Differences in fMRI activation between children with and without spelling disability on 2-back/0-back working memory contrast

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Abstract: Children (aged 10 to 12) with spelling disability (related to dyslexia) or with good spelling ability performed 2 fMRI nonverbal working memory tasks of comparable difficulty across groups in and out of the scanner—judging whether a pictured sea creature appeared two trials earlier (2-back) or was a target whale (0-back).The 2-back versus 0-back contrast captures ability of working memory to track changes over time. On this contrast, the good spellers and disabled spellers showed significant BOLD activation in many and generally the same brain regions. On group map comparisons, the good spellers never activated more than the disabled spellers, but the disabled spellers activated more than the good spellers in selected brain regions. Of most interest, 2 clusters of BOLD activation (distributed across brain regions) were observed in good spellers but 5 clusters were observed in disabled spellers. Within these clusters the good and disabled spellers differed in three regions (bilateral medial superior frontal gyrus, orbital middle frontal gyrus, and anterior cingulated), which are associated with cognition, executive functions, and working memory and were correlated with a behavioral spelling measure. Thus working memory is best described as a distributed architecture rather than a single mechanism; and good and poor spellers engage working memory architecture differently. We propose that spelling is an executive function for translating cognition into language (sounds and morphemes) and then into visual symbols rather than a mere transcription skill for translating words in memory into written symbols in external memory.

Keywords: n-back working memory task, working memory, normal spelling, and spelling disability

journal of
WRITING RESEARCH

Richards, T., Berninger, V., Winn, W., Swanson, H. L., Stock, P., Liang, O., & Abbott, R. (2009). Differences in fMRI activation between children with and without spelling disability on 2-back/0-back working memory contrast. *Journal of Writing Research, 1* (2), 93-123.
http://dx.doi.org/10.17239/jowr-2009.01.02.1

1. Introduction

1.1 Differences between Good Spellers and Disabled Spellers with Dyslexia

The current study is fourth in a series of fMRI studies of spelling that compared good and disabled spellers during middle childhood (ages 9 to 13) to identify brain-behavior relationships that characterize normal and non-normal spelling ability (Richards, Berninger, Nagy, Parsons, Field, & Richards, 2005; Richards et al., 2006a, 2007). For each of these studies we compared good spellers recruited from the community and matched in Verbal IQ with disabled spellers recruited from a family genetics study of dyslexia. Only children whose oral reading (accuracy and/or rate) of pseudowords, real words on a list, or real words in a text, and/or written spelling were/was below their Verbal IQ and the population mean and whose family had a multi-generational history of reading and writing problems participated in the family genetics study of dyslexia. Although many think of dyslexia as a reading disability, dyslexia has been shown to be both a writing (primarily spelling) and reading disorder (Berninger, Nielsen, Abbott, Wijsman, & Raskind, 2008). Berninger and colleagues replicated earlier work of Pennington and colleagues (e.g., Lefly & Pennington, 1991) and Bruck (e.g., Bruck, 1993) showing that the persisting phenotype (behavioral expression of the underlying genetic disorder) of dyslexia is spelling disability. Some but not all children with dyslexia also have handwriting problems; and the spelling problems of children and adults with dyslexia contribute uniquely to their written expression problems in composition (Berninger, Nielsen et al., 2008).

The goal of the current study was to compare the good and disabled spellers on working memory tasks while their brain was scanned to test the hypothesis that good and poor spellers engage their working memory differently. However, please keep in mind that results will generalize only to children who during middle childhood meet diagnostic criteria for dyslexia (Berninger, 2007a, 2007b) and have persisting spelling problems. In other fMRI research we are studying a different population of poor spellers recruited from a longitudinal sample of unreferred, normally developing writers and readers and comparing them to good spellers in the same longitudinal study. Recent longitudinal research in France has shown that although spelling and reading development is comparable in many children, some children are good spellers but poor readers and some are good readers yet poor spellers (Fayol, Zorman, Lété, in press). Thus, children may have spelling problems for many different reasons. Different developmental pathways to poor or disabled spelling may exist, which should be taken into account in designing research and generalizing and interpreting research findings related to spelling problems. .

The purpose of the current research is best understood in the context of (a) prior cognitive research on working memory and writing; (b) evolving models of working memory; and (c) brain research findings on working memory that are relevant to the tested hypothesis that good spellers and dyslexics with spelling disability engage their brains differently during working memory tasks. Three sections follow that cover each of these issues and provide the context for the current research study.

1.2 Working Memory and Writing

Cognitive research has shown working memory to be an important cognitive process in writing (e.g. Alamargot and Chanquoy, 2001; Hayes, & Chenoweth, 2006, 2007; McCutchen, 1994, 1996; and Swanson & Berninger, 1996). The concept of working memory is needed to explain how on-line storage and processing in temporary memory support goal-related writing tasks. In the cognitive research on working memory in writing, different aspects of working memory have been studied as a source of constraints or individual differences that influences the writing process and product. These include capacity constraints (eg., McCutchen, 1994, 1996; Swanson, 1999b), resource limitations (e.g., Swanson, 1999b), and temporal coordination of multiple processes (Berninger, 1999).

For many years, psychologists have assessed working memory with a single measure like Digit Span, which includes two tasks—repeating a forward series of an increasing number of digits and transforming a forward series to a backward series of an increasing number of digits. These measures has been shown in a number of studies to load on a factor that is more appropriately called Working Memory Index than Freedom from Distractibility Factor (e.g., Weiss, Saklofske, Schwartz, Prifitera, & Courville, 2006). Alternatively, the listening span task, introduced by Daneman and Carpenter (1980) and adapted for children by Swanson, is often used to assess working memory. This task requires listening to sets that increase in number of sentences, repeating the last word in each sentence to show that each sentence in an item set was stored, and answering a question to show that the content of the sentences was accurately processed (see Swanson, 1999a, 1999b, 2006). Results from a longitudinal study of writing suggest that word-level working memory factors explain unique variance in spelling or word reading factors, whereas sentence-level working memory factors explain unique variance in sentence- or text- level written language (Berninger et al., in press). A single working memory measure may not capture all the dimensions of working memory.

Of significance for research on working memory and writing, Alamargot and Chanquoy (2001) raised the intriguing question of whether working memory involves a single mechanism or multiple mechanisms organized within a working-memory architecture. The latter possibility suggested that multiple measures better characterize the working memory architecture than a single measure. Building on this possibility, we adopted the conceptual framework of a working memory architecture to organize the validity studies for the set of endophenotypes used in a family genetics study of dyslexia Although behavioral studies show that both phonological and working memory skills contribute to normal writing (Swanson & Berninger, 1996), and learning disabilities in general (Swanson & Siegel, 2001), researchers still debate whether one of these is the true causal mechanism in dyslexia. Research findings are mixed as to which working memory component may be most important in explaining dyslexia—only the phonological loop (e.g., Kibby, Marks, Morgan, & Long, 2004), only executive functions (e.g., Swanson, 1999a, 2006), both phonological loop and executive functions (e.g., Swanson & Ashbaker, 2000; Swanson, 2006), or both word form storage and executive functions (e.g., Baddeley, 2003).

