Neuroscience

Brain and Behavioral Assessment of Executive Functions for Self-Regulating Levels of Language in Reading Brain

Virginia W. Berninger[1,*], Todd L. Richards[2], and Robert D. Abbott[3]

[1] Educational Psychology, Learning Sciences and Human Development, [2] Integrated Brain Imaging Center, Department of Radiology, and [3] Educational Statistics and Measurement, University of Washington, Seattle, WA, USA

This brief research report examines brain-behavioral relationships specific to levels of language in the complex reading brain. The first specific aim was to examine prior findings for significant fMRI connectivity from four seeds (left precuneus, left occipital temporal, left supramarginal, left inferior frontal) for each of four levels of language—subword, word (word-specific spelling or affixed words), syntax (with and without homonym foils or affix foils), and multi-sentence text to identify significant fMRI connectivity (a) unique to the lower level of language when compared to the immediately higher adjacent level of language across subword-word, word-syntax, and syntax-text comparisons; and (b) involving a brain region associated with executive functions. The second specific aim was to correlate the magnitude of that connectivity with standard scores on tests of Focused Attention (D-K EFS Color Word Form Inhibition) and Switching Attention (Wolf & Denckla Rapid Automatic Switching). Seven correlations were significant. Focused Attention was significantly correlated with the word level (word-specific spellings of real words) fMRI task in left cingulum from left inferior frontal seed. Switching Attention was significantly correlated with the (a) subword level (grapheme-phoneme correspondence) fMRI task in left and right Cerebellum V from left supramarginal seed; (b) the word level (word-specific spelling) fMRI task in right Cerebellum V from left precuneus seed; (c) the syntax level (with and without homonym foils) fMRI task in right Cerebellum V from left precuneus seed and from left supramarginal seed; and (d) syntax level (with and without affix foils) fMRI task in right Cerebellum V from left precuneus seed. Results are discussed in reference to neuropsychological assessment of supervisory attention (focused and switching) for specific levels of language related to reading acquisition in students with and without language-related specific learning disabilities and self-regulation of the complex reading brain.

level of language | unique fMRI connectivity | brain executive functions | supervisory attention | focused attention | switching attention

As explained in (1), language is not a homogenous construct. It can be described, used, and understood at multiple levels ranging from subword units (smaller than a word) to word units to syntax units to text units containing multiple sentences. Likewise, language is not a single system in the brain. Rather, language links with sensory or motor systems to create four functional language systems: language by ear (listening), language by mouth (oral expression), language by eye (reading), and language by hand (written expression). Each of these systems is comprised of multiple levels of cascading units of increasing size that draw on adjacent units of smaller size: subword to word to syntax to multi-sentence text. Although these language systems are separable they also become integrated as language learners develop and interact with their language learning environment. Each level of language alone and in concert with other levels of language contributes to orchestration of mind (2) for language. Prior research showed that each level of language has a different pattern of significant fMRI connectivity (3), but that research did not examine whether there is some common as well as unique connectivity across adjacent levels of language cascading in size (e.g., subword and word or word and syntax or syntax and text). Executive functions were of interest because they may play a role in self-regulation of the components within each of the levels of language within the multi-level reading brain.

Methods

Participants

As described in (3), 30 students in grades 4 to 9 completed the fMRI study of reading tasks at multiple levels of language. All had completed comprehensive assessment and were assigned to groups based on current test scores [see (3) for details about ascertainment and assessment that included current and past educational and developmental histories as well as test scores and Table 1 of (3) for means and standard deviations of test measures]. Altogether 4 males and 5 females in grade 5 (n=1), grade 6 (n=2), grade 8 (n=3), or grade 9 (n=3) (age range 10 to 14) qualified for participation as typical readers in the control group. Altogether 10 males and 6 females in grades 4 (n=3), 5 (n=1), 6 (n=5), 7 (n=4), 8 (n=1), and 9 (n=2) qualified for the dyslexia group (impaired word level reading and spelling but no listening comprehension impairment). Altogether 2 males and 3 females in grades 4 (n=1), 5 (n=1), 6 (n=1), and 7 (n=2) qualified for the oral and written language learning disability (OWL LD group) (impaired listening comprehension, reading comprehension, oral expression, and/or written expression skills and a preschool history of struggling with oral language learning). All participants were in the age range of 10 to 14 and were of European-American ethnicity; and their biological or adoptive parents had at least some postsecondary education or a college degree.

