

The Development of Multi-Leveled Writing Brain Systems:

Brain Lessons for Writing Instruction

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Acknowledgments:

Grant P50HD071764 from the *Eunice Kennedy Shriver* National Institute of Child Health and Human Development (NICHD) at the National Institutes of Health (NIH) to the University of Washington Learning Disabilities Research Center supported, in part, the preparation of this chapter.

Until recently, most neuroscience research on the brain was based on autopsies of individuals who lost writing skills before death and, thus, acquired disorders later in development (e.g. Anderson, Damasio, & Damasio, 1990; Basso, Taborelli, & Vignolo, 1978; Brain, 1967), rather than on studies of developing children and youth. That all changed with the development of technology near the end of the 20th century to study the living brain, initially with adults but increasingly with children and youth. The purpose of this chapter is to review research on the developing brain as it relates to writing systems. It begins with an evidence-based, conceptual framework for writing systems of the brain grounded in current paradigms in neuroscience, developmental science, learning science, and instructional science. We then provide a brief overview of research methods used for studying the developing brain, followed by illustrative neuroscience findings for writing in early childhood, middle childhood, and adolescence/young adults. Finally, the significance of these brain findings is discussed in reference to five key ideas about how neuroscience can be used to inform educators interested in brain-based pedagogy and brain-based lessons for writing instruction.

Multiple Writing Systems in the Developing Brain

Despite frequent use of expressions that suggest a separation among language in general and reading and writing, research has shown that reading and writing must be considered parts of language (Berninger & Abbott, 2010). An evidence-based conceptual model of writing systems in the brain (Berninger, 2015; Berninger & Niedo, 2014) includes four language systems—auditory language perception, visual language perception, oral language production, and manual language production—each of which is multi-leveled (subword, word, multi-word syntax and idioms, and text). Moreover, each of the language systems interacts with the other language systems and with sensory/motor, social emotional, cognitive, and attention/executive function

systems in the brain. However, which of these systems are interacting with other systems or with specific levels or skills in those other systems depends on the developmental level of the writer and the specific language or writing task.

In interpreting brain research, it is important to consider whether participants were individuals learning to write with or without a struggle or individuals who had acquired and then lost writing skills. For example, *dysgraphia* is a word of Greek origin that means *impaired* graph production through hand—their letter writing is not legible and automatic. *Agraphia* is also a word of Greek origin that means *without* letter production capability because what was once acquired is now lost. This chapter focuses on the developing brain, as related to writing, rather than on acquired writing disorders due to brain injury or disease in adults following earlier normal writing acquisition.

Methods Used to Study the Developing Human Brain

For the most part, only noninvasive imaging, such as Computer Assisted Tomography (CT), *structural* Magnetic Resonance Imaging (MRI), *functional* MRI (fMRI), Diffusion Tensor Imaging (DTI), Electroencephalograms (EEG), and Event Related Potentials (ERPs), are FDA approved for use in research with children. Becoming a critical consumer of brain research requires synthesizing findings not only for specific brain regions but also the aspect of brain structure or function assessed by a particular imaging tool, none of which assesses all aspects of brain structure or function and which differ in what they do assess. Further, brain research has uncovered an organ that is highly synthesized and dynamic – one does not emphasize particular regions, but rather, *systems* in the brain that underlie given functions. These systems are comprised of groups of regions, interrelated, that have feedforward and feedback networks – they influence one another on many different levels. The interactions among regions are

influenced by experience, and this is most important for skills acquired as a result of explicit teaching. The underlying brain systems are shaped by interactions among teachers and learners.

Here we give a brief overview of the methods for imaging the brains of children that are discussed in this chapter. Some of these techniques assess brain *structure* (CT, MRI, DTI) and can provide valuable insights into changes in structure that occur over time. Other techniques assess brain *function* (fMRI, functional connectivity, ERPs) and are crucial for understanding how human behavior is produced. These imaging techniques, when coupled with behavioral measures, allow us to understand mechanisms that underlie writing acquisition and therefore add important information to what we can assess by the study of overt behaviors only.

Magnetic Resonance Imaging (MRI) produces structural images of the brain, whereas functional MRI (fMRI) allows for the localization and measurement of functional brain activity via the blood oxygen level dependent (BOLD) signal (Amso & Casey, 2006). This signal provides an indirect measure of neuronal activity (Heeger & Ress, 2002), based on neural activity coupled with local hemodynamic oxygenation, that is, increased oxygen level means increased neuronal activity (Thomas & Tseng, 2008). Regions of the brain that are using more oxygenated hemoglobin are identified through computer data analyses.