Using structural equation modeling, Berninger, Abbott et al. (2006) showed that a working memory architecture consisting of three word-form storage and processing mechanisms (phonological, orthographic, and morphological), a time-sensitive phonological loop for naming orthographic stimuli and creating automatic correspondences between letters and names (and their associated phonemes), and a set of executive functions (inhibition, rapid automatic switching, updating and self-monitoring during phonological processing of stimuli) fit the data well and explained many reading and writing outcomes (including spelling) in the children and adults with dyslexia. These results showed that a common phonological core deficit occurred in each of the three components in the working memory architecture—the *phonological* word-form storage and processing component, the *phonological* loop component, and the executive functions component for regulating *phonological* processing of written and spoken words. Thus, from a systems perspective that entertains an architecture with multiple components, the phonological core and working memory deficits are not competing explanations. The architecture model of working memory has been applied to integrating the family genetics and brain imaging study results by relating specific gene candidates for dyslexia to endophenotypes studied in both genetics and brain imaging (Berninger, Raskind et al., 2008). Moreover, recent research findings supported addition of an orthographic loop (from written words and letters in them to hand for producing letter writing and written spelling) (Berninger, Rutberg et al., 2006; Richards, Berninger, Stock, Altemeier, Trivedi, & Maravilla, in press) to the model for working memory architecture. Before considering how fMRI studies might advance understanding of the role of working memory in spelling, recent evolutions in working memory theory are reviewed.

1.3 Evolving Models of Working Memory

The concept of working memory, which was originally proposed in the cognitive research literature by Baddeley and Hitch, has been evolving (Baddeley, 2002). From the beginning, multiple components were proposed—a phonological store, visual-spatial scratch pad, articulatory loop, and central executive—but have been revised. The phonological and visual-spatial storage components have been expanded to include episodic storage units for integrating multiple codes and multidimensional information (e.g., Rudner, Fransson, Ingvar, Nyberg, & Ronnberg, 2007). The articulatory loop, with its focus on motor output units for speech, has been reconceptualized as a time-sensitive phonological loop with internal phonological as well as speech output capabilities. The phonological loop plays an important role in the cross-code integration in working memory that underlies oral vocabulary and written word learning (e.g., Gathercole, Alloway, Willis, & Adams, 2006). The central executive is no longer conceptualized as a single supervisory attention mechanism but rather as a set of specialized executive functions (e.g., Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). The phonological loop contributes to maintaining information in memory over time during processing, whereas executive functions self-monitor and update that maintained information over time (e.g., Miyake et al., 2000).

Growth mixture modeling studies showed that children with dyslexia differed from good spellers and readers in rapid automatic naming (RAN), which was hypothesized to be a behavioral measure of phonological loop for cross-code integration under timed conditions. Dyslexics fell in two classes—slow and slower and steady slow—whereas the non-dyslexics started faster and got faster or if they started at ceiling maintained their rapid naming (Amtmann, Abbott, & Berninger, 2007; also see Berninger, 2007a, 2007b). In growth mixture modeling study of at-risk writers in second grade, RAN predicted class of response to spelling instruction based on spelling words correctly during cognitively demanding, independent composing (Amtmann, Abbott, & Berninger, 2008).

Theory-driven multiple regression showed that for both typically developing writers and readers and children with dyslexia, Rapid Automatic Switching (RAS) (executive function for switching attention) uniquely predicted the most writing (and reading) learning outcomes over and beyond Inhibition (focus on the relevant and ignore the irrelevant, for example, on a color naming task with color-inconsistent color words). Thus, attentional control in performing clinical tasks is one of the executive functions (Bunting, Conway, & Heitz, 2004). Consistent with capacity limitation views of working memory, workload influences whether novel visual stimuli are processed automatically or exert distracting influences on attentional control (Spinks, Zhang, Fox, Gao, & Tan, 2004). To the extent that processes are automatic, attentional control may be able to handle the workload.

1.4 Brain and Brain-Behavior Relationships in Working Memory

The brain imaging tasks for studying working memory are also evolving from tasks used in behavioral studies such as the listening span task (e.g., Weismer, Plank, Jones, & Tomblin, 2005) and oral digit span recall or nonword repetition (e.g., Gathercole, Alloway, Willis, & Adams, 2006) to the n-back task (e.g. Nystrom, Braver, Sabb, Delgado, Noll, & Cohen, 2000) that increasingly is used more frequently. In this fMRI working memory paradigm, participants are asked to judge whether the current stimulus in a set of stimuli is the same one that appeared n-trials before (e.g., two trials before) or whether the current stimulus (0-back) matches a target stimulus; then brain activation in the n-back condition is compared to the 0-back condition to create a contrast related to ability to track change in working memory over time as the brain stores information and performs a goal-related task. Of interest is brain regions where Blood-Oxygen Level Dependent (BOLD) activation is significant for the fMRI contrast between a target on-task and a control off task in a single group of interest or between two groups (e.g., normal controls and a clinical group).

Collectively, fMRI studies of working memory are identifying brain regions involved in the multiple components of a working memory architecture: word storage, phonological loop and orthographic loop functions, and executive-functions. Crosson et al. (1999) identified BOLD uniquely associated with phonological, orthographic, and semantic storage and processing in working memory. Richards et al. (2005, 2006a) studied word-level phonological, orthographic, and morphological storage and processing in working memory. Richard et al. (2006b) reviewed their converging evidence from MRI structural, fMRS chemical activation, and fMRI BOLD activation that supports Triple Word Form theory, according to which phonological, orthographic, and morphological word-forms and their parts are stored and analyzed in working memory. More recently, behavioral studies showed that the three word forms reliably discriminate among poor, average, and superior spellers from grades 1 to 6 (Garcia, 2007; Berninger, Garcia, & Abbott, 2009) and a second-order factor underlying the three word forms explains unique variance in writing (and reading) outcomes better than do single word forms in normally developing writers and dyslexics (Berninger, Raskind et al., 2008). These studies provide additional imaging and assessment results consistent with the family genetics endophenotyping studies (e.g. Berninger, Abbott et al., 2006). Formation of episodic stores supports executive coordination of the three word forms and their parts, two and three at a time in the brain (Richards et al., 2005). Rudner et al.'s (2007) fMRI n-back study showed that transient networks in posterior brain regions may store and process word representations initially, but active engagement of frontal regions maintains them until processing is completed.

The n-back task assesses the demands placed on the central executive in monitoring *over time* what is stored and processed in working memory, but both subcortical cerebellar and cortical cerebral circuits may be involved in regulating timing in working memory. Phonological loop involves cerebellar (e.g., Fliessbach, Trautner, Quesada, Elger, Weber, 2007) and cerebellar-cerebral (e.g., Ziemus et al. (2007) networks. The orthographic loop network may include fusiform (Berninger & Richards, 2008) and left precuneus and superior parietal and right cerebellum (Richards et al., in press), depending on whether the task has orthographic or finger movement requirements, respectively. Dorsal premotor cortex may regulate binding/sequencing operations, whereas dorsal lateral prefrontal cortex may regulate segmenting/attentional executive functions (Abe, Hanakawa, Takayama, Kuroki, Ogawa, & Fukuyama, 2007).

Research Aims

Recent fMRI studies found differences between poor spellers and good spellers identified in a longitudinal study of normal writing development in BOLD activation in superior frontal regions associated with cognition and executive functions during idea generation for the purpose of writing (Berninger, Richards, Stock, Trivedi, & Altemeier, 2007; Berninger et al., in press) *and* during spelling judgments (Richards, Berninger, & Fayol, 2009). We wondered whether similar differences would be found between good spellers and disabled spellers with dyslexia on an n-back fMRI task. The n-back task was hypothesized to be a measure of executive functions for sustaining, monitoring, and updating information in working memory over time (Miyake et al., 2000). The goal was to compare children with and without spelling disability on a working memory contrast, based on 2-back and 0–back fMRI conditions to test the hypothesis that they would differ significantly in BOLD activation when sustained activation of working memory over time was required.

To equate the difficulty of the working memory task across spelling ability groups, nonverbal stimuli and tasks were used that did not require overt oral language, reading, or spelling on which dyslexics with spelling disabilities are likely to have difficulty. We wanted to assess their working memory apart from their language-based processing difficulties. Thus, pictures of sea creatures were used and children were asked to make two kinds of judgments about the pictures: whether the sea creature appearing now also appeared 2 trials back (2-back) and whether the current sea creature appearing now was a target whale (0-back). The 2-back versus 0-back contrast assessed ability to store, process, monitor, and update nonverbal information in working memory over time compared to storing and processing the same kind of information without demands for tracking nonverbal information over time.