Specific Aim 1

The first specific aim of the current extension of that prior research was to identify the unique significant connectivity across those adjacent levels, that is, that occurs only in the lower level of language (smaller unit size) and not in the next higher level of language (larger unit size composed of units of the lower level). A related goal of the first specific aim was then to identify which of the unique significant connections across adjacent levels of language involved brain regions known to be associated with executive functions.

Based on past research four brain regions were hypothesized to play a role in executive functions involved in self-regulation of levels of language in reading. The first was inferior frontal gyrus

Conflict of Interest: No conflicts declared.
* Corresponding Author. Email: vwberninger@comcast.net

(Broca's area). For evidence of the role of inferior frontal gyrus in the executive functions for language in the human brain see (4). The second was cingulum for which there is also substantial evidence for its role in executive control of language learning (5, 6). The third was insula. There is considerable evidence regarding the role of insula in limbic system and affect control, for example, the anxiety that some students with chronic struggles in learning may experience (7). However, evidence is also emerging for the role of insula in self-regulation of internal cognitive control and attentional processes related to the external environment as well as processing salient stimuli and coordinating with cingulate for rapid motor access for acting on the environment (8). The fourth was cerebellum which has been shown to coordinate not only timing of motor acts but also timing of cognitive and language tasks (9, 10).

Specific Aim 2

The second specific aim of the current study was to investigate clinical measures of executive functions that may self-regulate components within a specific level of language, namely two involved in supervisory attention: inhibitory control underlying focused attention and attentional flexibility underlying switching attention (11). Thus, for purposes of Specific Aim 2 the Delis-Kaplan Executive Functions D-KEFS (12) was used to operationalize inhibitory control and Rapid Automatic Naming (RAS) (13) was used to operationalize attentional flexibility. These clinical measures given to assess supervisory attention at the behavioral level were correlated with the magnitude of the unique fMRI connectivity involving brain regions associated with executive functions for each of the four levels of language assessed with fMRI tasks. The goal of the second specific aim was to identify significant correlations between supervisory attention at the behavioral level and brain connectivity at the neurological level involving executive functions for specific levels of language. Only the magnitude of the significant unique connectivity for a specific level of language in reading, which was identified on basis of both stated criteria in Specific Aim 1, was correlated with a behavioral measure of an executive function in Specific Aim 2.

fMRI Connectivity Acquisition and Analyses

FMRI scans were performed on a 3T Philips scanner with echo-planar gradient echo pulse sequence (single shot) with the following parameters: TR/TE 2000/25 ms; Field of view 240 × 240 × 99 mm; slice orientation transverse, acquisition voxel size 3.0 × 3.08 × 3.0 mm; acquisition matrix 80 × 80 × 33; slice thickness 3.0; dynamic scans 396, acquisition time 13:26 min.

An fMRI connectivity map for reading was generated for each individual using four seed points in the left precuneus cortex PCC (MNI -6,-58,28 mm, Jülich atlas label GM_Superior_parietal_lobule_7a_L), 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), in the left supramarginal gyrus SMG (MNI -52,-32,34 mm, Jülich atlas label GM_Inferior_parietal_lobule_PF_L), and in the left inferior frontal gyrus, IFG (MNI -52,20 34 mm, Jülich atlas label GM_Broca's_area_BA44_L). fMRI time- series were averaged within regions of interest (ROIs) formed from a 15 mm sphere centered at each seed point. The averaged time-series at each ROI was correlated with every voxel throughout the brain to produce functional connectivity correlation maps and converted to z statistics using the Fisher transformation.

Analyses of fMRI Tasks

In this brief research report extending a prior study we focus on the methods for the new analyses related to unique connectivity for specific levels of language in the multi-leveled reading brain (first specific aim). Six fMRI tasks were administered while a participant's brain was scanned. The first task involved subword level judgments—deciding if each one- or two-letter grapheme in a pair corresponds to the same phoneme.