Because fMRI has no risks, it is a safe measure to use repeatedly with developing populations (with the exception of those with ferromagnetic materials in or on the body). However, to image a brain using fMRI the participant must stay very still (usually only 5mm of movement is allowable) which is an obvious limitation for imaging developing children. The reason is that movement results in motor artifact. Thus, typically only children older than 4 years of age can participate in fMRI studies. Depending on the procedure, a 25% attrition rate in the 4 to 5 age range occurs, meaning children cannot lay still long enough to complete the procedure

(James lab data, unpublished); but children in the age 5-6 range have a 10% attrition rate.

However, the data from children younger than 4 years are virtually unusable without sedation.

Furthermore, the data from fMRI can be used to assess functional connectivity in the developing brain through a variety of analysis techniques including correlations, Granger causality, and Psychophysiological Interactions (PPI) analyses. These methods have the ability to measure the changing dynamics and functional connections between brain regions over the course of development. This procedure, in its many forms, allows the researcher to observe brain regions that activate together, suggesting that these interactive regions form a functional network. Because we know that human behavior is so complex that it requires the use of many brain systems for any given task, it is important to specify systems, and not just isolated regions that are required for a given task of interest.

The electroencephalogram (EEG) is an additional imaging tool used to assess cognitive function by recording oscillations in electrical activity from the surface of the scalp. In this method, participants are repeatedly presented with a particular stimulus to reduce random noise and to produce a waveform that reflects the neuronal response to that stimulus (Thomas & Casey, 2003). The averaged waveform is known as an event-related potential (ERP) for higher cognitive processes when the responses evoked by stimuli for eliciting specific cognitive processes are time-locked to the onset of the stimulus (Thomas & Casey, 2003; DeBoer, Scott, & Nelson, 2007). Deflections in the ERP waveform, known as components, reflect activity from large neuronal populations and indicate particular aspects of cognitive and sensory processes (DeBoer, Scott, & Nelson, 2007; Taylor & Baldeweg, 2002). While the temporal resolution of ERP data is accurately measurable within milliseconds, the spatial resolution is less precise due to the recording of electrical potentials at the scalp. Given the temporal resolution of this tool,

ERPs can be used, however, to address questions of cognitive functioning in which timing is pertinent. Additionally, ERPs have been successfully used to study development in children (Friedman, 1991), for example, in response to task-relevant and irrelevant stimuli in both passive and active tasks (Taylor & Baldeweg, 2002). Further, EEG and ERP can be used to assess temporal processing in the brain from birth and are therefore useful tools for study the writing brain early in development.

Development of the Writing Brain

Developmental Changes in the Brain

Similar to the ever changing platforms in our computer technology, the developing brain supporting writing undergoes continual change, in part, due to genes that regulate neural migration, regulation of neural development and function, and protein production, and, in part, due to interactions between the brain and environment of the developing child (Berninger, 2015, Chapter 7). In a groundbreaking longitudinal study using MRI, Giedd and colleagues (2009) identified neuroanatomical changes in the brain from early to middle childhood to adolescence. Thus, in this chapter the focus is on representative studies at these target developmental times with a focus on writing.

Infancy to Early Childhood

Although writing is not a skill pertinent to infants and very young children, longitudinal research using EEG and ERPs has shown that processes known to underlie letter and word perception may have sources in infancy. For example, ERPs collected at birth showed that auditory pitch processing differentiated children who were and were not at genetic risk for dyslexia, a specific learning disability associated with impaired oral word decoding and reading and written spelling, and also predicted letter knowledge and phonological skills prior to school

age and phoneme duration perception, spelling, and reading speed in 2nd grade (Leppänen et al., 2010). This line of research points to the importance of early screening and intervention to prevent spelling problems, which may be related to problems in differentiating sounds through the ears as well as later differentiating letters processed through the eyes and hands.

The early pitch perception problems may not be restricted to the auditory input mode alone but may reflect a broader problem in pattern analysis. Brem et al. (2010) in this same research group showed with concordant ERP and fMRI in nonreading kindergarten children that print sensitivity for fast (<250 ms) processes in posterior occipital-temporal brain regions, (where visual processes through the eye are integrated with language through the ear), is associated with learning letter-speech sound correspondences needed in both spelling and word reading. These studies suggest that systems used later for reading are developing very early on and may have significant impact on subsequent reading and writing skills.