Of interest was whether the good and disabled spellers would differ on the 2-back/0-back contrast in mean level of BOLD activation in specific brain regions and whether they would differ in the patterning of the brain activation, that is, clusters that included distributed regions. Although the behavioral studies found evidence for the working memory architecture, imaging allowed a more direct examination of whether a working memory architecture in the brain was engaged. We tested the hypotheses that good spellers and disabled spellers would differ in (a) amount of regionally specific BOLD activation, and (b) clusters of BOLD activation distributed across regions.

2. Methods

2.1 Participants

All good spellers (*n*=10) were recruited through parent response to flyers distributed in the community. The children with spelling disability (*n*=20) were recruited from a family genetics study for which they had met inclusion criteria for dyslexia—impaired spelling and oral reading of real words and pseudowords (for details see Berninger, Abbott et al., 2006). Research for nearly a decade in this multi-generational family study had shown that dyslexia is not only a reading disorder but also a spelling disorder, which is the most lasting behavioral expression of the phenotype during the upper grades of schooling and after schooling, and often interferes with development of written composition in children with dyslexia aged 9 and older and in affected adults (Berninger, Nielsen et al., 2008). In fact, after appropriate, specialized instruction, many children with dyslexia learn to read sufficiently well, if allowed to read silently and given sufficient time, that they may begin to deny they have reading problems. The most frequent request the multidisciplinary learning disabilities research center received was for instructional treatment for writing and consultation with schools to help them understand that students with dyslexia also need explicit instruction in writing (Berninger, 2006). Thus, this study was conducted to understand better the possible contribution of working memory to the spelling and writing problems of children aged 9 to 13 with dyslexia when writing requirements of school curriculum are increaseing.

Both the children with and without spelling disability completed the same test measures that are given to everyone in the family genetics study (see Berninger, Abbott et al., 2006). Parent responses to questionnaires about medical, developmental, and educational history were used to document that the children had a history of substantial difficulty in learning to spell despite special help at and/or outside school and spelling remained a problem whether or not their reading problems resolved. The disabled spellers did have residual problems in reading, especially phonological decoding of unfamiliar words during oral reading and oral reading fluency problems. The good spellers did not have a history of difficulty in learning to read or spell and on achievement measures were at or above the population mean and did not underachieve in spelling or reading for their verbal intelligence.

Parents also completed ratings of attention and behavior. None of the children met DSM IV diagnostic criteria for Attention Deficit Hyperactivity Disorder or Conduct Disorder and did not have other psychiatric or neurodevelopmental disorders. The sample therefore represents relatively pure good spelling or disabled spelling without confounding neurodevelopmental disorders that could affect cognitive or other kinds of functioning. The problems of the disabled spellers were specific to written language achievement.

Only those children who were right-handed and did not wear braces (or other non-removable metal) could participate and only children who could tolerate the closed-in space of the scanner could continue participation. Two children were discontinued because they had claustrophobia and could not stay in the scanner. Altogether ten good spellers and 20 disabled spellers completed brain imaging. All parents of participating children provided informed consent and all children granted assent using procedures approved by the Institutional Review Board. Investigators complied with the ethical standards of the American Psychological Association.

Of the 30 children (14 girls and 16 boys) in the final sample, all were European Americans except three; of these three, one reported being Hispanic (not of European origin); none reported being African American, Asian American, or Native American, but two reported other for ethnicity. Their prorated Verbal IQs on the Wechsler Intelligence Scale for Children, Third Edition (WISC III) (Wechsler, 1991) (subtests that are used for Verbal Comprehension Index) were not significantly different, *t*(28)=0.80, *p*=.43. Both the good spellers (*M*=115.70, *SD* =8.0) and disabled spellers (*M*=112.45, *SD*=11.44) had prorated Verbal IQs that fell in the above average range. The good spellers were not on average older (*M*=128.60 mos, *SD*= 8.03) than the disabled spellers (*M*=127.75 mos *SD*=12.97), *t(*28)=0.19, *p*=.85.

Table 1. Behavioral Differences between Children with (N=20) and without (N=10) Spelling Disability

	Good Spellers		**Disabled Spellers**		***t*(28)**	***p***
	M	*SD*	*M*	*SD*		
Spelling						
WIAT II Spelling	115.50	10.60	83.75	8.86	8.66	<.001
Reading						
WRMT-R Word Identification^a	114.4	8.29	87.10	13.12	5.98	<.001
WRMT-R Word Attack^a	108.80	3.88	87.10	8.86	7.35	<.001
TOWRE Real Word Reading Efficiency^a	112.20	10.92	91.15	13.07	4.38	<.001
TOWRE Pseudoword Reading Efficiency^a	120.90	9.61	87.50	8.53	9.70	<.001
Phonological Working Memory						
WJ R Digits Backwards^a	122.00	19.86	94.85	21.39	3.35	<.002

Scale ^{a}*M*=100, *SD*=15 ^{b}*M*=10, *SD*=3

WRMT-R=Woodcock Reading Mastery Test-Revised (WRMT-R) (Woodcock, 1987)

TOWRE=Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999)

Woodcock Johnson Revised (WJ-R) (Woodcock & Johnson , 1990)

However, the good spellers had significantly higher spelling achievement (more than two standard deviations difference, see Table 1) than the disabled spellers on the Wechsler Individual Achievement Test, Second Edition (WIAT II) Spelling subtest

(Psychological Corporation, 2002). Table 1 reports means and standard deviations for the spelling, reading, and working memory tests that show that the disabled spellers were significantly more impaired than the good spellers on spelling and reading achievement (oral reading of real and pseudowords) and phonological working memory (assessed by a digit span task requiring repetition of a series of familiar number names in reverse order). We realize that researchers debate whether this test assesses working memory, but most consider the digits reversed a better measure of working memory than digits forward. This measure does load on a working memory factor (e.g, Weiss et al., 2006), but it is unlikely that one and only one working memory measure will ever capture all the important dimensions of working memory. See Table 1 notes for names of tests.

2.2 Scan Acquisition

Structural MRI and fMRI scans were acquired on a GE Signa 1.5 Tesla Scanner (version 5.8) with a custom-built head-radiofrequency detector and a custom-built audiovisual system so that the subject was able to see the visual stimuli during the fMRI scan. The fMRI scan was obtained while participants performed the tasks inside the scanner. The fMRI sequence was acquired with an axial EPIBOLD pulse sequence with 21 slices (TR/TE 3000/50 msec), and structural sequence using a sagittal 3D gradient echo sequence (TR/TE 25/11 msec, 124 slices).

2.3 fMRI Image Analysis

Overview. To test the hypotheses stated in the introduction, the following analyses were conducted. Initially the fMRI data were analyzed using FSL software (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl) for both the first level (individual fMRI activation) and second level analysis (group maps combined from individual maps) in this on-off block design. The approach of supplementing group map analyses with ROI individual brain analyses has been applied in other studies combining brain imaging and treatment (Richards et al, 2005, 2006a). The fMRI contrast *z*-score maps were calculated for the comparison of brain signal: 2-back > 0-back. Clusters were neuroanatomically interpreted based on the Talairach templet brain (Talairach & Tournoux 1988).

To prepare the fMRI data for analysis, the time series fMRI data were motion corrected, scalp and non-brain tissue were digitally removed, and images were spatially smoothed. Time-series statistical analysis was carried out in a block-design, which means that the fMRI signal during the on condition was compared with fMRI signal during the off condition, and the resultant maps were co-registered to a standard brain. The results of the statistical analysis of the individual maps were combined to give a group map using a random effects analysis.

