH Copy Best		.38 *		.57 *
DASH Copy Fast				.65 **
WIAT 3 Spelling	-.42 **			.55 *
WIAT 3 Sentence Combining	-.48 **			
WJ III Writing Fluency			-.27 *	.58 *
WJ III Word Identification	-.44 **	-.50 **	-.35 **	
TOWRE Sight	-.42 **			
WJ III Word Attack	-.40 **			
TOWRE Phonemic	-.47 **		-.33 **	
WJ III Passage Comprehension	-.34 *		-.32 **	
Has Trouble Identifying the Main Idea				

Reading Item	Typical	Dysgraphia	Dyslexia	OWL LD
WJ III Oral Comprehension	-.46 ^{**}		-.34 ^{**}	
DASH Copy FAST				.56 [*]
WIAT 3 Spelling	-.35 [*]	-.57 ^{***}		
WIAT 3 Sentence Combining	-.50 ^{***}	-.35 [*]	-.27 [*]	
WJ III Word Identification	-.36 [*]	-.47 ^{**}		
TOWRE Sight	-.39 ^{**}		-.27 [*]	
WJ III Word Attack	-.33 [*]		-.25 [*]	
TOWRE Phonemic	-.35 [*]		-.33 ^{**}	
WJ III Passage Comprehension		-.50 ^{**}		
Has Trouble Remembering Details				ns
CELF 4 Formulated Sentences		-.57 ^{***}		
WIAT 3 Spelling		-.47 ^{**}		
WJ III Writing Fluency			-.26 [*]	
WJ III Word Identification	-.31 [*]	-.53 ^{**}	-.25 [*]	
TOWRE Sight				
WJ III Word Attack		-.38 [*]		
TOWRE Phonemic	-.32 [*]	-.40 [*]	-.31 ^{**}	
WJ III Passage Comprehension		-.49 ^{**}	-.36 ^{**}	
Has Trouble Following Written Directions				
WJ III Oral Comprehension			-.27 [*]	
CELF 4 Formulated Sentences		-.46 ^{**}		
WIAT 3 Spelling	-.33 [*]	-.44 [*]		
WIAT 3 Sentence Combining			-.26 [*]	
WJ III Word Identification		-.45 [*]	-.37 ^{**}	
TOWRE Sight		-.39 [*]		-.72 ^{***}
WJ III Word Attack			-.27 [*]	
WJ III Passage Comprehension			-.35 ^{**}	

Note.

*
 $p < .05$

**
 $p < .01$

 $p < .001$.

ns = not statistically significant.

Table 5.

Pearson product moment correlations (*r*'s) between CELF 4 parent ratings for writing and behavioral measures of listening, speaking, reading, and writing.

Writing Item	Typical	Dysgraphia	Dyslexia	OWL LD
Has Trouble Writing Down Thoughts	ns	ns		
WJ III Oral Comprehension				.68**
DASH Copy Fast			-.35**	
WJ III Writing Fluency			-.27*	
Uses Poor Grammar When Writing			ns	ns
WJ III Oral Comprehension				
DASH Copy Best		.47**		
WJ III Oral Comprehension	-.36*			
WIAT 3 Spelling	-.43**			
WIAT3 Sentence Combining	-.34*			
TOWRE Phonemic	-.32*			
Has Trouble Writing Complete Sentences				
DASH Copy Best				-.56*
WIAT 3 Spelling			-.26*	-.48*
TOWRE Sight		-.42*		
TOWRE Phonemic	-.32*			
Writes Short, Choppy Sentences		ns	ns	
DASH Copy Fast	-.42*			
DASH Copy Best				-.54*
Has Trouble Expanding on an Answer or Providing Details When Writing		ns		
WJ III Oral Comprehension	-.51**			
DASH Copy Fast	-.36*		-.29*	
DASH Copy Best				-.57*
WJ III Writing Fluency			-.30*	
Has Trouble Putting Words into the Right		ns		
Order When Writing Sentences				
WIAT 3 Spelling			-.27*	-.49*
WIAT 3 Sentence Combining	-.38*			
WJ III Writing Fluency	-.48**			
WJ III Word Attack			-.27*	

Note.

* $p < .05$

** $p < .01$

 $p < .001$.

ns = not statistically significant.

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Table 6.

Significant correlations of CELF 4 parent ratings for listening items with fMRI connectivity of significant magnitude from seeds for written words with brain regions associated with motor regions.

<u>Listening—Has trouble looking at people when talking or listening</u>	
fMRI connectivity from Left Occipital Temporal seed with Right Primary Motor BA4a, $r = -.30$, $p = .05$	
fMRI connectivity from Left Inferior Frontal Gyrus (Broca's Area) with Right Primary Motor Area BA4a, $r = -.33$, $p = .04$	
<u>Listening—Has trouble paying attention</u>	
fMRI connectivity from Left Inferior Frontal Gyrus (Broca's Area) with Left White Matter Corticospinal Tract, $r = -.33$, $p = .03$	
fMRI connectivity from Left Inferior Frontal Gyrus (Broca's area) with Right White Matter Corticospinal Tract, $r = -.33$, $p = .03$	
<u>Listening—Has trouble remembering things people say</u>	
fMRI connectivity from Left Inferior Frontal Gyrus (Broca's Area) with Left White Matter Corticospinal Tract, $r = -.33$, $p = .03$	
fMRI connectivity from Left Inferior Frontal Gyrus (Broca's Area) with Right White Matter Corticospinal Tract, $r = -.33$, $p = .03$	

Note. No significant DTI findings for cerebellum on any CELF 4 listening item.