Early Childhood

Networks for visual word forms as well as grapho-motor planning. It is well established that a network of brain regions is activated when written words and their letters are processed in literate adults (e.g., Cohen, Lehericy, Chochon, Lemer, Rivaud, & Dehaene, 2002). This system of regions includes the left fusiform gyrus, which is sometimes referred to as the “visual word form” area, left superior temporal gyrus/supramarginal gyrus, and left inferior frontal gyrus. However, because the left fusiform gyrus responds differently depending on whether an individual perceives the written word or the written letter (James, James, Jobard, Wong, & Gauthier, 2005), others refer to the ‘visual word form’ area as an orthographic coding area.. Of note, consistent with the results for early childhood, the posterior fusiform (near the back of the brain) has been shown in direct recording on the adult brain (not scalp) prior to surgery to

process word-like letter strings, whereas the anterior (near the front) fusiform processes single letters, which may in turn be linked to sounds (Nobre, Allison, & McCarthy, 1994), and importantly, to forms that are written (James & Gauthier, 2006).

To investigate why the left anterior fusiform gyrus may be recruited more during single letter perception than word or letter string perception in young children, several neuroimaging (fMRI) studies were performed by James and colleagues (James, 2010; James & Engelhardt, 2012; Kersey & James, 2013). Their hypothesis was that single letters are the components of the words that are written one at a time – that is, individual letters may have motor plans associated with them that words and groups of letters do not. Having a motor program associated with each word in the language would be inefficient given that the groups of letters would change each time a word was produced. The initial evidence for this hypothesis came from studies that showed that during letter perception, a motor system was also active in addition to the typical letter sensitive regions (See Figure 1) (James & Gauthier, 2006; see also Longcamp, Anton, Roth, & Velay, 2003). Thus, orthographic codes may link with motor codes, and this cross-code link may be involved in single letter perception.