The second task involved word level judgments—deciding if word pairs were correctly spelled real words (word-specific spellings) or were not (homonym foils—pronounced the same as a real word but not spelled correctly for that real word). This judgment requires knowledge beyond permissible grapheme-phoneme correspondences; the reader must integrate orthographic and phonological patterns and semantic knowledge for the whole lexical unit. Orthographic spelling specific to the phonology and semantics for the whole word is crucial for making a correct decision (14, 15, 16). Consider *sammon* and *salmon*, both of which are pronounced the same, but only one is a correctly spelled word with meaning.

The third task involved word-level judgments—deciding if word pairs did and did not have true affixes. English is a morphophonemic orthography (17, 18) and common spelling units may or may not function as true affixes (19, 20). For example, summer and swimmer both have an er, but it is a true suffix only in the second word. A true morpheme at the end of a word transforms a word base as to tense or number (inflectional suffix) or grammar (derivational suffix) (21) but may sometimes change the phonology of the base word (22); or at the beginning of a word, a true morpheme (prefix) qualifies the meaning of a base word (23). For example, *–al* in *national* transforms a noun *nation* into an adjective, but also changes the pronunciation of the base word *nation;* and the prefix in *inter*national transforms the meaning of nation to mean beyond a single nation.

The fourth task involved syntax/sentence level judgments—deciding if sentences with and without homonym foils are meaningful. The presence of a misspelled foil rendering a sentence meaningless might be missed if the foil is erroneously decoded phonologically into a real word.

The fifth task also involved syntax/sentence level judgments—deciding if sentences with and without affix foils are meaningful. The presence of these affixes can affect whether a sentence is meaningful, depending on whether the affixed word fits the context of the sentence syntax.

The sixth task involved multi-sentence text level reading of multiple sentences and deciding if the conclusion at the end, which requires inferential thinking as well as comprehension of each sentence, was true or false.

To identify unique connectivity across adjacent levels of language (first specific aim), the fMRI subword task was compared to each of the word-level tasks, and each of the word-level tasks was compared to the syntax task with and without the same kind foil (with or without homonym foils or with or without affix foils). Each of the syntax tasks was compared to the multi-sentence text task. Connectivity for each of the six fMRI tasks had been assessed from four seeds (regions of interest) relevant to reading written words. The first seed—left precuneus—has been shown to be involved in the orthographic coding of word-specific spellings underlying both reading and writing during middle childhood and early adolescence (24, 25). Precuneus, referred to as the rich club in the human connectome, participates in many functional systems and plays a key role across the neural networks (26). Three other seeds were used based on a meta-analysis of written word production (27) and word processing (reading and spelling): left occipital temporal (e.g., 28, 29), left supramarginal (e.g., 28, 30), and left inferior frontal (e.g., 30, 4). Thus the tables also report the seed from which unique significant connectivity was observed for a specific level of language. The unique connectivity to assess was selected based on inspection of results for typical language learners in Richards et al. (2016), but tested in the current study that included both typical language learners and students with specific learning disabilities in reading.

Clinical Measures for Assessing Executive Functions

Pertinent to the second specific aim, two measures of supervisory attention of working memory had been included in the diagnostic assessment for assigning participants to research groups. The first was the *Delis Kaplan Executive Functions D-KEFS* (12) *Color Word Form Inhibition* (reliability ranges from .62 to .76) based on the classic Stroop task. For this measure the task is to read orally a color word in black and then name the ink color for a written word in which the color of the ink conflicts with the color name of the word (e.g., the word red written in green ink). The index of focused attention (inhibition of irrelevant information) is based on the difference in time for reading the words in black and naming the color of the ink that conflicts with the name of the color word. Raw scores are converted to scaled scores for age (*M*=10, *SD*=3). The second was *Rapid Automatic Switching* (RAS)—letters and numerals (test-retest reliability .90) (13). For this measure the task is to name alternating lower case printed letters and written numerals arranged in rows. The time required to name all the alternating letters and numerals in all the rows is the total score that provides a measure of switching attention. It is converted to a standard score (*M*=100 and *SD* =15). Each of these clinical neuropsychological measures was correlated with the brain measures for unique connectivity for a given level of language that involved brain region associated with executive functions.