Table 7.

Significant correlations of CELF 4 parent ratings for speaking items with fMRI connectivity of significant magnitude from seeds for written words with brain regions associated with motor regions.

<u>Trouble using complete sentences when talking</u>	
fMRI connectivity from Left Precuneus with Left Primary Motor Area, BA4a, $r = .32$, $p = .04$	
fMRI connectivity from Left Occipital Temporal with Left Primary Motor Area, BA4a, $r = .31$, $p = .05$	
fMRI connectivity from Left Occipital Temporal with Left Primary Motor Area, BA4p, $r = .42$, $p < .01$	
fMRI connectivity from Left Supramarginal with Left Primary Motor Area, BA4a, $r = .37$, $p < .05$	
fMRI connectivity from Left Supramarginal with Right Primary Motor Area, BA4a, $r = .34$, $p < .05$	
fMRI connectivity from Left Supramarginal with Left Primary Motor Area BA4p, $r = .41$, $p < .01$	
fMRI connectivity from Left Supramarginal with Right Primary Motor Area BA4p, $r = .32$, $p < .05$	
<u>Trouble staying on subject when talking</u>	
fMRI connectivity from Left Supramarginal with Right Primary Motor Area, BA4p, $r = -.30$, $p = .05$	
Talks in short, choppy sentences	
fMRI connectivity from Left Supramarginal with Left Primary Motor Area, BA4p, $r = .31$, $p < .05$	

Note. No significant DTI findings for cerebellum on any CELF 4 speaking item.

Table 8.

Significant correlations of CELF 4 parent ratings for reading items with fMRI connectivity of significant magnitude from seeds for written words with brain regions associated with motor regions.

<u>Reading—has trouble sounding out words when reading</u>	
fMRI connectivity from Left Precuneus with Right Primary Motor Area, BA4a, $r = .31, p < .05$	
DTI connectivity for Right Fractional Anisotropy in Cerebellum, $r = .35, p < .05$	
DTI connectivity for Left Axial Diffusivity in Cerebellum, $r = -.31, p = .05$	
<u>Reading—has trouble understanding what read</u>	
fMRI connectivity from Left Precuneus with Right Primary Motor Area, BA4p, $r = .31, p = .05$	
fMRI connectivity from Left Precuneus with Right Primary Motor Area, BA4a, $r = .33, p < .05$	
fMRI connectivity from Left Precuneus with Left Premotor Area, BA6, $r = .30, p = .05$	
fMRI connectivity from Left Precuneus with Right Premotor Area, BA6, $r = .33, p < .05$	
DTI connectivity for Left Axial Diffusivity in Cerebellum, $r = -.37, p < .05$	
DTI connectivity for Left Radial Diffusivity in Cerebellum, $r = -.31, p < .05$	
DTI connectivity for Left Mean Diffusivity in Cerebellum, $r = -.32, p < .05$	
<u>Reading—has trouble explaining what was read</u>	
fMRI connectivity from Left Precuneus with Left Primary Motor Area, BA4a, $r = .31, p < .05$	
DTI connectivity for Left Axial Diffusivity in Cerebellum, $r = .31, p = .05$	
<u>Reading—has trouble following written directions</u>	
DTI connectivity for Left Axial Diffusivity in Cerebellum, $r = -.35, p < .05$	
<u>Reading—has trouble identifying the main idea</u>	
fMRI connectivity from Left Precuneus with Right Primary Motor Area, BA4a, $r = .33, p < .05$	
fMRI connectivity from Right Precuneus with Right Primary Motor Area, BA4p, $r = .35, p < .05$	
<u>Reading—has trouble remembering details</u>	
fMRI connectivity from Left Precuneus with Left Primary Motor Area, BA4a, $r = .31, p < .05$	
fMRI connectivity from Left Precuneus with Left Primary Motor Area, BA4p, $r = .34, p < .05$	
fMRI connectivity from Left Precuneus with Right Primary Motor Area, BA4p, $r = .32, p < .05$	
DTI connectivity for Left Axial Diffusivity in Cerebellum, $r = -.40, p = .01$	
DTI connectivity for Left Radial Diffusivity in Cerebellum, $r = -.34, p < .05$	
DTI connectivity for Left Mean Diffusivity in Cerebellum, $r = -.32, p < .05$	

Table 9.

Significant correlations of CELF 4 parent ratings for writing items with fMRI connectivity of significant magnitude from seeds for written words with brain regions associated with motor regions.

<u>Writing—trouble putting words in right order when writing sentences</u>	
fMRI connectivity from Left Occipital Temporal with Left White Matter Corticospinal Tract, $r = -.34$, $p < .05$	
fMRI connectivity from Left Occipital Temporal with Right White Matter Corticospinal Tract, $r = -.33$, $p < .05$	
fMRI connectivity from Left Occipital Temporal with Right Primary Motor Area, BA4a, $r = -.37$, $p = .05$	
fMRI connectivity from Left Occipital Temporal with Left Primary Motor Area, BA4p, $r = -.41$, $p < .05$	
fMRI connectivity from Left Inferior Frontal Gyrus (Broca's Area) with Left Primary Motor Area, BA 4a, $r = .32$, $p < .05$	
fMRI connectivity from Left Inferior Frontal Gyrus (Broca's Area) with Left Premotor Area, BA6a, $r = -.32$, $p < .05$	
<u>Writing—has trouble writing down thoughts</u>	
DTI connectivity for Left Axial Diffusivity in Cerebellum, $r = -.31$, $p = .05$	