2.4 fMRI Tasks and Analyses

An n-back task was adapted for the purposes of this study for reasons explained in the introduction. Stimuli were colored photographs of six sea creatures (e.g., orca or humpback whale, shark, ray, otter, seal). In the *0-back (control) condition*, one third of the pictures were of whales (orca or humpback) and two-thirds were of other sea creatures (shark, ray, otter, seal). For this condition, children were asked to press a button each time they saw a whale (orca or humpback). In the *2-back condition,* subjects were instructed to push the button whenever the sea creature they saw (any one of the six above) was the same as the picture 2-back from the current picture (i.e., identical to the picture immediately preceding the picture that immediately preceded the current picture). Both conditions required the child to look at pictures and make a judgment, but only the 2-back task required the child to remember the picture over a short period of time and compare the remembered picture to one that was currently being viewed.

Size of visual stimuli in the "on" (2-back condition) and "off" (0-back) conditions was comparable. However, the position of the same sea creature in 2-dimensional space showed slight variations across the stimulus presentation trials. Thus, correct responding required storage of the sea creature image and processing of identity of the sea creature irrespective of slight variations in visual-spatial position. For both the "on" and "off" tasks, children pressed a button held in their dominant hand for yes responses. To control for random guessing, for each condition, a “yes” answer was the correct response for one-fourth of the trials.

Presentation order and timing of conditions were as follows. Order of conditions with duration in seconds was fixation (18), on (30), off (30), on (30), off (30), fixation (18), on (30), off (30), on (30), off (30), fixation (18). Before each "on" or "off" condition, a slide with instructions appeared for 6 seconds. Five pictures were presented during each "on" and "off" condition, for a total of 20 "on" and 20 "off" items. Sea Creature pictures were presented for 6 seconds, with no inter-stimulus interval. Total scan time was 5 minutes and 42 seconds.

Children were taught and practiced the 2-back and 0-back tasks outside the scanner before performing them during brain scanning. Thus, because children understood task instructions well and had practiced applying them before they entered the scanner, when the slide with visual instructions appeared during scanning, it served as a prompt for which task was to be performed in the alternating task conditions—not as instructions children had to process for the first time. Accuracy data were collected for the 2-back and 0-back tasks outside and inside the scanner and analyzed for significant differences in means for tasks and for groups.

Comparison of alternating "on" and "off" trials (the 2-back/0-back contrast) isolated storage and processing when tracking over time was and was not required. Thus, the contrast between “on” and “off” conditions reflects to a large degree the time-related aspects of processing stimuli in working memory. Some visual processing was obligatory for correct responding, but children could have adopted a covert phonological loop strategy of naming the sea creatures and keeping that name code active in working memory to render their 2-back decisions.

Correlations between Brain Activation and Behavioral Spelling Measures

Following group map analyses, individual brain activation values were computed for regions where good and poor spellers differed in BOLD activation. These individual BOLD activation values were correlated with standard scores for age on a spelling dictation test.

3. Results

3.1 E-Prime Behavioral Results outside and in the Scanner

Both the good spellers and disabled spellers performed each task with high accuracy near ceiling (24 items) during the training session. On 0-back, the good readers had a mean of 23.8 correct (*SD*=0.6), and the children with dyslexia had a mean of 23.7 correct (*SD*=0.6). On 2-back, the good spellers had a mean of 22.7 correct (*SD*=2.4), and the disabled spellers had a mean of 23.2 correct (*SD*=1.2). The good spellers and disabled spellers did not differ significantly on either the 0-back or 2-back task. The tasks were not significantly different in difficulty level, and both children with and without spelling disability performed at a high level of accuracy on both tasks. Accuracy was also assessed during scanning, although there is some missing data due to occasional malfunction of response buttons. In the scanner, good spellers and disabled spellers did not differ in accuracy (48 items) or reaction time, except that the disabled spellers were slightly more accurate on the 0-back task than the good spellers. Thus, because the n-back tasks and trials appeared to be generally equated in difficulty both in and out of the scanner, all trials during scanning were used in the analyses that follow.

3.2 Group Map Differences

Cluster quantifications for the group difference map for the 2-back on- and off- task contrast are in Table 2 for the good spellers, in Table 3 for disabled spellers, and in Table 4 for regions where disabled spellers activated more than good spellers. No regions were found where good spellers activated significantly more than disabled spellers on the 2- back versus 0-back contrast.

Regions of significant BOLD activation are in Table 5 for good spellers and in Table 6 for disabled spellers (see appendix). For Tables 5 and 6, the MNI coordinates and Brodmann Areas for each brain region showing significant activation are reported, and information on translating these regions into the clusters in Tables 2 and 3 is provided. This information allows examination of BOLD activation in individual brain regions and clusters across brain regions, which may reflect distributed neural networks. With both kinds of information, good and disabled spellers can be compared in both specific regions of significant activation and the distributed neural networks across those specific regions. Table 7 shows regions where disabled spellers had significantly more BOLD activation than good spellers within specific clusters.

Table 2. Cluster List for Good Spellers during 2-Back versus 0-Back Contrast

Cluster Index	Voxels	P	Log10(P)	Z-MAX	Z-COG X (vox)	Z-COG Y (vox)	Z-COG Z (vox)
2	6675	1.02E-14	14	4.31	0.656	-63.8	45.2
1	3086	2.29E-08	7.64	4.05	-1.39	-1.45	53.7

Table 3. Cluster List for Disabled Spellers during 2-Back versus 0-Back Contrast

Cluster Index	Voxels	P	Log10(P)	ZMAX	Z-COG X(vox)	Z-COG Y(vox)	Z-COG Z (vox)
5	11729	2.51E-19	18.6	5.67	2.59	-66.9	40.6
4	7196	1.10E-13	13	5.62	25.6	18.7	38.5
3	2755	9.54E-07	6.02	5.89	-35	1.25	44.4
2	1384	0.000656	3.18	4.49	-32.6	52.1	2.92
1	1170	0.00216	2.67	4.35	-33.1	-63.3	-48.7

Table 4. Cluster List for Disabled Spellers > Good Spellers during 2-Back versus 0-Back Contrast

Cluster Index	Voxels	P	-log10 (P)	Max Z	COG x (mm)	COG y (mm)	COG z (mm)	Max COPE	Mean COPE
1	1969	6.43e-05	4.19	4.59	-1.89	45.6	-0.526	77.7	32.3

Notes: P = *p* value that the cluster activation could have occurred by chance; Max Z = maximum *z*-score within cluster; COGx; COGx; COGy = center of gravity in Talaraich x,y,z coordinates of the cluster, Max COPE = maximum contrast of parameter estimate (related to the average fMRI signal intensity change between the on and off contrast) within the cluster; Mean COPE = mean value of the COPE within the cluster.

Good spellers. As shown in Table 5 (appendix) the good spellers showed significant BOLD activation on the 2-back on- and off- task contrast in 26 regions that fell in two significant clusters (see Table 2) indicating at least two large distributed neural networks are probably involved in their working memory. The first cluster involves primary and supplementary motor regions and middle and superior frontal regions associated with executive functions (e.g., Abe et al., 2007; Becker et al., 1994; Marklund, Fransson, Cabeza, Petersson, Ingvar, & Nyberg, 2007; Picchoni et al., 2007; Ziemus et al., 2007) and working memory (e.g., Protzner & McIntosh, 2007). The second cluster involves occipital and parietal regions associated with visual processing and parietal regions associated with working memory. The occipital and parietal occipital activation are consistent with the findings of Picchioni et al. (2007). Figure 1 displays labeled regions of significant BOLD activation in the good spellers. See figure caption for information on the brain view displayed. By convention, activation in the left side of the brain is depicted on the right and activation on the right side of the brain is depicted on the left in each of the figures.