Results

Specific Aim 1

The first three tables list only those brain regions showing significant unique connectivity across levels of language that also involved a brain region associated with executive functions. These results, which are organized by each of four levels of language and include connectivity from each of four seeds described in the methods, are relevant to the first specific aim. See Table 1 for analyses of subword versus word levels with contrasting linguistic features (homonyms or affixes). See Table 2 for word versus syntax levels with contrasting linguistic features (homonym or affix foils). See Table 3 for syntax with contrasting linguistic features (homonym or affix foils) versus multi-sentence text levels. Only the magnitude of the connectivity for those regions listed in Tables 1, 2, or 3 was entered into the correlational analyses with clinical measures of supervisory attention for the second specific aim.

Specific Aim 2

Relevant to the second specific aim related to brain-behavior correlations for executive functions for self-regulation (supervisory attention) of specific levels of language are the results displayed in Table 4. There was one significant correlation for Inhibition (Focused Attention), but six significant correlations for RAS (Switching Attention). The correlation for Inhibition (Focused Attention) was the only one involving the cingulum (on left). The correlations with RAS involved the left and/or right cerebellum V. Neither of the clinical measures of supervisory attention assessed in this research report predicted fMRI connectivity involving insula.

Table 1. Identifying Unique fMRI Connectivity in Brain Regions Associated with Executive Functions between Subword Level Grapheme-Phoneme Correspondence and Word Level Reading (Word Specific Spellings or Affixed Words)

Contrast IA Subword Grapheme-Phoneme Correspondence versus Word Specific Spelling
Unique to Subword Level—Grapheme-Phoneme Correspondence
From supramarginal seed with right insula R Ig2
Unique to Word Level Correctly Spelled Words versus Homonymns
From left precuneus seed with left Broca's (L BA44 and L BA45)
From left precuneus seed with right Broca's (R BA44 and R BA45)
From left precuneus seed with left cingulum
From left precuneus seed with right cingulum
From left precuneus seed with left cerebellum V
From right precuneus seed with right cerebellum V
From left interior frontal with right Broca's (R BA44)
Contrast IB Subword Grapheme-Phoneme Correspondence versus Affixed Words
Unique to Subword Level—Grapheme-Phoneme Correspondence
From left precuneus seed with left cerebellum V
From left occipital temporal seed with right Broca's 44
From left occipital temporal seed with left cerebellum V
From left occipital temporal seed with right cerebellum V
Unique to Word Level— Words with True Affixes or Fake Affixes
From left supramarginal seed with left insula L Ig2 L Id1
From left inferior frontal seed with right Brocas's BA 44

Table 2. Identifying Unique fMRI Connectivity in Brain Regions Associated with Executive Functions between Word Level Reading (Word Specific Spellings or Affixed Words) and Syntax in Sentences with and without Homonym Foils or Affix Foils

Contrast IIA Word Specific Spelling vs Sentence Syntax with and without Homonym Foils
Unique to Word Level—Word Specific Spelling
From left precuneus seed with right cerebellum
From left occipital temporal seed with right Broca's BA 44
From left occipital temporal seed with left cerebellum V
From left occipital temporal seed with right cerebellum V
From left supramarginal seed with left insula (L Id and L Ig2)
From left supramarginal seed with right insula (R Id and R Ig2)
From left inferior frontal seed with left cingulate
Unique to Syntax Level—Sentences with and without Homonym Foils
From left inferior frontal seed with left Broca's BA45
Contrast IIB Affixed Words vs Sentence Syntax with and without Affix Foils
Unique to Word Level -- Affixed Words
None
Unique to Syntax Level—Sentences with and without Affix Foils
From left occipital temporal seed with left cerebellum V
From left occipital temporal seed with right cerebellum V
From left supramarginal seed with right Broca's (R BA44)

Only the word-level fMRI task for word-specific spelling exhibited significant correlations involving more than one brain region associated with supervisory attention—with left cingulum from left inferior frontal seed for Inhibition (focused attention) and with right cerebellum V from left precuneus seed for RAS (Switching Attention).The significant correlation at the word level for Inhibition in left cingulum was from the left inferior frontal seed which is also associated with executive functions. The significant correlation at the word level for Switching Attention in right Cerebellum V was with connectivity from the left precuneus seed associated with linguistic awareness (24).

