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Trends Neurosci Educ. Author manuscript; available in PMC 2017 September 01.

Published in final edited form as:

Trends Neurosci Educ. 2016 September ; 5(3): 146–155. doi:10.1016/j.tine.2016.07.005.

Idea units in notes and summaries for read texts by keyboard and pencil in middle childhood students with specific learning disabilities: Cognitive and brain findings

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Abstract

Seven children with dyslexia and/or dysgraphia (2 girls, 5 boys, *M*=11 years) completed fMRI connectivity scans before and after twelve weekly computerized lessons in strategies for reading source material, taking notes, and writing summaries by touch typing or groovy pencils. During brain scanning they completed two reading comprehension tasks—one involving single sentences and one involving multiple sentences. From before to after intervention, fMRI connectivity magnitude changed significantly during sentence level reading comprehension (from right angular gyrus→right Broca's) and during text level reading comprehension (from right angular gyrus→cingulate). Proportions of ideas units in children's writing compared to idea units in source texts did not differ across combinations of reading-writing tasks and modes. Yet, for handwriting/notes, correlations insignificant before the lessons became significant after the strategy instruction between proportion of idea units and brain connectivity at all levels of language in reading comprehension (word-, sentence-, and text) during scanning; but for handwriting/summaries, touch typing/notes, and touch typing/summaries changes in those correlations from insignificant to significant after strategy instruction occurred only at text level reading comprehension during scanning. Thus, handwriting during note-taking may benefit all levels of language during reading comprehension, whereas all other combinations of modes and writing tasks in this exploratory study appear to benefit only the text level of reading comprehension. Neurological and educational significance of the interdisciplinary research findings for integrating reading and writing and future research directions are discussed.

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Keywords

Idea units in source material; Student notes; Student summarizes; Reading-writing relationships; Handwriting and touch typing; Changes in fMRI connectivity after strategy; instruction; Levels of language

1. Introduction

The current study is part of programmatic research on computerized instruction for students with and without SLDs in written language during middle childhood and transition to adolescence. The first study showed that computerized handwriting, spelling, and composing instruction could improve writing skills on normed measures in both those with and without SLDs in written language [8]. The second study showed that computerized instruction could improve reading as well as writing skills on normed measures in both those with and without SLDs in written language [58]. The third study showed that for students with persisting SLDs despite earlier intervention computerized lessons using multiple modes of language input (reading or listening) and letter production (stylus or pencil, and keyboarding—hunting and pecking or touch typing) for written language output could improve letter production and related writing skills on normed measures for students with SLDs in written language (Thompson et al., in press [60]). Moreover, the group that alternated between pencil and touch typing outperformed the group that alternated between stylus and hunting and pecking on keyboard when taking notes about heard text through earphones. In all these studies explicit strategies were taught for generating the next sentence (Level I translation) and for linking the very next sentence to the evolving multi-sentence text (Level II translation); these strategies were observed in typically developing students in a longitudinal study (Niedo & Berninger, in press) [40] and the students with SLDs taught these strategies used them in their notes and summaries ([39], and submitted).

The first research aim of the current study was to extend that earlier work to a more in-depth examination of the cognitive expression of ideas during note-taking and summary writing. Much of the research on students with SLDs in written language has focused primarily on their impaired language skills rather than on their idea expression related to integrating reading and writing. Of interest in the current study was comparison, before and after strategy instruction and practice in note taking and writing summaries for read source material, of their coded idea expression in both their written notes and summaries by contrasting modes of letter production.

The second research aim of the current study, which is the first in the programmatic research of this research group to combine brain imaging with the computerized instruction, was to evaluate whether (a) brain changes in magnitude of connectivity were observed from before to after the twelve weekly computer lessons on reading and writing about source material; and (b) nonsignificant correlations before intervention (time 1) between the brain connectivity and coded idea units in notes and summaries by keyboarding or handwriting became significant correlations after intervention (time 2). Only those students who were right handed, did not wear metal that was non-removable, and had participated in a brain imaging study before and after the twelve computer lessons teaching strategies for reading

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source material, taking notes, and writing summaries were included in the current, exploratory study of brain response to integrated reading and writing instruction.

Both research aims were grounded in a theoretical model of the five domains of development and related brain systems that support reading and writing development, as depicted in Fig. 1. In this model there are four language systems, each working collaboratively with a sensory input or motor output mode—language by ear (listening), language by eye (reading), language by mouth (oral expression), and language by hand (written expression). Each of these four language systems is multi-leveled and over the course of literacy development needs to learn to work collaboratively with the other language systems, across levels of language within a given language system, and with the cognitive domain as well. Supervisory executive functions coordinate this communication across language systems, across levels within a language system, and across the cognitive and language domains (see [5]). For example, although reading and writing are often taught as separate subjects in the curriculum and investigated independently of each other as separate skills by researchers, successful completion of written assignments at school and at home and tests requires integration of reading and writing [3,30–32], each of which draws on multiple levels of language. The rationale for each of the two research aims is now discussed.

The first research aim was, therefore, focused on how cognitive idea expression might vary across levels of language in contrasting reading-writing tasks—notes that tend to be single words, word phrases, and listed sentences or summaries that tend to be sentences with or without text level structures—and with mode of letter production through the hand—alternating touch typing or pencil handwriting. For this purpose, idea units were coded and examined. Idea units have been defined in varied ways by different researchers, but in the current study they were operationalized as subjects and predicates in single words or phrases. Idea units were coded on two contrasting reading-writing tasks—notes and summaries—for the following reasons.