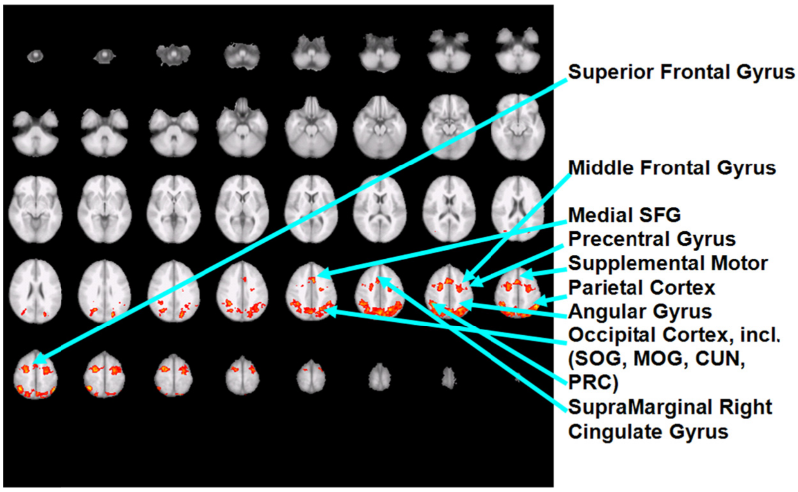

Figure 1. Areas of BOLD activation on 2-back versus 0-back contrast for only good spellers (Group map calculated from FSL's higher level FLAME software) (SOG=Superior Occipital Gyrus; MOG=Middle Orbital Gyrus; CUN=cuneus; PRC=precuneus).

Disabled spellers. As shown in Table 6 (appendix), the disabled spellers activated in all the same regions as the good spellers, but in addition showed significant BOLD activation in the following 14 regions in which the good spellers did not: bilateral superior frontal (orbital), middle frontal (orbital), inferior frontal (operculum, operculum, triangularis), anterior cingulum, left postcentral, and right superior frontal (medial). Figure 2 displays labeled regions of significant BOLD activation in the disabled spellers. See figure caption for information on the brain view displayed.

In contrast to the good spellers whose regions of significant BOLD activation occurred in two significant clusters, for the disabled spellers the regions of significant BOLD activation fell in five significant clusters. Of note, one of these clusters included five regions of left cerebellum. A second cluster involved the left inferior frontal gyrus (orbital), left middle frontal (orbital), and left superior frontal gyrus (orbital), which also activated more in poor spellers (not from the family dyslexia study) than good spellers in another study (Richards et al., 2009). A third cluster was a left network including precentral gyrus, superior frontal gyrus, middle frontal, inferior frontal gyrus (operculum), and inferior frontal gyrus (triangularis). The fourth cluster was mainly on the right and in frontal lobe (except left supplementary motor and superior frontal medial) and bilateral anterior and middle cingulate. The fifth cluster was primarily bilateral and parietal with occasional occipital and temporal activation (see Table 6). That the disabled spellers showed more clusters of activation distributed across brain regions, supports the notion that their working memory architecture is inefficient in tracking storage and processing over time.

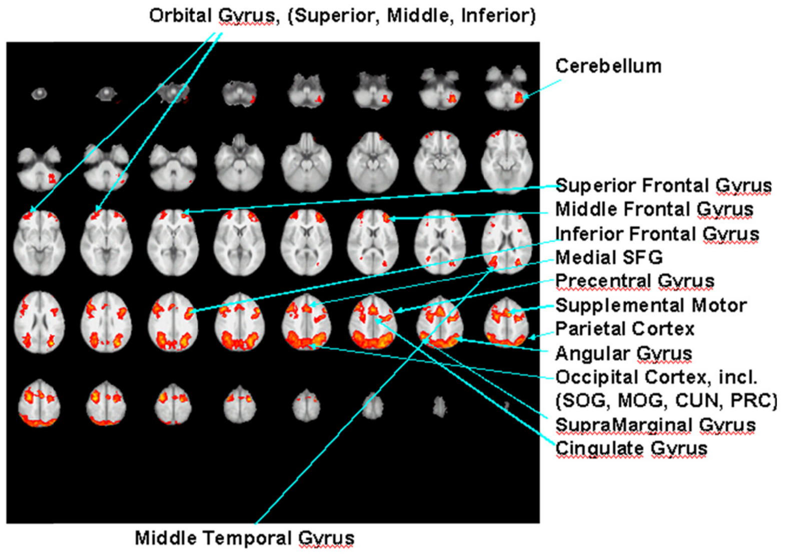

Figure 2. Areas of BOLD activation on 2-back versus 0-back contrast for only disabled spellers (Group map calculated from FSL's higher level FLAME software) (SOG=Superior Occipital Gyrus; MOG=Middle Orbital Gyrus; CUN=cuneus; PRC=precuneus).

Comparison of good and disabled spellers. The fMRI group map results showed that significant BOLD activation for the 2-back versus 0-back contrast occurred on both the right side and left side of the brain in good spellers and disabled spellers. For the most part, children with and without spelling disability activated the same regions on this contrast, with the exceptions as noted. Statistical analyses were performed to evaluate which regions differed significantly in mean level of BOLD activation between the children with and without spelling disability. No significant differences were found where good spellers showed more BOLD activation than did disabled spellers. In contrast, regions were found where disabled spellers activated more than good spellers.

Disabled spellers activated more than good spellers in these regions where only the disabled spellers activated: bilateral superior frontal (orbital), right middle frontal (orbital), bilateral inferior frontal (operculum, triangularis, and orbital), and bilateral anterior cingulate. Both disabled and good spellers activated significantly in left superior frontal (medial), but disabled spellers did so significantly more. Again, these findings suggest neural inefficiency in specific brain regions as reflected in greater BOLD activation on the contrast involving temporal tracking about storage and processing in working memory. As shown in Table 7, these regions of difference were found in the second, third, and fourth clusters discussed in the section above for disabled spellers (see Figure 3). Thus, the good and disabled spellers showed different patterns of significant clusters of BOLD activation for the 2-back/0-back contrast, suggesting that the good and disabled spellers differ in how they engage neural networks, especially those involving the executive functions, to track storage and processing over time in a working memory architecture.

Table 7. Brain Regions Where BOLD Activation Was Greater for Disabled Spellers Compared to Good Spellers for 2-Back versus 0-Back Contrast (see note at bottom)

region #	**brain region (Cluster 1 in Table 4)**	***z*score**	**MNI x**	**MNI y**	**MNI z**	**BA**	**cluster # from Table 3**
5	**Frontal_Sup_Orb_L**	2.451	-8	56	-20	11	2
23	**Frontal_Sup_Medial_L**	2.675	-4	60	16	10	4
24	**Frontal_Sup_Medial_R**	2.568	12	46	8	32	4
25	**Frontal_Mid_Orb_L**	2.826	-2	50	-12	11	2
26	**Frontal_Mid_Orb_R**	2.722	0	52	-12	11	4
27	**Rectus_L**	2.661	-2	52	-16	11	na
28	**Rectus_R**	2.569	2	52	-16	11	na
31	**Cingulum_Ant_L**	2.923	-8	40	4	11	4
32	**Cingulum_Ant_R**	2.628	4	34	12	24	4

Note. For each region only disabled spellers showed significant BOLD activation except for (a) left superior frontal (medial) on which good and disabled spellers activated but the latter more so; and (b) bilateral rectus on which neither group showed significant BOLD.