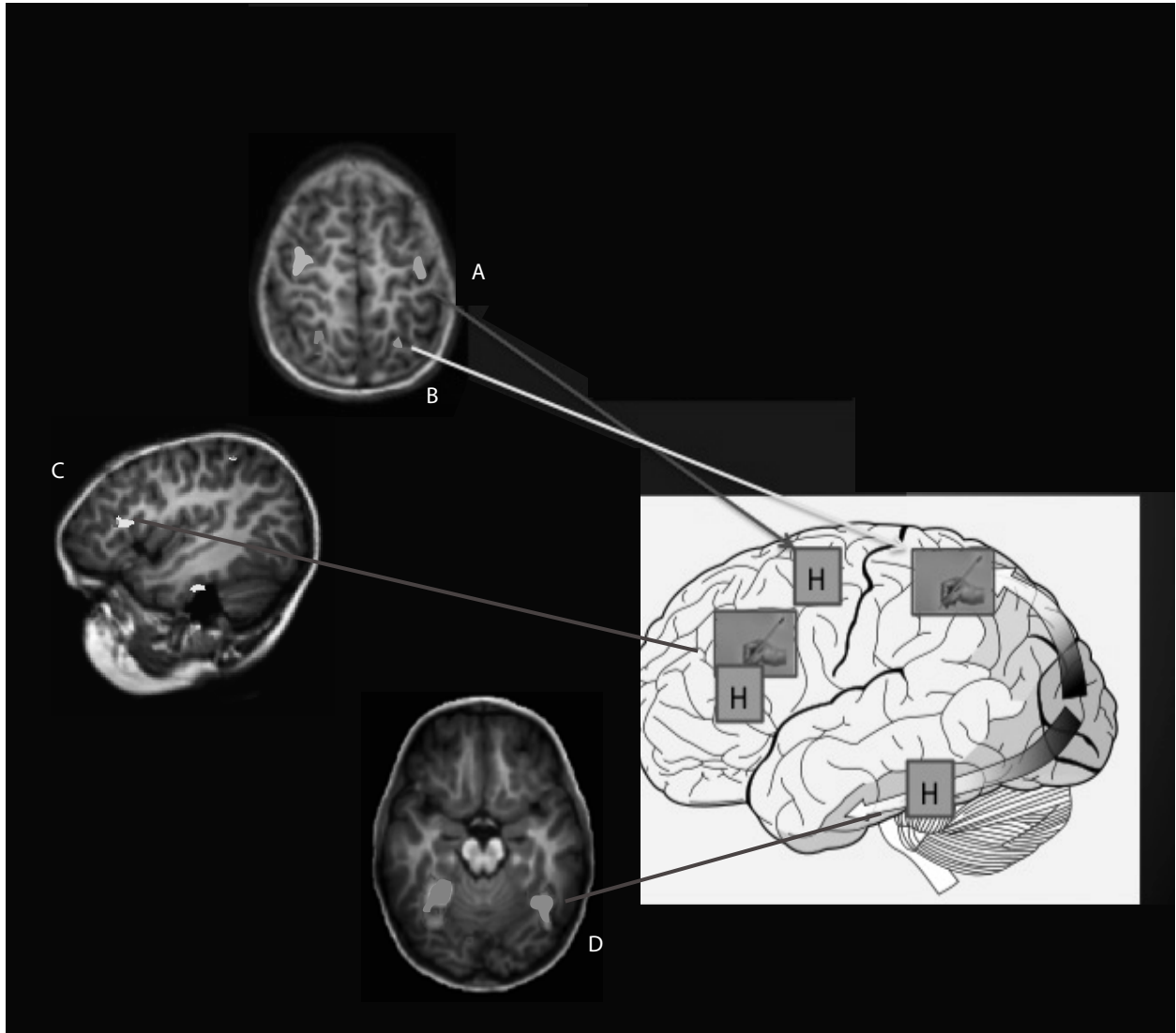


Figure 1.

Brain regions that are more active during letter perception after printing experience than typing experience and visual-auditory practice: A. Precentral Gyrus and Premotor region, B. Inferior Parietal Lobule, C. Inferior Frontal Gyrus and 'Exner's Area', D. Fusiform Gyrus.

Role of writing experience on visual perception for children. James (2010) trained two groups of pre-literate 4-5 year olds to identify letters of the alphabet and then imaged them before and after training: one group learned them by printing the letters when they were presented visually (copying); and the other group repeated the names of the letters instead of copying them. Children looked at letters, numbers and simple shapes while BOLD activation patterns were measured in fusiform gyrus. Prior to the training experience (20 minutes, once a week for 4 weeks, modeled after Longcamp et al., 2003), neural activation did not differentiate among letters, shapes, and numbers. After training, the group that only learned the letters visually without writing did not show any differential activation to letters, shapes or numbers – the brain did not differentiate among these stimuli. In contrast, the group that learned to print the letters showed significant activation in the left fusiform gyrus to letters, but not to shapes or pseudoletters (forms that follow the same rules of letter but are unfamiliar) and showed significant activation in the left premotor cortex after training (see Figure 1). Thus, their brains had become specialized for processing letters, in a way that was similar to the literate adult. This intriguing finding suggests that the role of the left fusiform gyrus in processing and producing letters is not due to visual experience alone, but may be contingent upon motoric production of the letter. Interestingly, the motor cortex was not recruited during the perception of simple shapes, suggesting that the motor cortex is recruited specifically during letter perception.

Nonetheless this study did not compare printing to other forms of motoric practice; perhaps any type of motor practice would facilitate recruitment of the letter processing network.

Various types of motor experience and the effects on neural processing of letters. In a follow up study, James and Engelhardt (2012) tested the effects of different types of motor experience on letter processing at the neural level. In this work, they trained children, again, preliterate 4-6 year olds, prior to fMRI scanning. All children learned to produce both letters and simple shapes by three modes—printing them through copying, typing them, and tracing; all children participated in all conditions, but the letters that were used for each condition were counterbalanced. Subsequent to the training episode, neuroimaging was performed during passive visual viewing of all letters learned as well as letters not learned during training. In this within-subjects design, they compared brain activation patterns between the letter experience conditions in the whole brain. Results indicated that printing experience resulted in the largest activation in the fusiform gyrus, parietal cortex and premotor cortex, which is often reported in adult and child studies of neural networks in reading (e.g., see Booth, 2007). There were different patterns, however, for the different training conditions. In the left fusiform gyrus, printing letters resulted in the highest activation, compared to all the letter and shape conditions, whereas no differences were found in the right fusiform gyrus. In addition, premotor, frontal regions associated with letter processing were active more after printing training than typing or tracing training; the parietal regions were more active after tracing than typing training, and another frontal region was more active after tracing than typing practice (see Figure 1).