Note taking was studied because, although good note-taking is critical to academic success, there are relatively few studies of note-taking in upper elementary and middle school grades. Yet, beginning with the later grades in elementary school, the amount of information students are required to understand increases dramatically [59]; and most of the information is presented during reading expository texts [38,55] and listening to lecture [48] in forms many students find difficult to process and few have been prepared to write about. Thus, it makes sense to study and teach note taking beginning in upper elementary and through the high school years because college students rate lecture note-taking as an important educational activity [20]; and almost all college students take notes in classes (approximately 98%; [42,62]). Results from an ongoing survey from the laboratory of the second author indicate that 99.8% of undergraduates from different universities take notes at least some of time (N=421). Research has also shown that recording and reviewing notes from both read and heard texts is related to good test performance (*Lecture*–[12,26,27,29,44,45,47,54,61]; *Text*—[46]).

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Writing summaries is also beneficial to learning to integrate reading and writing. In programmatic research on the generative processes in reading comprehension, written summarization was shown to be effective [63]. Eighteen peer reviewed research studies reviewed by the National Reading Panel (NRP) in the US showed that summarization is an effective strategy for reading comprehension; these are posted on a website http://education.stateuniversity.com/pages/2348/Reading-COMPREHENSION.html for broad dissemination.

Also of interest in comparing idea units expressed on different writing-reading tasks was mode of letter production while writing notes or writing summaries—by handwriting with a pencil or by touch typing on a keyboard—for several reasons. On the one hand, brain research has shown that letter formation facilitates letter perception in words and thus reading words, both in young children [22–24,35] and adults [11,23,33,34]. Instructional research has also demonstrated that letter formation in English and character formation in Chinese, can transfer to improved word reading [7,10,57], presumably because perception of letter or character in word context is facilitated by formation of them in handwriting. On the other hand, research in English-speaking countries has shown that typically developing writers during early and middle childhood write longer texts and write faster [6,18], and even may express more ideas [21], by pen(cil) than keyboard. However, by early adolescence an advantage for keyboarding emerges ([15]; also see [21]).

Even with young adults, however, the findings are mixed with some indicating no differences [2,19], and others finding an advantage for notes taken by computer [13] or by hand [37]. Also, there is very little research on the efficacy of handwritten versus computer recorded notes on exam performance in middle school or high school. What research exists is focused mostly on college undergraduates.

Nevertheless, the issue of which mode of letter production is superior may be more complex than researchers have previously realized because studies have not carefully identified which participants may be using hunting and pecking and which may be using touch typing on a keyboard. If hunting and pecking, a writer may use one or both hands but looks at the keys to find them while writing notes or summaries. If touch typing, a writer does not look at the keys but rather looks at the monitor where the letter on the pressed key appears and relies on the somatosensory touch of keys in standard keyboard position to find the keys to press. Thompson et al. (in press) [60] showed that computerized instruction can teach middle school students with SLDs in written language to do touch typing.

The second research aim was focused on how functional brain connectivity during reading tasks at multiple levels of language—word, sentence, or multi-sentence text— performed during brain scanning might change in response to twelve lessons on integrated reading and writing that involved note taking and summary writing by different modes of letter production. The word-level task required a judgment about whether a word was a correctly spelled real word or was a homonym foil (sounds like a real word but not correctly spelled). Brain research has shown that spelling and reading share some common neural structures [51]. Instructional research has also shown that word spelling instruction can transfer to improved word reading [65]. The sentence-level reading comprehension task required a

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judgment about whether a sentence was meaningful or not; half of the sentences had only correctly spelled words; and the others had one homonym foil which sounded like a real word but was not spelled correctly for its meaning in the sentence context. The text-level reading comprehension task required reading multiple sentences and answering a yes/no question at the end, based on processing the stated facts and inferential thinking about the unstated relationships among the sentences.

Functional connectivity was of interest given the paradigm shift in brain research from analysis of single regions of interest (ROIs) to connectivity of significant magnitude, after control for multiple comparisons, from a seed of origin (R01) with other regions in the complex connectome of the human brain [56]. Thus, in the current study statistically significant magnitude of fMRI functional connectivity was measured from angular gyrus, a seed known to be involved in reading comprehension [1], with other regions, and from right Broca's area, a seed known to be involved in executive functions for language especially written words [4]. Two kinds of fMRI functional connectivity analyses were performed: (a) response to intervention (brain RTI) following completion of the twelve computer lessons (once a week across three months); and (b) correlations between the magnitude of statistically significant fMRI connectivity and idea units expressed in each reading-writing task (notes or summaries) and mode of writing (touch typing by keyboard or handwriting by pencil) at time 1 before instruction and time 2 after instruction.

2. Methods

2.1. Participants

Participants were recruited by flyers distributed to local schools for a study on defining and treating specific learning disabilities. Interested parents contacted the university research team who conducted a screening interview by phone, and, if it appeared the child would qualify and informed consent/assent was granted, scheduled assessment at the university. Procedures, which were described in Berninger, Richards, and Abbott [9], were used. Both test scores on normed measures of written and oral language and parental questionnaire responses were taken into account in assigning participants to diagnostic groups according to whether (a) the student was scoring outside the average range in handwriting or below expected level based on verbal reasoning (translation of cognitions into oral language) in word reading or spelling, and (b) parent reported a history of past and current persisting reading and/or writing problems despite intervention. If based on these dual criteria the assessment confirmed a specific learning disability (SLD) affecting written language, the student was invited to participate in the after school computerized instruction program. In addition, if the child was right handed and did not wear metal which could not be removed, an invitation was extended to participate in a related brain imaging study both before the computerized lessons began and after they were completed. All procedures for this process were approved by the Institutional Review Board at the university where the research was conducted.