Table 3. Identifying Unique fMRI Connectivity in Brain Regions Associated with Executive Functions between Syntax in Sentences with and without Homonym or Affix Foils and Multi-Sentence Text

Contrast IIIA Sentence Syntax with and without Homonym Foils
Unique to Sentence Syntax Level
none
Unique to Multi-Sentence Text Level
From left precuneus seed with left Broca's (L BA44 and L BA45)
From left precuneus seed with right Broca's (R BA44 and R BA45)
From left precuneus seed with left cerebellum V
From left precuneus seed with right cerebellum V
From left supramarginal seed with left Broca's (L BA44 and L BA45)
From left supramarginal seed with right Broca's (R BA44 and R BA45)
From left supramarginal seed with left insula (L Ig2)
From left supramarginal seed with right cerebellum V
From left inferior frontal seed with left insula (L Ig2)
From left inferior frontal seed with left cingulum
From left inferior frontal seed with right cingulum

Contrast IIIB Sentence Syntax with and without Affix Foils versus Multi-Sentence Text
Unique to Syntax Level—Sentences with and without Affix Foils
From left precuneus seed with right cerebellum V
From left occipital temporal seed with left cerebellum V
From left occipital temporal seed with right cerebellum V
Unique to Multi-Sentence Text
From left precuneus seed with left cerebellum V
From left precuneus seed with left Broca's (L BA44 and L BA45)
From left precuneus seed with right Broca's (R BA44 and R BA45)
From left supramarginal with left Broca's (L BA45)
From left supramarginal with left insula (L Ig2)
From left inferior frontal with left cingulum
From left inferior frontal with right cingulum
From left inferior frontal with left insula (L Ig2)

Table 4. Significant Correlations between Unique Brain Regions for Specific Levels of Language Associated with Executive Functions and Clinical Neuropsychological Measures of Supervisory Attention (D-KEFS Inhibition or Wolf and Denckla RAS) (For Contrasts IA and IB, IIA and IIB, and IIIA and IIIB—see Tables 1, 2, and 3)

	r	p
Unique Grapheme-Phoneme Correspondence in Contrast IA (Word-Specific Spelling vs Homonyms)		
Left supramarginal seed with left cerebellum V and RAS	.36	.05
Left supramarginal seed with right Cerebellum V and RAS	.43	.02
Unique Grapheme-Phoneme Correspondence in Contrast IB (True vs Fake Affixes)	all ns	
Unique Word-Specific Spelling vs Homonyms in Contrast IIA (Syntax + or - Homonym Foils)		
Left precuneus seed with right cerebellum V and RAS	.38	.04
Left inferior frontal seed and left cingulum and DK-EFS Inhibition	.36	.05
Unique Words with True or Fake Affixes in Contrast IIB (Syntax + or – Affix Foils)	all ns	
Unique Syntax + or - Homonym Foils in Contrast IIIA (Multi-Sentence Text)		
Left precuneus seed and right cerebellum V and RAS	.38	.04
Left supramarginal seed and right cerebellum V and RAS	.36	.05
Unique Syntax + or – Affix Foils in Contrast IIIB (Multi-Sentence Text)		
Left precuneus seed and right cerebellum V and RAS	.36	.05

At least one of the significant correlations with RAS occurred at each unique level of language in the analyses for the first specific aim. In addition to the one at the word level just described were two at the subword level and three at the syntax level; it was not possible in the design to identify unique text level connectivity compared to a next higher level. Of the two correlations with Switching Attention unique to the subword level of language (grapheme-phoneme correspondences), both occurred in left and right Cerebellum V with connectivity from left supramarginal seed. Two were unique to syntax with and without homonym foils (in right Cerebellum V with connectivity from the left precuneus seed and in right Cerebellum V with connectivity from the left supramarginal seed). One was unique to syntax with and without affix foils in right Cerebellum V with connectivity from the left precuneus seed.