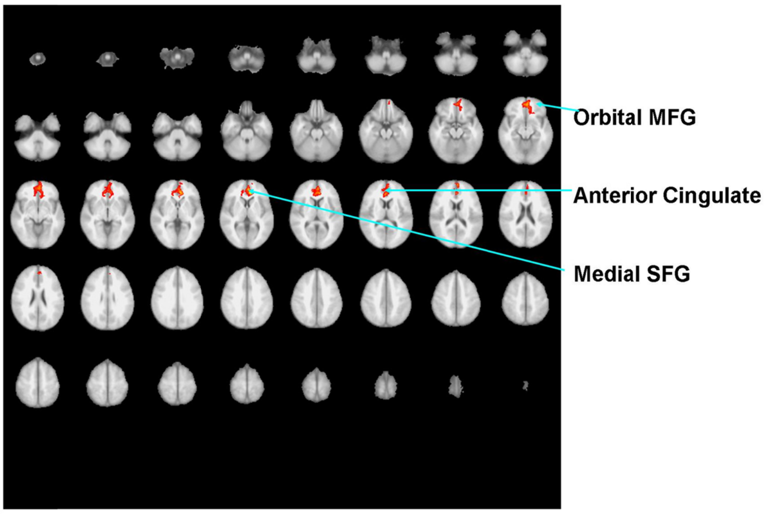

Figure 3. Regions where BOLD activation for 2-back versus 0-back contrast is greater for disabled spellers than for good spellers (Group difference map calculated from FSL's higher level FLAME software). (MFG=Middle Frontal Gyrus; SFG-Superior Frontal Gyrus)

3.3 Correlations between Significant BOLD Activation and Behavioral Measures of Spelling

Significant correlations between brain activation in regions related to cognitive, executive functions, and working memory *and* behavioral measures of spelling ability lent further support for significant brain-behavior relationships underlying spelling. For disabled spellers, the following regions that were activated significantly more in the disabled than good spellers were correlated significantly with WRAT 3 spelling (Wilkinson, 1993): bilateral superior frontal (medial) (*r*= .591, *p*=.006 on left; *r*= -.572, *p*=.008 on right), left middle frontal gyrus (*r*= -.496, *p*=.026), and bilateral anterior cingulate (*r*= -.461, *p*=.041, on left; *r*= -.483, *p*= .031, on right). In all cases, the correlations were negative indicating that the higher the BOLD activation value, the lower the spelling score.

4. Discussion

4.1 Overview of Important Findings

Please note that the differences between the good and disabled spellers were generally not in mean level of BOLD activation in specific regions as the first hypothesis predicted, but rather in number of significant clusters (reflecting distributed networks), as the second hypothesis predicted. (See Tables 3 for the two clusters in good spellers, Table 4 for five clusters in disabled spellers; Table 5 for the specific regions in the two clusters that activated significantly in good spellers, Table 6 for the specific regions in the five clusters that activated significantly in the disabled spellers, and Table 7 for where the disabled spellers activated significantly more than good spellers within these clusters.)

Good spellers. As shown in Table 5, the good spellers showed significant BOLD activation during the 2-back/0-back contrast in multiple regions in *cluster 1* (bilateral precentral—primary motor region, bilateral supplementary motor area; bilateral superior frontal; bilateral middle frontal; bilateral middle cingulum; and left superior medial frontal region). This frontal, mainly bilateral network, has been associated with motor planning and output, working memory, executive functions, and cognition. The good spellers also showed significant BOLD activation in *cluster 2* (bilateral cuneus, bilateral superior occipital, bilateral middle occipital, bilateral superior parietal, bilateral interior parietal, bilateral precuneus, bilateral angular gyrus, and right supramarginal gyrus) (see Table 5). This posterior, mainly bilateral network, has been associated with visual, orthographic, phonological, and morphological processes and their integration and working memory for storage and processing of word forms and their parts. Neither cluster involved cerebellar activation.

Disabled spellers. As shown in Table 6, the disabled spellers showed significant BOLD activation in multiple regions in *cluster 1* (five regions of cerebellum on left; *cluster 2* (left superior frontal orbital, left middle frontal orbital, left inferior frontal orbital), *cluster 3* (left precentral, left superior frontal, left middle frontal, left inferior operculum, left inferior triangularis, left postcentral)*, cluster 4* (right precentral, right superior frontal, right superior orbital, right middle frontal, right middle orbital, right inferior operculum, right inferior triangularis, right inferior orbital, bilateral superior medial frontal, bilateral anterior and medial cingulum, and bilateral supplementary motor, and *cluster 5* (bilateral cunceus, bilateral superior occipital, bilateral middle occipital, bilateral superior parietal, bilateral inferior parietal, bilateral angular gyrus, bilateral precuneus, and right superamarginal gyrus and right middle temporal gyrus).

Overall, these disabled spellers seemed to differ from the good spellers more in the frontal circuitry, where instead of one integrated frontal circuit, they had three distinct clusters (2, 3, and 4). Whether the problem in cluster 1 (cerebellar regions) is the consequence of or causes the problems in clusters 2, 3, and 4 cannot be determined in this study, but is an issue future research might address if these findings replicate. The disabled spellers did not differ as much from the good spellers in the posterior *cluster 5.*

Comparison of the good and poor spellers in distinct brain regions within specific clusters. As shown in Table 7, all significant differences where disabled spellers showed significantly more BOLD activation than good spellers occurred in clusters 2, 3, and 4 (from Table 3), that is, in frontal and cingulate regions associated with working memory and executive functions: bilateral superior frontal medial, bilateral middle frontal orbital, and left superior frontal orbital, and bilateral anterior cingulum. Thus, the greatest differences between the good and disabled spellers were in brain regions associated with cognitive and executive functions on the nonverbal working memory contrast involving temporal tracking of storage and processing.

Conclusions. Good and disabled spellers differed in the number of clusters reflecting significant, distributed BOLD activation and in certain brain regions in specific clusters (see Table 7 and Figure 3). These results provide supportive evidence for a brain architecture underlying working memory rather than a single mechanism. Furthermore the brain fMRI activation differences between good and disabled spellers (due to dyslexia) during middle childhood were observed in frontal and posterior neural networks, but the significant regional differences within these neural networks were in frontal regions associated with the executive functions of working memory, even on a nonverbal working memory task.

Significance for Understanding Good and Disabled Spelling

The good and poor spellers differed significantly on a behavioral measure of working memory that assesses lexical-level storage and processing of spoken names (see Table 1). Consistent with a growing body of behavioral evidence for a working memory deficit in dyslexia (Swanson, 1999-a, 1999-b; 2006; Swanson & Ashbaker, 2000; Swanson, Howard, Saez, 2006; Swanson & Siegel, 2001), the BOLD activation differed significantly between the good and disabled spellers in three frontal regions bilaterally, which have been associated in other studies with executive functions and working memory. Thus, for disabled spellers in grades 4 to 6 with persisting spelling problems, executive functions of working memory may be impaired (Denckla, 1996; Lyon & Krasnegor, 1996) as Berninger, Abbott et al. (2006) also found.

However, results supporting a working memory deficit do not rule out a concurrent phonological core deficit. Research with the same sample but a different set of fMRI tasks for the contrast, Aural Report versus Aural Discrimination (analyze phonemes in an aural pseudoword and reproduce it orally versus decide if pair of aural pseudwords match in phonemes) showed differences in BOLD activation in supramarginal gyrus, which is known to be associated with phonological processing (Richards et al., 2007). Thus, consistent with the behavioral research in family genetics, the disabled spellers with dyslexia were different from good spellers in brain activation associated with both executive functions (current study) and phonological storage and processing (Richards et al., 2007). Again, both executive functions and phonological skills may contribute to dyslexia.

4.2 Neurological Significance

Left or bilateral working memory? Significant BOLD activation on both the left and right occurred for both the good spellers and disabled spellers (see Figures 1 and 2). Although children with and without spelling disability differed primarily in three frontal regions on the left (see Table 7), regions of significant BOLD activation on the 2-back contrast occurred bilaterally in many regions and in only in a few instances only in regions on the right or left (see Tables 5 and 6).