The current study included seven children (two girls and five boys with SLDs in written language) who completed the assessment, all lessons in the fourth iteration of the computerized learning activities (with explicit instruction in note taking and summaries and

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use of touch typing and use of groovy pencils, Thompson et al., in press [60]) and had usable brain imaging data both before and after completing the computerized learning activities. However, one child who could not complete the second scan due to illness, but had completed the computerized lessons was also included in coding of idea units. Their average age was 11 years 8 months, with range from 111 to 160 months. Six met research criteria for dyslexia (impaired word reading or spelling) with or without co-occurring dysgraphia, and one met research criterion for dysgraphia (impaired handwriting which may also interfere with spelling). In fact, all were impaired in word level written language—spelling, according to test scores and parent-reported current and past history. Relevant to one of the modes used in the computerized lessons—touch typing—none of the participants had prior experience with touch typing. All were of European American heritage and all their parents had post-secondary education.

2.2. Computerized lessons

After the first imaging session, all children participated in an after school program in which HAWK™ [58] delivered on iPads taught strategies for reading source material, strategies for taking notes, and strategies for writing summaries. University graduate research assistants served as lead teachers who helped log in children and monitored their compliance with procedures in sessions that generally lasted about one hour.

Children were taught strategies first for reading source material and then note taking and finally writing summaries. Next, they read expository source material of comparable length (number of words) and content (first six lessons on history of math in human civilization and last six lessons on world geography and cultures) across lessons, which were also used in all prior studies in this programmatic research, for example, see Tanimoto et al. [58]; but the strategies for reading source material, taking notes, and writing summaries were not introduced until iteration 4. They could look at the source material and reread while taking notes; but during writing summaries they could refer only to their notes. The illustrated source material they read was displayed on an upright stand to the right of the iPad. Each lesson began with a touch typing warm-up, described in Thompson et al. (in press) [60], which compared iteration 4 (touch typing) and iteration 3 (no touch typing). Then children alternated across sequential lessons between touch typing by keyboard on iPad and writing on paper by groovy pencil with indented grooves to write their notes and summaries. Groovy pencils, which are available from Amazon, Dixon Ticonderoga, and some Office Depot Stores, were used in iteration 4 for the first time because of the somatosensory feedback provided by the grooves, which is thought to facilitate the pencil grip.

In all lessons before the students read source material, wrote notes, or wrote summaries, the strategies that follow were first taught by the computer teacher as children listened to her voice through ear phones and read the strategies visually displayed on the monitor. The first time the strategies were presented the students had to listen to each strategy in standard order and click to advance to the next. Thereafter, while reading source text, writing notes, or writing summaries, children had access to display on screen with the full list of strategies and could review any section they wanted by tapping on it whenever they chose to do so. Lead teachers in the room while students completed the reading-writing learning activities

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reported that students were observed clicking on the menu while reading source material, writing notes, and writing summaries. Thus, they seemed to refer to them in their reading and writing activities.

The exact wording on the screen was as follows for *Strategies for Reading Source Material:*

- For each sentence, think what is the key idea?
- For the whole text, think what is the main idea? Or ideas?
- For each idea, think what is the information that supports that idea or ideas?

The exact wording on the screen for *Strategies for Taking Notes after Reading* was as follows:

- Record the main idea or ideas. Use your own words rather than copying sentences word- by- word.
- Explain why you think the idea or ideas are important.
- Record the important details that support the main idea or ideas.

The exact wording on the screen for *Strategies for Writing Summaries of Read Material* was as follows:

- Explain each of the key ideas.
- Tell what they are.
- Tell which information in the text supports those ideas.
- Tell why the ideas are important.
- Use your own words rather than copying each sentence and each word in it.
- Weave the ideas together so that someone who did not read what you read could understand your summary. Pretend you are teaching it to someone else.

Then, in each of the twelve lessons, before reading the expository text source material, the students did a touch typing warm up for which they wore blindfolds. To begin, they placed the fingers of their right and left hands over each corresponding key on the right and left sides of keyboard in touch typing position in home (middle row). Then the computer teacher named each letter on that row but in a different order than on keyboard. When the teacher named the letter, the children's task was to type the letter. Next, the same procedures were followed for the bottom row, and then for the top row. Finally, the children typed the alphabet in order from memory using keys from right and left and all three rows.

Following the touch typing warm-up, children removed the blindfold, and were instructed by the computer teacher to take notes using either touch typing or groovy pencil on the first lesson and then alternate between the modes thereafter. When using touch typing, they were instructed during note-taking not to look at the keys, but rather to look only at written text on the stand just to the right of the iPad screen or at the iPad screen to view notes they had already written. During summary writing they were likewise instructed to look only at their notes or at the screen to view what they had written and not to look at the keys. Teaching

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assistants monitored to make sure students did not look at keys, and if children did, reminded them to redirect their gaze to the screen.

For note-taking, children were instructed to write notes about the text they had read. They were given five minutes for note-taking. While taking notes, they could re-read the source text and access the list of strategies for note-taking by clicking on the menu. For lessons in which the children typed on the keyboard, the system recorded what keys they pressed and when. After every fifty keystrokes data on the nature and timing of keystrokes and the time it took the child to finish were uploaded to a secure server; the data were batched, and the notes were also stored for future analyses. For lessons in which the children wrote by groovy pencil on paper, they were given paper on a clipboard and told to write their notes on it. If writing by pencil, the notes were stored in each child's writing portfolio for future analyses.

For writing summaries, children were given ten minutes to summarize the material they had just read from their notes. The original source material was turned over on the stand so that the text was not visible. Children were only given access to their notes and the menu with list of writing summaries strategies in the computer lesson. If they ceased writing before ten minutes when using the keyboard, the computer teacher reminded them to keep writing, and when writing by pencil, a lead teacher reminded them to keep writing until a message appeared on monitor that time was up. If writing by keyboard, the summaries were stored by the server for future analyses. If writing by groovy pencil, the summaries were stored in each child's writing portfolio for future analyses.