Therefore, not only was the left fusiform more active after printing practice, but frontal regions associated with motor tasks were also more active after printing practice, and to a lesser extent, tracing practice. These results add to growing evidence that writing, either copying or

tracing, leads to significantly more activation in the network associated with letter perception and reading than does typing, or no practice. Thus, writing seems crucial for establishing brain systems used during letter perception and by extension, reading acquisition; typing may not be an advisable accommodation for students who struggle with handwriting in the early grades who need handwriting instruction. However, see discussion below.

Premotor activations seen in these studies could be reflecting the recruitment of a premotor region referred to as “Exner’s area” (middle frontal gyrus, Roux, Dufor, Giussani et al., 2009). This region, termed the “graphic motor image center,” and first specified as a result of individuals with agraphia having damage to the region, is thought to underlie writing by hand once an individual is proficient. Specifically, Exner’s area is thought to bridge orthography and motor programs that are specific to handwriting. However, recent studies have shown that spelling via typing may also activate regions near Exner’s area as part of a left hemisphere network including the inferior frontal gyrus, intraparietal sulcus, and inferior temporal/fusiform gyrus, a subset of regions of which are involved in both spelling and reading (Purcell, Napoliello, & Eden, 2011; Purcell, Turkeltaub, Eden, & Rapp, 2011).

Writing letters versus observing others write letters. To investigate whether or not active, self-production of letter forms was key to the subsequent activation of the letter and reading network, Kersey and James (2013) compared two printing conditions in 7 year olds: one in which children printed letters themselves, and another in which children watched an experimenter produce the letters. Both groups viewed letters unfolding over time, but only one group produced the letters themselves. The crucial comparison here was whether self-production resulted in the previously identified processing network, or if any experience of letter production would suffice. In the premotor cortex and in the left fusiform gyrus, actively learned letters

resulted in greater neural activity than passively learned letters. Interestingly, in the left fusiform gyrus, passively learned letters did not result in activity that was greater than baseline. Basically, this region acted as if the letters were not learned. Taken together, the results from the fMRI studies during early childhood show that: a) Printing practice recruits the letter/reading processing network more than does seeing/hearing letter names and typing and tracing letters; and b) learning to write must involve self-production of printing-that is, writing is essential for developing the networks involved in letter processing.

Functional connectivity in very young writers. Functional connectivity analyses can be used to assess regions of the brain that are co-activated during events that are being investigated. A generalized psychophysiological interactions (gPPI) functional connectivity analysis (see Friston et al., 1997; McLaren, Ries, Xu, & Johnson, 2012) was used to evaluate connectivity using data from 16 right-handed, 4-to 5- year old children. Results from this analysis showed that when printing letters, the left fusiform gyrus was functionally connected to the right middle frontal gyrus, which is associated with working memory and contains Exner's Area, a writing center, the left precentral gyrus, which is associated with fine motor skill, and the left postcentral gyrus (associated with touch information). Contrasts in connectivity between the printed letters versus typed letters conditions, showed that only regions in the left precentral and postcentral gyri were co-activated with the left fusiform more for printing letters rather than typing letters. It is important to keep in mind that for this analysis, children were simply viewing letters that they had learned with the different methods (Vinci-Booher & James, in preparation). This analysis suggests that printing letters results in a system of activation connecting the left fusiform, where orthographic codes in letters are first processed, with both touch sensory and motor production regions of the brain.

Collectively, these results show that during the early childhood years (preschool and P-K transition to school years), a network is developing in the brain that supports letter writing and perception and the role of forming letters in learning to recognize them in words in learning to read. That is, there is neuroscientific evidence for a writing route to reading as early as the preschool and kindergarten years. Also, results document the value of forming letters (handwriting) over pressing letters (key touch) in learning to perceive the letters.

Middle Childhood

Handwriting. Similar to what James and colleagues found during early childhood for orthographic coding and fine motor planning, the fusiform differentiated fifth graders with and without handwriting problems on an fMRI on-off comparison for writing a familiar letter (Richards, Berninger, Stock, Altemeier, Trivedi, & Maravilla, 2011). Richards et al. (2009) also found that, during a finger sequencing task which requires sequential motor planning, the same children differed robustly in engaging multiple regions of the brain involved in this task; behavioral measures of printing the alphabet (sequencing component letter strokes), spelling written words (sequencing letters), and written composing (sequencing words) correlated with the same five regions activated during finger sequencing.