Discussion

Specific Aim 1: Mental Self Government of Brain

At a time in the history of brain research that is increasingly grounded in the connectome paradigm for understanding the complex human brain (26; 31), research on the brain's self-government for managing that complexity is timely and needed. In this research report two executive functions for such self-regulation—inhibitory control and flexible switching—were investigated for a very specific role in the brain's mental self-government, namely, for self-regulating specific unique levels of language. In the field of neuropsychology both focused attention and switching attention are relevant to assessing supervisory attention, which is a kind of executive function for self-regulation of language learning that plays a role in the mental self-government of language. Other mechanisms for such mental self-government exist that manage and orchestrate larger parts of the system than only a single level of language and have also been investigated. For example, clustering coefficients informed by graph theory showed that adaptive control (cingulum opercular network) and components of working memory (its word-form storage and processing units and loops for integrating internal codes with external output modes in addition to supervisory attention) are also involved in the mental self-government of the complex reading brain as well as writing brain systems (32).

In the current study, however, the focus has been on separate unique levels of language as contrasted with the next higher adjacent level of language. Supervisory attention such as focused attention (enabled by ability to inhibit what is irrelevant and focus on what is relevant) and switching attention (what was relevant becomes irrelevant and what was irrelevant becomes relevant) were shown to contribute to the self-government at a specific level of language. An analogy to human government is that there are different levels of government all of which are needed spanning federal government, state government, and local city/town government. Whereas a prior study (32) investigated mental self-government of the larger brain system, the current study investigated local unique levels of language.

Specific Aim 2: Clinical and Educational Applications

The brain-behavioral correlations for one kind of executive function (supervisory attention—focused and switching) identified in the current study have potential applications to clinical assessment and instruction. Clinical neuropsychologists infer underlying brain bases from behavioral measures rather than directly assessing the brain through imaging. The current results provide validation for the use of *D-KEFS Color Word Form Inhibition* and *Wolf and Denckla Rapid Automatic Switching*

(RAS) clinical measures as indicators of the brain bases of supervisory attention in language learning during middle childhood and early adolescence.

The significant correlations may also have potential applications to instruction. Of interest, neither inhibitory control nor flexible switching significantly predicted contrast IIB in Table 2 which involved affixed words. Other kinds of self-regulation strategies for managing affixes at end of words in isolation or in syntactic context may need to be taught, for example, (a) segmenting base words and affixes at the end and beginning of a word; and then (b) self-reflection on how the affix may affect the base word (modify its meaning as with prefixes, or mark tense, number, or comparison as with inflectional suffixes, or transform part of speech as with derivational suffixes, or cause phonological shifts in pronunciation of the base word, or require deletion or addition of spelling units when adding the suffix to the base word). Only one of the significant correlations, which was with Switching Attention, involved affixes in the unique connectivity, namely syntax with and without affix foils.

Of the seven significant correlations between brain measures for executive functions for unique levels of language (first specific aim) and behavioral clinical measures of executive functions for supervisory attention for self-regulation of language, (second specific aim), only one involved Inhibition underlying focused attention; it was unique to the word level for correct word-specific spellings versus homonym foils (pseudowords that sound like real words when pronounced but are not correctly spelled). Teaching strategies that emphasize focused (selective) attention to the orthography of a word spelling, then focused (selective) attention to its phonology, and then focused (selective) attention to its semantic vocabulary meaning before integrating all three sources of word knowledge may be helpful in teaching word-specific spellings (14,15).