2.3. Coding notes and summaries

First, idea units in each of twelve texts, which were the source material read for the notes that were then summarized, were identified by the second author based on Kintsch [28]. Idea units were a noun or noun phrase, verb or verb phrase, and object (s) and modifiers of each (e.g., "Babies are born with a sense of number" consists of three idea units; babies/are born with/a sense of number). Idea units also included dates, indicators of temporal order (first, next) and words that indicated critical structures in text (e.g., "'because' as an indicator of cause and effect). Next, three participants were randomly identified, and the idea units in each of their notes and summaries from both conditions (reading/typing; reading/handwriting) were coded independently by two raters (the second and third authors). Within each condition (reading/typing; reading/handwriting), the raters scored the idea units in the notes and summaries for seven lessons. The reliability of scoring for the reading/typing condition (notes and summaries combined) was .983 and for the reading/handwriting condition (notes and summaries combined) was .970. Differences in scoring were settled by consensus. The remaining protocols were split between the two raters and scored independently.

Then idea units were coded in both the notes and summaries the children had written by both modes of letter production. Although the texts that children read as source material had the same number of words, they differed in idea units. Therefore, instead of analyzing the absolute number of idea units each child produced for each reading-writing task and mode, the proportion of the idea units in each source material text that appeared in each child's notes and summaries was computed. That is, the number of coded idea units in the child's

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notes or summaries was divided by the total number of coded idea units in the source material text they read. Then the mean differences in these proportions of idea units were compared for notes and summaries by touch typing on keyboard and by handwriting with pencil on paper. Finally, for the seven participants who had usable data for both idea units and brain imaging, these values for proportion of idea units for each writing task by mode of letter production were correlated with brain data for functional connectivity.

2.4. Brain imaging

Before children entered the scanner they were taught and practiced each of the three reading tasks that they would perform in the scanner. They had to reach the criterion of 90% accuracy on each of the tasks before they could enter the scanner.

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

The following MRI series were scanned while the children performed the fMRI reading tasks: 1) 3-plane scout view with gradient echoe pulse sequence: TR/TE 9.8/4.6 ms; Field of view 250 × 250 × 50 mm; acquisition time 30.3 s; 2) reference scan (used in parallel imaging) with gradient echoe pulse sequence: TR/TE 4.0/0.75 ms; Field of View 530 × 530 × 300 mm; acquisition time 44.4 s; 3) B0 field map imaging with gradient echoe pulse sequence and 2 echoes; TR/TE 11/6.3 ms; delta TE 1.0 ms; slice orientation transverse, Field of view 240 × 240 × 129 mm; voxel size 1.5 × 1.5 × 3.0 mm; acquisition matrix 160 × 160 × 43, output image magnitude and phase, acquisition time 2:29 min/s; 4) MPRAGE structural scan: TR/TE 7.7/3.5 ms, Field of view 256 × 256 × 176 mm, slice orientation sagittal, voxel size 1 × 1 × 1 mm, inversion pulse delay 1100 ms, Sense factor 2 in the AP direction, acquisition time 5:33 min/s; and 5) fMRI during the reading tasks used these MRI acquisition parameters: echo-planar gradient echo pulse sequence (single shot): 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, SENSE factor in the AP direction 2.3; epi factor 37; bandwidth in the EPI frequency direction 1933 Hz, SoftTone factor 3.5, sound pressure 6.1 dB; 5 dummy scans; fold over direction AP, 396 dynamic volumes/repetition times.

The fMRI reading tasks were all programmed, timed, and coordinated with the scanner triggers using E-prime and in-house LabView software. For each of the three fMRI tasks, the scanning session for each of the three tasks lasted for two minutes during which (a) items (half correct and half incorrect) were presented randomly; (b) and visual presentation for a single item lasted until the students pressed a key to indicate their decision, after which the

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next stimulus item was presented. That is, within the two-minute time limit for each task, each item was self-paced.

For the *word-level word-specific spelling task,* participants were instructed to press the Yes Button if the written word on screen is a correctly spelled real word, but press the No Button if the written word on screen is not a correctly spelled word, even though when pronounced it sounds like a real word. Examples are "bus" for yes trial, and "eer" for no trial.

For the *sentence-level single sentence reading comprehension task*, participants were instructed to press the Yes Button if the sentence was a meaningful sentence, but the No Button if it was not. The "no" items differed from the "yes" items by only one word, which was a homonym foil. This is an example of a no sentence: "The bee, witch buzzes, can sting you." This is an example of a yes sentence: "The bee, which buzzes, can sting you." A homonym foil rendering a sentence not meaningful could occur in any word position in the sentence except the last word.

For the *multi-sentence reading comprehension task*, the participant was instructed to read each of the four sentences, which appeared on the monitor one at a time, press the yes button when finished reading each one, and finally press the Yes Button if the fifth (last) sentence in the set was true based on the four prior sentences just read or the No Button if it was not true. An example set of false being the correct answer follows:

> Sentence 1 Tomorrow is the day of the picnic.
>
> Sentence 2 If it rains, the picnic will be canceled.
>
> Sentence 3 Amy listens to the weather report.
>
> Sentence 4 She hopes it will rain.
>
> Sentence 5 Amy wants to go to the picnic. True or False? (press key to answer) (False).

An example set of a true response being correct follows.

> Sentence 1 John handed Bill a note.
>
> Sentence 2 It was from Sarah.
>
> Sentence 3 Sarah had written that she wanted to talk to Bill.
>
> Sentence 4 Bill frowned when he read the note.
>
> Sentence 5 Bill was not pleased with what Sarah had written. True or False? (press key to answer) (True).