Spelling. In a pioneering study linking genes, brains, and endophenotypes, Schulte-Körne and colleagues studied the relationships among spelling, genes, and brain activity in children with and without dyslexia, which is associated with impaired spelling as well as word decoding (e.g., Roeske et al., 2009). They found that children with disordered spelling have an abnormal component in ERP signals during an auditory processing task, which assesses ability to discriminate between two acoustic stimuli presented in succession. They found discrimination abnormalities in both an early and a late ERP component when exposed to two similar sounding

phonemes such as /ba/ and /da/. Although the earlier time window (beginning after 100 ms post stimulus onset) has been shown to be abnormal in dyslexia, their group has described abnormalities in a later time window (beginning at about 350 ms post stimulus onset) that seems to be more specifically related to other language skills besides listening and reading. Their findings also point to genetic variations on two different chromosomes, one involved in switching attention to auditory units over time within single incoming words through ear, and one involved in regulating energy production (blood oxygenation of glucose), which may be inefficient in those with genetic variants.

Booth and colleagues (e.g., McNorgan et al., in press) conducted studies of experience-dependent developmental changes in brain organization for written word learning in children learning to spell and read. McNorgan et al. collected fMRI BOLD while children ages 8 to 14 made rhyming judgments for sequentially presented word and pseudoword pairs in which these monosyllabic word-level stimuli were presented within the same mode (auditory only or visual only) or crossmodal (audio and visual). Regression analyses of the relationships between pairs with overlapping orthography and phonology and only overlapping phonology replicated prior findings by this group that in planum temporale: higher level written word skill was correlated only with cross modal processing for known words. Such known written words are often referred to as word-specific spelling, which integrates phonological, orthographic, and morphological codes and their connections to semantic representations (vocabulary meaning), and was the persisting developmental difference at fifth grade between those with and without dysgraphia (Berninger & Hayes, 2012). Thus, learning to write and perceive letters during early childhood may affect learning to spell and read words during middle childhood.

Family genetics and brain imaging research programs at the University of Washington yielded converging evidence for a model of a working memory architecture supporting oral and written language learning containing multiple components: phonological, orthographic, and morphological codes for storing and processing single words and syntax for accumulating words; phonological and orthographic loops; and supervisory attention (focusing, switching, sustaining, monitoring). This model of working memory components also informed the design and interpretation of brain imaging studies of handwriting, spelling, and composing at the transition of middle childhood to early adolescence. See Berninger and Richards (2012), and Nieto et al. (2014) for reviews of the brain and behavioral research evidence for these working memory components; for their applications to writing assessment and instruction for dysgraphia, dyslexia, and oral and written language learning disability (OWL LD), see Silliman and Berninger (2011).

Idea generation. Berninger et al. (2009) analyzed idea generation during scanning before composing outside the scanner and compared it to the rest condition during scanning. Results showed that typically developing writers recruited a larger network of brain regions including regions previously associated with specific aspects of cognition, language, and executive functions, working memory, motor planning, and timing, but those with dysgraphia showed a different pattern of activation, including more regions in back than frontal cortical regions as well as different locations within BA 46, a frontal region associated with working memory. The current connectivity work on idea generation is comparing the default network for self-generated thinking at rest and the strategic network for composing on a topic given by the researchers during scanning but written about subsequently outside the scanner.

Systems approach to the writing brain. Recent research on writing at the University of Washington is exploring applications of the paradigm shift in neuroscience to the multi-level

connectome of human brain (e.g. Sporns, 2011, 2012) to the writing brain. Fair et al. (2009) have shown that changes in these neural networks can inform developmental changes in brain-behavior relationships.

Adolescence and Young Adults

Handwriting. James and Gauthier (2009) determined psychophysical thresholds for adults given the task of identifying letters presented in visual noise, which varied in amount across trials, on a computer screen. Subsequently, letters were presented near threshold and participants were required to identify the letters while they wrote a letter or drew a simple shape at the same time. The rationale was that if letter perception invoked a motor plan specific to that letter, then writing a different letter or simple shape would interfere with letter perception, but if the same letter was written and perceived, then no interference would occur. Results from this study demonstrated that letter perception thresholds were raised (worse performance) only when participants wrote a different letter from that perceived, or drew a shape. The results suggested that motor plans specific to individual letters are invoked during letter perception and letter representations involve both visual information and motor information related to specific letters. As with young children, a network of activation specific to letter processing—left fusiform, premotor cortex, and inferior frontal cortex—was found in adults.