The remaining six significant correlations all involved Supervisory Attention and left and/or right Cerebellum V but in contrasting ways for different levels of language in the comparisons of adjacent levels of language and from different seeds. The finding that more of the correlations involved switching attention than focused attention is consistent with prior research with both typically developing language learners and students with specific learning disabilities (33). Thus, it is important to teach strategies for switching attention for letters (e.g., among component strokes with numbered arrow cues), for switching attention across a written word for sequential 1- and 2-letter graphemes that correspond to phonemes (e.g., by writing each grapheme in left to right direction in an alternative color ink), and for switching attention across words in syntax (e.g., by solving sentence anagrams and rearranging word order to create a sensible sentence) (34, 35).

Limitations, Future Directions, and Conclusions

This research is limited by a relatively small sample size, although it was carefully ascertained and assessed using both comprehensive clinical measures at the behavioral level and fMRI connectivity analyses for six fMRI tasks at the brain level. Nevertheless, the current findings might inform and stimulate additional research on the role of executive functions in managing each of the levels of language in the multi-leveled reading brain and even their coordination so that they are orchestrated in time (2). Continued research on various aspects of the mental self-government of the developing reading brain of learners will not only advance basic science, but also has potential for educational applications. Currently research has emphasized the importance of explicit instruction in specific reading skills, which are taught by a teacher and learned by a student. Multiple research studies have shown that aiming reading instruction at all levels of language close in time is an effective way to teach struggling readers (1). Yet, independent, self-regulated learning of the developing reader, that is, learning to learn on one's own, also plays an important role in literacy acquisition (32). Underlying that learning to learn written language is the mental self-government within each level of language as well as across all levels of language of the complex, multi-leveled brain supporting language learning.

Acknowledgements

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) to the University of Washington Learning Disabilities Research Center. One of the aims of the funded multidisciplinary center grant was to advance understanding of both the brain and behavioral bases of the multiple levels of language in the functional reading system of students during middle childhood and early adolescence who do and do not have specific learning disabilities in written language (SLDs-WL).

1. Berninger, V., Richards, T. 2002. *Brain literacy for educators and psychologists*. New York: Academic Press. Currently distributed by Elsevier.
2. Posner, M., Rothbart, M. 2007. Research on attention networks as a model for the integration of psychological science. *Ann Rev of Psychol. 58:*1-23.
3. Richards, T., Nagy, W., Abbott, R., Berninger, V. 2016. Brain connectivity associated with cascading levels of language. JSIN. *2:* 219-229.
4. Mesulam, M. 1990. Large-scale neurocognitive neworks and distributed processing for attention, language, and memory. *Ann Neurol 28*: 597-613.
5. Bettcher, B.M., Mungas, D., Patel, N., Elofson, J., Dutt, S., Wynn, M. et al. 2016. Neuroanatomical substrates of executive functions: Beyond prefrontal structures. *Neuropsychologia 85*: 100-109.
6. Dibbets, P., Bakker, K., Julles, J. 2006. Functional MRI of task switching in children with specific language impairment (SLI). *Neurocase. 12*: 71-79.
7. Stein, M., Simmons, A., Feinstein, J., Paulus, M. 2007. Increased amygdala and insula activation during emotion processing in anxiety-prone subjects. *American Journal of Psychiatry. 164*: 318-327.
8. Menon, V., Uddin, L. 2010. Saliency, switching, attention and control: A network model of insula function. *Brain Struct and Funct.214*: 655-667.
9. Nicoloson, R., Fawcett, A. 1999. Developmental dyslexia: The role of the cerebellum. *Dyslexia, 5*: 155-177.
10. Salman, M. S. 2002. The cerebellum: It's about time! But timing is not everything—new insights into the role of the cerebellum in timing motor and cognitive tasks. *J Child Neurol. 17*: 1-9.
11. Hughes, C. 2013. Executive function: Development, individual differences, and clinical insights. In J. Rubenstein & P. Rakic (Eds.), *Neural circuit development and function in the brain. Comprehensive developmental neuroscience* (pp. 429-445). Science Direct: Elsevier.
12. Delis, D., Kaplan, E., Kramer, J. 2001. *Delis-Kaplan Executive Function System.* San Antonio: The Psychological Corporation/ Pearson.
13. Wolf, M., Denckla, M. 2005. *RAN/RAS Rapid Automatized Naming and Rapid Alternating Stimulus Tests*. Austin, TX: Pro-Ed.
14. Ehri, L. 1980. The role of orthographic images in learning printed words. In J. F. Kavanaugh, & R. Venezky (Eds.), *Orthographic reading and dyslexia* (pp. 307-332). Baltimore, MD: University Park Press.