2.5. fMRI connectivity

For this purpose, temporally concatenated ICA in FSL Melodic on all reading data from 10 representative control participants was run. A set of language-related components was identified by visual inspection. Components were broken into large clusters (k > 100) and divided into peaks >30 mm apart. Spheres (r=5 mm) drawn around each peak were confirmed as written language-related by comparison with Neurosynth [64]. Neurosynth is a

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platform for large-scale, automated synthesis of functional magnetic resonance imaging (fMRI) data based on meta-analysis of fMRI studies, which in our case used functional specificity of reading-related fMRI brain regions. FSL software randomize was used to control for multiple comparisons and to identify significant connectivity within the group. There were 8 seed regions generated as follows: 1) right superior parietal/angular gyrus; 2) left anterior inferior parietal sulcus; 3) left posterior middle/superior temporal gyrus; 4) left IFG/broca's area; 5) right temporooccipital; 6) right inferior temporal; 7) left inferior lateral occipital cortex; and 8) right precentral gyrus. Because the first one involving the angular gyrus generated by these group analyses showed it was of statistically significant magnitude and matched the results of a meta-analysis [64], it was chosen for use in the study linking the fMRI connectivity data with the reading-writing tasks the children had performed during instructional intervention.

Functional images were corrected for motion using FSL MCFLIRT [25], and then high-pass filtered at sigma=20.83. Motion scores (as given in the MCFLIRT report) were computed for each participant. Spikes were identified and removed using the default parameters in AFNI3s 3dDespike. Slice-timing correction was applied with FSL3s slicetimer and spatial smoothing was performed using a 3D Gaussian kernel with FWHM=4.0 mm. Time series motion parameters and the mean signal for eroded (1 mm in 3D) masks of the lateral ventricles and white matter (derived from running FreeSurfer3s reconall on the T1-weighted image) were analyzed. Co-registration of functional images to the T1 image was performed using boundary based registration based on a white matter segmentation of the T1 image through epi_reg in FSL. The MPRAGE structural scan was segmented using FreeSurfer software; white matter regressors were used to remove unwanted physiological components. fMRI time-series were averaged within regions of interest (ROIs) from each seed described above. The averaged time series at each ROI was correlated with every voxel throughout the brain to produce functional connectivity correlation maps, converted to *z*-statistics using the Fisher transformation.

3. Results

3.1. Differences in proportion of coded idea units

Comparison of the combinations of two writing tasks—notes and summaries—and two modes—pencil and touch typing—across the twelve weekly lessons showed similar, but low, proportions of idea units in source material that were expressed in the children's written notes and summaries: Handwriting—Notes, *M*=.12, *SD*=.05; Handwriting—Summary, *M*=.11, *SD*=.05; Touch Typing—Notes, *M*=.10, *SD*=.08; and Touch Typing—Summaries, *M*=.10, *SD*=.06. As shown in Table 1, within subjects ANOVA showed neither a main effect across the four conditions (Writing Tasks—Notes or Summaries—OR Modes—Handwriting or Touch Typing on Keyboard), nor an interaction between writing tasks and modes in proportion of idea units produced. Across the twelve lessons, developing writers with SLDs in written language could produce a comparable proportion of idea units whether writing notes or summaries or by keyboard or pen.

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3.2. Significant changes in mean levels of reading fmri connectivity from time 1 to time 2

fMRI connectivity between right angular gyrus and cingulate during the multiple-sentence reading comprehension task changed from Time 1, M=.598, SD=.16 to Time 2, M=.397, SD=.06, $t(5)=3.37$, p=.02. See Fig. 2. The seed point is known to be involved in reading [1,50]; and the region with which it is connected, the cingulate, is known to be involved in executive functions for written language [4,14].

fMRI functional connectivity between right angular gyrus and right Broca's area during the single-sentence reading comprehension task also changed from Time 1, M=.21, SD=.085 to Time 2, M=.534, SD=.234, $t(4)= -3.09$, p=.037. Like the first change in fMRI connectivity, the seed was angular gyrus involved in reading, but in this case the connectivity was with a brain region associated with executive functions for orthographic coding of single words [4] (Fig. 3).

3.3. Changes in correlations of brain connectivity and proportion of idea units

Correlations were computed for both handwriting and keyboarding modes between (a) fMRI functional connectivity from right angular gyrus as seed point, and (b) proportion of idea units in read source material that were observed in notes or summaries by touch typing or groovy pencil. These were computed both at time 1 before participating in the computerized learning activities for reading source material, writing notes, and writing summaries by alternating touch typing and groovy pencil, and at time 2 after completing those learning activities. Results are reported by each combination of mode (handwriting then keyboarding) and writing task (notes then summaries). Of interest is whether correlations that were not significant at time 1 were significant at time 2. Note that for these correlations connectivity from all seed points that had been shown to be significant, after controlling for multiple comparisons, were considered (see Section 2).

3.3.1. For handwriting and notes—To interpret the neurocognitive significance of these findings keep in mind that Left Broca's is associated with executive functions for language in general [36], whereas right Broca's has been associated with executive functions for orthographic coding of written words [4]; and cingulate gyrus is associated with executive functions for supervisory attention [14]. Thus five of these significant correlations at time 2 for reading comprehension tasks, but not time 1, involved connectivity with a brain region associated with executive functions. However, although significant emergent correlations at time 2 were observed at all levels of language in the fMRI tasks, the one for multi-sentence reading comprehension showed an increase in negative correlations, whereas the four word-level reading or sentence-level reading comprehension ones showed an increase in positive correlations. A negative correlation shows that as proportion of ideas increases, magnitude of connectivity decreases as may happen if an existing network becomes more efficient. A positive correlation shows that as the proportion of ideas increases, magnitude of connectivity increases as may happen when a network is increasingly being used.

For multiple-sentence reading comprehension, the correlation became more negative between proportion of ideas during note taking by pencil: fMRI connectivity for angular gryus with cingulate gyrus was $r= -.517$ ns at time 1, but $r = -.946$, p=.015 at time 2.