Because literate adults already have mental letter representations, James and Atwood (2009) focused on how novel forms that looked like letters but were not real letters would be represented after various types of experiences. The research question was whether the representations of novel shapes would invoke the motor system after participants were trained to write the forms. One group of adults practiced writing the novel shapes, while the other group had an equal amount of exposure but only viewed them and practiced saying the names of the

forms. Results showed that the letter network—left fusiform and premotor cortex-- was active after the writing practice but not the viewing practice.

Multiple representations of letters. Rothlein and Rapp (2014) used cutting-edge imaging Multivariate Pattern Analysis-Representational Similarity Analysis (MVPA-RSA) searchlight methods to analyze BOLD while young adults (all women) viewed single letters to test competing views of whether adult letter representation is modality-specific (linked to motor codes through hand or mouth, speech sounds through ears, or visual codes through eyes), or amodal (abstract and not coded for input or output mode). For adults, who have had years of experience with perceiving and producing letters, there was evidence for neural substrates associated with both modality-specific representations (visual, phonological, and motoric) as well as abstract letter representations.

Spelling. Booth, Cho, Burman, and Bitan (2007) collected fMRI BOLD as 9 to 15 year old participants decided if heard auditory rimes did or did not have the same spelling. Based on increased activation in left inferior parietal lobes in older students for the non-conflicting versus conflicting sound-spelling relationships, the researchers proposed that adolescents have a more elaborate mapping of phonemes, onset-rimes, and syllables across phonology and orthography. For review of brain changes over age in orthographic, phonological, semantic, and syntactic processing of oral and written language, see Booth (2007).

Handwriting versus typing. Some adult studies have demonstrated that increased speed of transcription results in better quality of notes as well as recall (Bui, Myerson, & Hale, 2013; Peverly, 2006; Peverly, Ramaswamy, Brown, Sumowski, Alidoost, & Garner, 2007), but the results are mixed as to whether typing or handwriting are better. One study found that typing resulted in better recall of the material (Bui et al., 2013), but another one found that handwriting

had an advantage over typing (Mueller, & Oppenheimer, 2014). Faster transcription speeds during handwriting increase word production automaticity in both adults and children, which lessens the workload of working memory and results in higher quality writing (Peverly, 2006; Peverly et al., 2007). The relative advantages may depend on level of language—word spelling or text composing—and developmental level of writer—advantages for keyboarding often emerge in adolescence but not for all writing tasks (e.g., Hayes & Berninger, 2009). Clearly, further research is needed on the relative advantages of handwriting and typing for specific writing tasks in adolescents and adults.

Five Key Ideas from Brain Research and Implications for Writing Instruction

Key Idea 1: In the Information Age Handwriting Instruction Is Necessary for Literacy

Many believe that if children learn to read, they will automatically be able to write. James and colleagues' research reviewed in this chapter supports the opposite: The act of writing a letter enhances the perception of letter forms, as shown by activation of both premotor and fusiform cortex, which supports reading acquisition. However, brain activation of both the premotor cortex, involved in motor planning and sequential finger movements, and the left fusiform gyrus, involved in orthographic coding of letter forms, also shows that handwriting instruction should help students develop their orthographic loop for integrating letter codes with sequential finger movements during handwriting (Berninger & Richards, 2010, 2012). *Brain Lesson 1: It is important to teach handwriting, beginning in early childhood and continuing through middle childhood, with attention to both the motor and letter coding processes involved, and integrating handwriting with reading, spelling, and composing* (see Berninger, 2012, 2013).

Key Idea 2: Teach Developing Spellers to Store, Process, and Integrate Phonology, Orthography, and Morphology

Brain research shows common and unique brain activation during tasks requiring storage and processing of phonological word forms (heard and spoken words), orthographic word forms (viewed and written words), and morphological word forms (bases and affixes in both oral and written words) and evidence for cross-code integration of these three word forms in response to spelling instruction (e.g., Richards et al., 2006). *Brain Lesson 2: Even though spell checks flag spelling errors, to choose the correct spelling, developing writers need to learn how to integrate phonological coding of spoken words, orthographic coding of written words, and morphology (bases and affixes) to create word-specific spellings for English, a morphophonemic orthography* See Berninger (2015, Chapters 4, 5, and 6 and companion websites).