Separate working memory system or shared executive functions? Results showing significant BOLD activation in frontal regions supported the hypothesis that the 2-back/0-back contrast was associated with the executive processes for sustaining, monitoring, and updating information in working memory over time (Miyake et al., 2000). Frontal systems are involved in executive functions in verbal working memory (Becker et al., 1994; Marklund et al., 2007), episodic memory (Marklund et al., 2007), and nonverbral working memory (the current study). Like Nystrom et al. (2000) who showed that frontal executive systems are activated in both nonverbal and verbal working memory, we found that the executive systems are activated on a nonverbal working memory task on which good and poor spellers differed in mean level and patterning of BOLD activation in brain regions associated with executive functions. Thus, executive (and other) systems may be shared across many brain systems (see MacDonald, & Christiansen, 2002). If so, the debate about whether executive functions are part of the working memory architecture or executive functions exist outside working memory, which supports them, may not be the most relevant question. *Brain structures and functions may flexibly organize according to the task at hand.* Lower-order executive functions may be an integral part of the working memory architecture but some higher-order executive functions may contribute to the regulation of cognitive processing for a variety of tasks independent of working memory architecture and operations (Altemeier et al., 2008).

4.3 Significance for Theories of Working Memory

Collectively, these findings show that it is important to consider both the patterning of brain activation across brain regions as well as mean level of BOLD activation in specific brain regions. The results support the view that working memory is a distributed architecture rather than a single mechanism (Alamargot and Chanquoy, 2001). For the good spellers, two significant clusters were observed in the 2-back versus 0-back working memory contrast. For the disabled spellers, five significant clusters were observed on the same fMRI contrast. The specific regions where disabled spellers over-activated compared to good spellers fell in three of those clusters associated with executive functions.

Working memory appears to include frontal and posterior regions in good spellers on a nonverbal working memory task (see Table 5). However, working memory may be engaged differently by disabled spellers who also activated cerebellar, parietal, and three different frontal regions for the same task (see Table 6). The engagement of the cerebellar and inferior frontal regions may indicate that the disabled spellers relied more on phonological loop (e.g. naming the sea creatures) to sustain processing in working memory. For role of cerebellum in phonological loop, see Fliessbach et al., 2007). For role of cerebellar-cerebral networks, see Ziemus et al., 2007). Also see http://www.memoryzine.com/howmemoriesaremadeinbrain.html for evidence that cerebellum is involved in memory. For the role of dorsal premotor cortex in regulating binding/sequencing operations and the role of dorsal lateral prefrontal cortex in regulating segmenting/attentional executive functions, see Abe et al. (2007). Even though the working memory stimuli and task requirements were essentially nonverbal, the working memory impairments related to timing of children with dyslexia and persisting spelling disabilities were evident. Given the language processing problems of dyslexics, a nonverbal working memory task should have been easier for them than a verbal working memory task.

4.4 Significance for Theories of Writing

Although Berninger and Swanson (1994) initially reported that working memory does not appear to contribute uniquely to writing until fourth grade and above, this position has been revised based on recent longitudinal study findings. The earlier work was based on the sentence span tasks and capacity theory of working memory. The more recent research separated working memory tasks that required storage and processing of subword and word units in working memory and storage and processing of sentence units in working memory; results showed that the subword and word-level working memory tasks uniquely and robustly explained individual differences in spelling and composing skills in the primary grades (ages 6 to 8); the sentence-level tasks began to contribute uniquely in grades 4 and above (Berninger et al., in press). The current study adds by showing that, in addition to levels of language in the working memory architecture, the ability to monitor and update information related to what is stored in working memory across time, is related to differences in spelling (and reading) ability during middle childhood and early adolescence.

The current study may be the first to report evidence in support of a distributed neural network for working memory architecture and differences between good and disabled spellers on an fMRI nonverbal working memory contrast sensitive to temporal tracking. In addition, this study shows that good and disabled spellers do not differ in the mean level of BOLD activation in most regions of this neural architecture for working memory. The disabled spellers appear to use the same regions as the good spellers but to engage them differently and to engage additional regions, probably because of inefficiencies in their working memory architecture for executing and monitoring storage and processing over time.

That the poor spellers engage the distributed neural networks of nonverbal working memory architecture differently than good spellers do is of interest because dyslexia has been assumed to be a language disorder. Recent research synthesized behavioral, genetic, and brain research to support a general model in which specific writing disabilities can be diagnosed on the basis of which word-form storage and processing components of working memory architecture are impaired: orthographic resulting in dysgraphia, orthographic and phonological resulting in dyslexia, or orthographic, phonological, morphological, and syntactic (for storing and processing accumulating word units) resulting in oral and written language learning disability (OWL LD) (Berninger, 2006, 2007a, 2007b, 2008a, 2009; Berninger, Raskind et al., 2008). Each of these specific writing disabilities may have impairment in phonological loop and orthographic loop function and executive functions related to coordinating the three word forms and their parts. Depending on which working memory components are genetically and neurologically constrained and the quality of instruction the child has received, the child may have problems in handwriting automaticity (dysgraphia), spelling (dyslexia), and/or compositional fluency(OWL LD) or a combination of these specific writing disabilities (Berninger, Raskind et al., 2008).

The results for superior frontal gyrus (see Tables 5, 6, and 7) are of interest in light of prior findings that good and poor writers in another sample, who were significantly impaired in spelling, differed in this region too. Poor writers over-activated in left superior frontal gyrus during Idea Generation (Berninger, Richards et al., 2007, in press). Good spellers activated significantly in right superior frontal gyrus but the poor spellers activated significantly more in left superior frontal gyrus than did good spellers (Richards et al., 2009). In the current study the disabled spellers also activated more than the good spellers in left superior frontal gyrus. Because past imaging studies show this region is associated with conceptual understanding (reviewed in Berninger & Richards, 2002) and recent brain imaging results show this region is associated with executive functions in working memory (du Boisgueheneuc, Levy, Volle, Seassau, Duffau, Kinkingnehun et al., 2006), we propose that spelling may be more than a transcription process for translating words in working memory into written symbols for words in external memory.

Spelling may also be an executive function for translating the concepts in the vast unconscious mind in implicit memory into language in conscious working memory. Thus, the superior frontal brain region may serve as the *cognitive portal* where cognition gains access to language via word-level spellings, which are then expressed in writing. If so, spelling is not a mechanical skill but rather an important executive function for translating between cognition and language. It follows that spelling should be taught in a highly intellectually engaging way with close connection to vocabulary (word meaning) development. Additional instructional implications are discussed next.

4.5 Significance for Writing Instruction

Spelling has been shown to be uniquely related to written composition in both typically developing children (Graham, Berninger, Abbott, Abbott, & Whitaker, 1997) and children and adults with dyslexia (Berninger, Nielsen et al., 2008). Following the current fMRI study, participating children received a comprehensive reading-writing treatment program that taught automatic eye-to-mouth, grapheme-phoneme correspondences followed much later in the session with reflective, untimed activities to develop phonological awareness in spoken words and reflective, untimed ear-to-hand, phoneme-grapheme correspondences (Berninger, Winn, Stock, Abbott, Eschen, Lin, et al., 2008, Study 2). Although evidence of brain normalization was found in supramarginal gyrus for this kind of treatment (see Richards et al., 2007), no brain normalization was found when the current fMRI 2-back/0-back nonverbal working memory contrast was repeated after treatment—either in the children who received the spelling treatment described above in the context of comprehensive writing instruction including composition or the control nonverbal, science problem solving treatment using sea creatures, see Winn et al., 2006). We do not report these treatment effects on brain activation during a working memory contrast, which are the first null results we have ever found for instructional treatment for children with dyslexia ages 9 to 13. These null results do suggest that impairments in working memory architecture may be more difficult to overcome than impairments in specific word-form language processes, which have resulted in normalized brain activation following certain instructional treatments (e.g., Richards et al., 2005, 2006a, 2006b, 2007).