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However, the other four emerging significant correlations involved increase in the positive direction. For the single-sentence reading comprehension task, the correlation from left superior temporal gyrus with left Broca's area was $r = -.659$ ns at time 1, but $r=.872$, $p=.05$ at time 2. For right temporooccipital region with left Broca's area, the correlation was $r=.209$ ns at time 1, but $r=.941$, $p=.017$ at time 2. From right precentral gyrus with Broca's area on right was $r=.515$ ns at time 1, but $r=.878$ $p=.05$ at time 2. For single word reading, the correlation between the proportion of ideas and fMRI connectivity involved an increase in correlation in the positive direction from right temporooccipital region with Broca's area on right, $r=.401$ ns at time 1, but $r=.894$ $p=.041$ at time 2.

3.3.2. For handwriting and summaries—Only one correlation emerged for handwriting summaries when writers could refer only to their notes. For multi-sentence reading comprehension, a negative correlation emerged between proportion of ideas and connectivity of the right temporooccipital with the left inferior occipital cortex: $r=.074$ ns at time1, but $r= -.934$, $p=.020$ at time 2. In contrast to handwriting and note-taking, for handwriting and summaries, only one correlation emerged at time 2 that was not significant at time 1—for text-level summaries; however, like handwriting and note-taking the correlation for handwriting and summaries was negative.

3.3.3. For touch typing and notes—Only one significant correlation was observed for this mode and reading-writing task: The proportion of ideas in notes by touch typing and fMRI connectivity during the multi-sentence reading comprehension task from left inferior occipital cortex with left fusiform was $r = -.019$ ns at time 1, but $r = -.885$, $p=.046$ at time 2. Fusiform is associated with orthographic coding of words [16,17]. Of note, significant correlations were observed only at the text level for touch typing and note-taking; and, as for handwriting and note-taking at this level of language in reading comprehension, the correlation increased from time 1 to time 2 in negative direction.

3.3.4. For touch typing and summaries—Only one significant correlation was observed for this mode and reading-writing task: Correlation between proportion of ideas and connectivity between left inferior occipital cortex and left fusiform was $r=.073$ ns at time 1, but $r = -.881$ $p=.049$ at time 2. The network of connectivity was the same as for touch typing and notes, and the direction of the change in correlations was also in a negative direction. Also the correlation was only observed for the fMRI multi-sentence, text-level reading comprehension task as had been the case for touch typing and note taking.

4. Discussion

4.1. Controversy over handwriting versus keyboarding

The current research findings generalize only to the relative advantages of handwriting by groovy pencil versus keyboarding by touch typing after twelve introductory lessons to touch typing for students in middle childhood with diagnosed, persisting SLDs in written language (dyslexia or dysgraphia). In the current study the correlations between proportion of idea units in writing activities during computerized learning activities and brain connectivity during fMRI reading tasks increased significantly in magnitude in a positive direction only

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for fMRI word-level and sentence-level reading tasks when handwriting had been the mode of letter production during note taking. However, the correlations between the proportion of idea units in writing activities during computerized learning activities and the fMRI text-level reading task increased significantly in magnitude in a negative direction across modes of letter production during summary writing. Future research should evaluate whether these findings replicate. If the findings replicate, then studies should be designed to sort out the reason(s) for the contrasts in direction of the change and nature of the change.

On the one hand, change in the positive direction may indicate increase in connectivity supporting a reading task at specific levels of language (word and sentence), but change in the negative direction may indicate improved efficiency resulting in less connectivity supporting a reading task drawing on an additional level of language (text as well as word and sentence). On the other hand, the fMRI multi-sentence reading comprehension task draws on both multi-leveled language skills and cognitive (inferential thinking) skills to a greater degree than the word-level or sentence-level fMRI tasks do. At the text level of language either mode during writing summaries (or typing during note taking) may decrease brain connectivity and thus increase efficiency of the connectivity among the language, cognitive, and executive function systems involved in cross-domain, text-level reading comprehension in the functional reading system (see Fig. 1).

There are several possible explanations for these findings related to mode, nature of reading-writing task, level of language, and direction of change in correlation. To begin with, the advantage of handwriting at the both the word- and sentence- levels during note-taking involving a change in a positive direction may stem from formation of letters stroke by stroke by pen(cil) enhances perception of letters during reading and creation of networks to support word level reading (James & Atwood, 2010; [33,34]) in and out of sentence context. In addition, improved neural network support for word reading may in turn facilitate sentence reading when the meaningful and non-meaningful sentences differ by just one word. Thus, the fMRI word-level task (related to spelling impairment in dyslexia and dysgraphia) and the sentence level reading comprehension task involving those words and their homonym foils may benefit from use of handwriting during note taking because that mode increases brain connectivity at those levels of language more than does writing notes by selecting and pressing letters on keys of a keyboard.

At the same time, one explanation for the observed decrease in connectivity between right angular gyrus and right Broca's area for summary writing is that summary writing draws not only on written language and cognitive skills but also a high-level executive function for cross-domain translation of cognitions into written language [41]. As this cross-domain translation process becomes more efficient, so does the neural circuitry and thus the magnitude of the connectivity is reduced. Also this cross-domain process at the text-level of cognitive-linguistic translation during reading comprehension may be less affected by writing mode when writing summaries than is the word-level and sentence-level reading comprehension. Another possible explanation is that findings may be related, in part, to the reader-writers being able to reread the source expository text while taking notes but not while writing summaries. Also it should be noted that changes observed from insignificant to significant correlations varied across the seeds from which magnitude of brain

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connectivity was measured. Clearly, more research is needed on issue of handwriting versus keyboarding, but the current results show promise for integrating cognitive and brain relationships in future research.

To summarize, the current results are consistent with an advantage for handwriting in note-taking in older students and typically developing writers [43]. In the current study only handwriting during note-taking showed significant correlations between brain connectivity at all levels of language studied and proportion of idea units emerging at time 2 after computerized instruction in reading source material, taking notes, and writing summaries, even if they were positive at the word- and sentence-levels but negative at the text-level. Thus, the nature of the writing task—note-taking or summary writing—may matter for the nature of the advantage of handwriting and its relationship to reading.