Key Idea 3: Multi-Component Working Memory Supports the Multi-Leveled, Multiple Language Systems Involved in Writing

Brain and behavioral research have shown that a working memory system, which includes these multiple components, supports written language learning (a) storage and processing units for orthographic, phonological, and morphological word forms and syntax for accumulating words, (b) loops that integrate internal codes and output units through hand and mouth, and (c) supervisory attention for focusing, switching, sustaining, and monitoring attention (for review, see Berninger & Richards, 2010; Niedo et al., 2014). A common reference to language, reading, and writing fails to acknowledge the multiple language systems (by ear, mouth, eye, and hand) involved in written expression of ideas and the multiple levels (subword, word, syntax, and text) within each of these language systems which affect how they interact with each other (Niedo et al., 2014). Emerging research on the complexities of the human connectome for the writing brain is shedding insight into how these multi-leveled, multiple language systems work together to support writing acquisition. *Brain Lesson 3: Instructional*

designers should keep all these working memory components and multiple levels of multiple language systems in mind in designing writing instruction to teach letter production, word spelling, sentence construction, and text generation to create functional writing systems.

Key Idea 4: Executive Functions for Self-Regulating the Writing Process

A recent review of neuropsychological research evidence based on brain and behavioral studies supports teaching both lower-level executive functions in supervisory attention of working memory (focus attention, switch attention, sustain attention, and self-monitor) and higher-order executive functions for planning (setting goals and making plans to reach them), translating cognitions into language, reviewing, and revising during composing (Berninger et al., 2014). Indeed, the deep structure may not be in the language itself, but rather in the higher order executive functions that support the bidirectional cognitive-linguistic translation process (Niedo et al., 2014). The inferior frontal gyrus, along with other brain structures connected to it, may play a role in these executive functions for the writing brain (cf., Mesulam, 1990). *Brain Lesson 4: Writing instruction should teach multiple low-level and high-level executive function strategies to help developing writers self-regulate their developing writing skills* (Berninger et al., 2013; Arfe, Dockrell, & Berninger, in press).

Key Idea 5: Teaching Students to Become Hybrid Writers in the Information Age

Brain research reviewed in this chapter clearly shows the advantage of forming letters compared to selecting them with keys early in writing development and even in adults learning novel letters (Longcamp et al., 2003, James & Atwood, 2006). Behavioral research shows the advantage of handwriting over keyboarding in composing texts during middle childhood (Berninger, Abbott, Augsburger, & Garcia, 2009) and in taking notes during class lectures in adolescence and adulthood (Mueller & Oppenheimer, 2014), and the value of handwriting for

both note-taking and test-taking (Peeverly, 2006; Peeverly, Ramaswamy, Brown, Sumowski, Alidoost, & Garner, 2007) during adolescence and young adulthood. Yet, behavioral research has also shown an advantage for keyboarding emerging in early adolescence for students with specific learning disabilities (Alstad, 2014), perhaps because of increased myelination in early adolescence of right-left fibers supporting the bimanual coordination needed for touch typing with a keyboard. Moreover, writing interventions for students with spelling disability during middle childhood and early adolescence, which were designed with all the working memory components in mind during spelling, and combined handwriting during first drafts and keyboarding for revision during composing (MacArthur, & Graham, 1987; MacArthur, Schwartz, & Graham, 1991), normalized brain function (Berninger & Richards, 2010). *Brain Lesson 5: The goal of writing instruction in the Information Age should be developing hybrid writers who are adept with multiple writing tools including pens and keyboards (see Berninger, 2012, 2013).*

Conclusions and Future Research Directions

The observable output of the brain is action: developing writers convey internal processes through speech (by mouth), locomotion, limb and eye movements (embodied cognition), and manipulation of objects including writing tools (pens, pencils, markers, keyboards, styluses, fingers) that produce letters, words, sentences, and text (by hand). Actions influence how sensory information is selected and processed, which, in turn, influence the selection and execution of subsequent actions. At one level, writing can be understood in terms of *action-perception loops*. The specific kind of experience that is needed for individual letters may be different than for words (e.g., James, James, Jobard, Wong, & Gauthier, 2005; James, & Maouene, 2009) or

sentences and text, but developing students will need instruction at the letter as well as these other levels of language in order to externalize their cognition through written words, sentences, and text (Berninger & Winn, 2006). Future research should include more (a) interdisciplinary research on the developing and learning writing brain, and (b) more writing educators and researchers on the interdisciplinary research team to design the research and interpret and disseminate the findings.

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