However, in a previous study that trained *both phonological loop* for timed, automatic grapheme-phoneme correspondences in the eye-to-mouth direction *and orthographic loop* for timed phoneme-to-grapheme correspondences in the ear-to-hand direction *close in time* (Berninger 2008, Study 1), analysis of a continuous phoneme mapping task (adaptation of Aylward et al., 2003 task for fMRI connectivity analysis), showed that *this combined phonological loop and orthographic loop treatment close in time normalized temporal connectivity of neural networks from the inferior frontal gyrus (associated with phonological loop function) and the middle frontal gyrus (associated with working memory and executive functions) to other frontal regions and to posterior regions* (Richards & Berninger, 2008).

From a neuroscience perspective on writing (Berninger & Richards, 2002), this ability to coordinate working memory components in time is probably critical to building a normal writing brain and teaching spelling, other writing, and reading skills from the very beginning of literacy instruction (Berninger, 2007b, 2008a; Berninger et al., 2008). Both orthographic loop and phonological loop need to be trained to automaticity close in time because the hand plays a unique role in engaging the cognitive, language, and executive systems needed to learn to spell and express ideas in writing (Berninger & Richards, 2008a, 2008b; Berninger, Richards, & Abbott, 2008, 2009; Richards et al., in press). Clearly more research is needed to understand how to overcome most effectively the brain-based constraints of the working memory architecture that contribute to the struggles some children, especially those with dyslexia, encounter in the journey to become skilled writers.

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Acknowledgements

Grant Nos. P50 33812 and HD25858 from the National Institute of Child Health and Human Development (NICHD) supported this research (P.I., V. W. Berninger).

The authors thank Larrisa Stanberry and Kate Eschen for assisting with e-prime during scanning; Cecil Hayes for constructing a new coil with motion restraining devices; MR technicians Jeff Stevenson, Jenee O'Brien, and Neva Oskin; and electrical engineer, Mark Mathis. They also thank the participants for their contributions and the graduate students in school psychology who did the task training outside the scanner with e-prime: Michelle Proulx, Leah Altemeier, Kate Eschen, Cindy Lin, Pamala Trivedi, and Annie Boyd.

Appendix

Table 5. Brain Regions in Group Map Where Good Spellers Had Significant BOLD Activation during 2-Back versus 0-Back Contrast

region #	brain region	zscore	MNI x	MNI y	MNI z	BA	cluster # from table 2
1	**Precentral_L**	2.674	-24	-16	64	6	1
2	**Precentral_R**	2.704	26	-8	56	6	1
3	**Frontal_Sup_L**	2.818	-24	-8	60	6	1
4	**Frontal_Sup_R**	2.969	22	-6	62	6	1
7	**Frontal_Mid_L**	2.656	-28	-8	52	6	1
8	**Frontal_Mid_R**	2.736	28	-2	54	6	1
19	**Supp_Motor_Area_L**	2.722	-2	12	48	32	1
20	**Supp_Motor_Area_R**	2.794	6	8	48	6	1
23	**Frontal_Sup_Medial_L**	2.710	-4	18	40	32	1
33	**Cingulum_Mid_L**	2.797	-6	10	40	24	1
34	**Cingulum_Mid_R**	2.634	8	8	44	32	1
45	**Cuneus_L**	2.819	-18	-80	34	18	2
46	**Cuneus_R**	2.522	24	-62	28	19	2
49	**Occipital_Sup_L**	2.732	-20	-76	30	18	2
50	**Occipital_Sup_R**	2.685	26	-64	28	19	2
51	**Occipital_Mid_L**	2.539	-22	-60	38	7	2
52	**Occipital_Mid_R**	2.585	30	-66	34	19	2
59	**Parietal_Sup_L**	2.825	-26	-64	46	7	2
60	**Parietal_Sup_R**	2.819	42	-54	56	40	2
61	**Parietal_Inf_L**	2.815	-48	-54	52	40	2
62	**Parietal_Inf_R**	2.917	44	-54	58	0	2
64	**SupraMarginal_R**	2.642	50	-46	44	40	2
65	**Angular_L**	2.707	-42	-64	46	39	2
66	**Angular_R**	2.818	42	-56	54	40	2
67	**Precuneus_L**	2.836	0	-68	52	7	2
68	**Precuneus_R**	2.674	2	-70	42	7	2

Table 6. Brain Regions where Disabled Spellers Had Significant BOLD Activation during 2-Back versus 0-Back as a Group Map

region #	brain region	zscore	MNI x	MNI y	MNI z	BA	cluster # from table 3
1	Precentral_L	3.244	-48	12	34	44	3
2	Precentral_R	2.927	28	-6	56	6	4
3	Frontal_Sup_L	3.253	-26	-6	68	6	3
4	Frontal_Sup_R	3.305	30	-6	60	6	4
5	Frontal_Sup_Orb_L	2.922	-26	54	-2	11	2
6	Frontal_Sup_Orb_R	2.856	26	60	-4	11	4
7	Frontal_Mid_L	3.166	-50	14	36	44	3
8	Frontal_Mid_R	3.051	34	6	62	6	4
9	Frontal_Mid_Orb_L	2.768	-40	56	-6	46	2
10	Frontal_Mid_Orb_R	2.610	24	60	-16	11	4
11	Frontal_Inf_Oper_L	3.357	-48	16	32	44	3
12	Frontal_Inf_Oper_R	3.161	48	18	36	44	4
13	Frontal_Inf_Tri_L	3.003	-48	16	30	48	3
14	Frontal_Inf_Tri_R	3.139	42	24	30	48	4
15	Frontal_Inf_Orb_L	2.672	-40	54	-12	47	2
16	Frontal_Inf_Orb_R	2.521	40	48	-4	47	4
19	Supp_Motor_Area_L	3.396	-6	4	52	6	4
20	Supp_Motor_Area_R	3.196	4	16	46	32	4
23	Frontal_Sup_Medial_L	3.179	2	18	42	32	4
24	Frontal_Sup_Medial_R	3.134	4	20	44	32	4
31	Cingulum_Ant_L	2.888	0	30	30	24	4
32	Cingulum_Ant_R	2.678	4	32	28	32	4
33	Cingulum_Mid_L	2.964	-6	20	38	32	4
34	Cingulum_Mid_R	3.005	4	16	44	32	4
45	Cuneus_L	2.532	-2	-74	32	0	5
46	Cuneus_R	2.818	22	-78	44	19	5
49	Occipital_Sup_L	3.198	-24	-70	30	19	5
50	Occipital_Sup_R	3.156	28	-68	32	19	5
51	Occipital_Mid_L	3.688	-30	-74	28	19	5
52	Occipital_Mid_R	3.092	30	-70	32	19	5
57	Postcentral_L	2.588	-40	-10	46	6	3

59	**Parietal_Sup_L**	3.641	-26	-76	42	7	5
60	**Parietal_Sup_R**	3.061	14	-72	54	7	5
61	**Parietal_Inf_L**	3.597	-28	-76	40	0	5
62	**Parietal_Inf_R**	3.310	48	-56	52	40	5
64	**SupraMarginal_R**	2.935	50	-44	44	40	5
65	**Angular_L**	3.475	-46	-66	48	39	5
66	**Angular_R**	3.166	48	-60	54	39	5
67	**Precuneus_L**	3.149	-6	-80	54	7	5
68	**Precuneus_R**	3.120	20	-70	42	7	5
86	**Temporal_Mid_R**	2.900	40	-68	22	39	5
91	**Cerebelum_Crus1_L**	2.602	-38	-54	-42	0	1
93	**Cerebelum_Crus2_L**	3.057	-34	-64	-46	0	1
99	**Cerebelum_6_L**	2.455	-32	-54	-38	0	1
101	**Cerebelum_7b_L**	3.047	-34	-62	-46	0	1
103	**Cerebelum_8_L**	2.793	-32	-64	-48	0	1