4.2. Implications for the neuroscience of language

Of neurological significance, many of the changes from time 1 to time 2 in mean fMRI connectivity involved angular gyrus, which has been shown to be involved in reading comprehension [1,50]. In addition, many of the functional connections in brain observed in the current study for reading tasks coincide with ones that have been identified in meta-analyses for handwriting [49] and word spelling [52]. For example, Planton et al.'s meta-analysis identified these regions associated with handwriting: left frontal dorsal extent of Broca's not just precentral gyrus, left superior parietal, left fusiform, and cerebellum. All but the last were involved in functional connectivity observed in the current study. Purcell et al.'s meta-analysis identified left fusiform, left supra-marginal, left precuneus, and left Broca's. The first and last were observed in the functional connectivity observed in the current study for reading comprehension. Reading and writing brains share common and unique brain circuitry, but are not inverses of each other—completely identical processes regardless of whether written language is the input through eyes or output through hands. Clearly, more interdisciplinary research is needed on these issues, from a brain perspective, regarding differences in handwriting and touch typing related to use of a dominant hand only versus both hands, respectively, and the potential significance of left-right connectivity, right-right connectivity, and left-left connectivity during integrated reading-writing in larger samples of students with and without SLDs in written language during middle childhood and other stages of development.

Finally, this research supplements prior research showing that typically developing readers and writers differ in structural and functional connectivity on handwriting and spelling tasks and planning for text-level composing [53]. Only those with dyslexia with and without dysgraphia or with dysgraphia were included in the current study, which showed response to instruction in that correlations between brain connectivity and proportion of ideas units in notes and summaries increased after specialized instruction. That instruction included both explicit strategy instruction and supported practice in implementing the strategies across different reading and reading-writing tasks. Future research could extend the current study by (a) comparing typically developing writers without SLDs and developing writers with SLDs in a larger sample in school settings; and (b) examining whether being able to reread source material during note-taking but not written summarization (based only on notes

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taken) might influence the results for relationships between brain connectivity-idea expression on different, contrasting reading-writing tasks.

4.3. Implications for education

On the one hand, the results suggest handwriting in note-taking is related to reading at the word, single sentence, and multi-sentence levels. On the other hand, the results show that instruction in strategies for reading expository texts, strategies for taking notes, and strategies for writing summaries can change the associations between magnitude of connections from a seed point involved in language processing with a brain region involved in executive functions *and* the proportion of ideas expressed in integrated reading-writing tasks. Moreover recommending technology for accommodations for students with SLDs in written language without providing explicit instruction in using the technology for integrated reading-writing tasks and other reading and writing tasks is not sufficient (Thompson et al., in press) [60]. More worldwide and cross-disciplinary research is needed on the most effective ways to do so.

5. Summary and conclusions

Overall, the results support the benefit of explicit strategy instruction in integrating reading and writing for students with SLDs in written language beginning in middle childhood to prepare them for the integrated reading-writing requirements in the upper secondary and postsecondary grades. Strategies for reading source material and writing notes and summaries of it by different modes of letter production—touch typing and pencils—are beneficial and should also include practice in implementing the strategies, with access to the strategies for review as needed during the reading and writing processes. In contrast to much research on effective instruction, which evaluates efficacy of instruction based on changes in normed measures for age or grade or on researcher-designed behavioral measures, this study evaluated response to intervention (RTI) based on changes in magnitude of brain connectivity from a region known to be involved in reading comprehension with a region known to be involved in executive functions and emerging correlations between this brain connectivity and expression of ideas in notes and summaries of read source material. Importantly, such interdisciplinary research linking brain and behavioral data shows that writing is not an act that occurs only in the observable external environment. Rather, writing involves an interaction of internal processes and representations in the brain and observable acts and stimuli in the external environment.

Acknowledgments

Supported by Grant P50HD071764 from the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development (NICHD) to the University of Washington Learning Disabilities Research Center, this research has been a team effort: The first author collected and analyzed the DTI and fMRI connectivity data. The second and third authors developed and applied the idea unit coding scheme for the notes and summaries. The fourth author conducted the data analyses linking the coded idea units in notes and summaries by keyboard and pens with brain data. The fifth and sixth authors developed the platform for administering the learning activities for taking notes and summaries by keyboards and pen and storing what participants wrote for analyses. The seventh and eighth authors developed the reading tasks given during imaging and the note taking and summary learning activities. The last author also recruited the sample and supervised the computer lessons.

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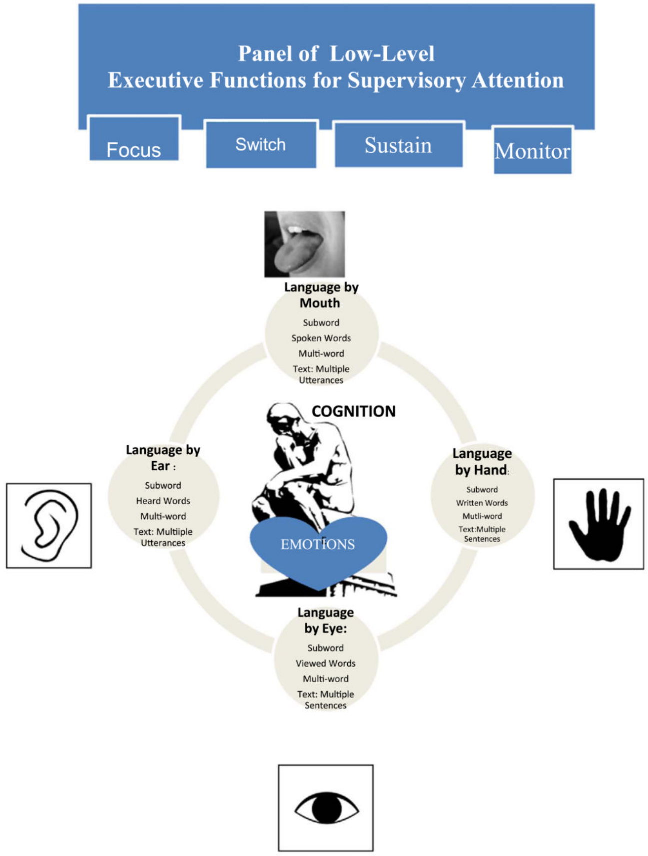

Fig. 1.