15. Olson, R., Forsberg, H., Wise, B., Rack, J. 1994. Measurement of word recognition, orthographic, and phonological skills. In G. R. Lyon (Ed.), *Frames of reference for the assessment of learning disabilities* (pp. 243-277). Baltimore, Brooks.
16. Perfetti, C. 2007. Reading ability: Lexical quality to comprehension. *SSR. 11*: 357-383.
17. Nunes, T., Bryant, P. 2009. *Children's reading and spelling. Beyond the first steps.* Oxford UK: Wiley-Blackwell.
18. Venezky, R. 1970. *The structure of English orthographyy*. The Hague: Mouton.
19. Nagy, W., Berninger, V., Abbott, R. 2006. Contributions of morphology beyond phonology to literacy outcomes of upper elementary and middle school students. *J Ed Psy. 98:134-147*.
20. Nunes, T., Bryant, P., Bindman, M. 1997. Morphological spelling strategies: Developmental stages and processes. *Dev Psy 33:* 637–649.
21. Nagy, W., Diakidoy, I., Anderson, R. 1993. The acquisition of morphology: Learning the contribution of suffixes to the meaning of derivatives. *J Read Behav. 25:* 155–170.
22. Carlisle, J., Stone, C. A., Katz, L. 2001. The effects of phonological transparency on reading derived words. *Ann of Dys. 51:* 249–274.
23. Pillon, A. 1998. The pseudoprefixation effect in visual word recognition: A true—neither strategic nor orthographic—morphemic effect. *Q J Exp Psych: Human Exp Psych, 51A:* 85–120.
24. Richards, T., Berninger, V. Fayol, M. 2009. FMRI activation differences between 11- year-old good and poor spellers' access in working memory to temporary and long-term orthographic representations. *J Neuroling, 22,* 327-353.
25. Richards, T.L, Grabowksi, T., Askren, K., Boord, P., Yagle, K., Mestre, Z. et al. 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 Clin*. *8,* 1-14.
26. Van den Heuvel, M., Sporns, O. 2011. Rich-club organization of the human connectome. *The J Neuroscience.* 31: 15775–15786.
27. Purcell, J., Turkeltaub, P.E., Eden, G.F., Rapp, B. 2011. Examining the central and peripheral processes of written word production through meta-analysis. *Front in Psych. 2*: 1-16.
28. Cohen, L., Lehéricy, S., Chochon, F., Lemer, C., Rivaud, S. Dehaene, S. 2002. Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain. 125*: 1054–1069.
29. Dehaene, S. 2002. Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain, 125*: 1054–1069.
30. Price, C. 2012. A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language, and reading. *NeuroImage. 62*: 816-847.
31. Sporns, O. 2013. The human connectome: Origins and challenges. *Neuroimage. 80*: 53–61.
32. Richards, T. L., Abbott, R.D., Yagle, K., Peterson, D., Raskind, W. Berninger, V. 2017. Self-government of brain's response to instruction informed by cingulo-opercular network for adaptive control and working memory components for language learning JSIN *3*: 1-12.
33. Altemeier, L., Jones, J., Abbott, R., Berninger, V. 2006. Executive factors in becoming writing-readers and reading-writers: Note-taking and report writing in third and fifth graders. *Dev Neuropsych*. 29: 161-173.
34. Berninger, V. W. (2015). *Interdisciplinary frameworks for schools: Best professional practices for serving the needs of all students.* Washington, DC: American Psychological Association. http://dx.doi.org/10.1037/14437-002. Companion Websites with Readings and Resources and Advisory Panel.
35. Berninger, V., & Wolf, B. (2016). *Dyslexia, dysgraphia, OWL LD, and dyscalculia: Lessons from teaching and science, Second Edition.* Baltimore: Paul H. Brookes. Also available as e-book.