Understanding integrated reading-writing in the context of the five domains of development: cognition, multi-leveled language, sensori-motor, social emotional, and attention/executive functions. Adapted from Figure 9.1 in Berninger, V.W. (2015). Interdisciplinary Frameworks for Schools. Washington, D.C.: APA Books.

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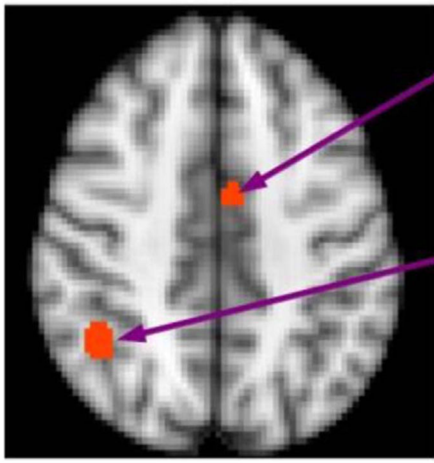

Fig. 2.

Brain region locations of significant fMRI connectivity from time 1 to time 2 for fMRI connectivity during the multiple-sentence reading comprehension task. The Voxels of the seed cluster in the angular gyrus (MNI coordinates, 42, −50, 44 mm) and voxels in the cingulate cortex (MNI coordinates, −6, −2,44) showing significant functional connectivity with angular gyrus are overlaid on the standard MNI brain.

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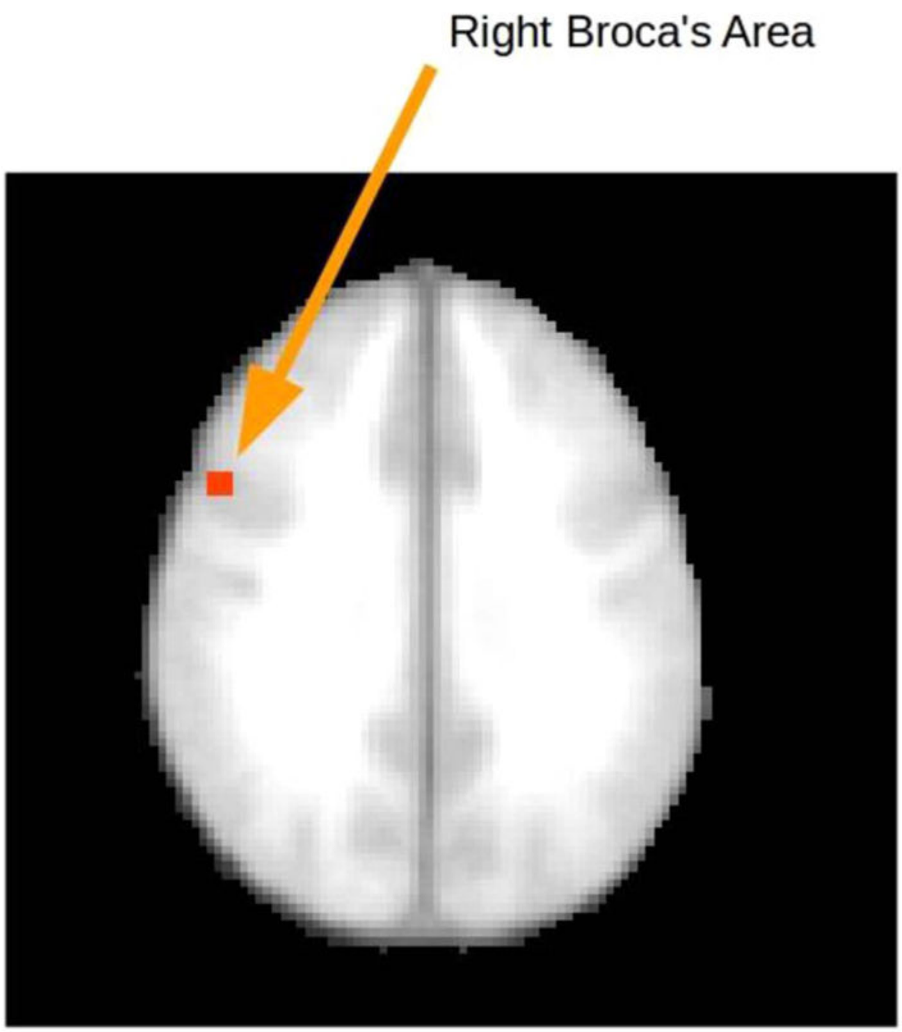

Fig. 3.

Location of one region with significant fMRI connectivity from time 1 to time 2 for fMRI connectivity during the multiple-sentence reading comprehension task. The voxels in the right Broca's area (MNI coordinates, 52,14,32 mm) showing significant functional connectivity with seed region angular gyrus are overlaid on the standard MNI brain.

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Table 1

Proportion of idea units in two tasks (notes and summaries) and two modes (handwriting and summaries).

	F (df)=	p
Main effects		
Notes vs summary	.009 (1,7)	.929
Handwriting vs touch typing	.634 (1,7)	.452
Interaction		
Writing task-mode	.472 (1,7)	.514