CHAPTER 8

The Development of Multileveled Writing Systems of the Brain

Brain Lessons for Writing Instruction

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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). That all changed with the development of technology near the end of the 20th century, when studies then focused on the living brain, initially with adults but increasingly with children and youth. This chapter reviews research on the developing brain as it relates to writing systems. We begin 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, we discuss the significance of these brain findings 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—language by ear, language by mouth, language by eye, language by hand—each of which is multileveled (subword, word, multiword 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 dividuals 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 by hand—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 imag- g, such as computer-assisted tomography (CT), *structural* magnetic resonance aging (MRI), *functional* MRI (fMRI), diffusion tensor imaging (DTI), electroencephalograms (EEGs), and event-related potentials (ERPs), are approved by the U.S. Food and Drug Administration (FDA) for use in research with children. Becoming a critical consumer of brain research requires synthesizing findings not only for specific brain regions but also for 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 that does not emphasize particular regions in isolation, but rather, *systems* in the brain that underlie given functions. These systems are composed of interrelated groups of regions 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 meth- s 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.

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 fMRIs carry 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 5 mm of movement is allowable), which is an obvious limitation for imaging developing children. The reason the child must be absolutely still 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-year-old range occurs, meaning children cannot lie still long enough to complete the procedure; but children in the age 5- to 6-year-old range have a 10% attrition rate. However, the data on children younger than 4 years are virtually unusable unless the children are sedated.

Furthermore, the fMRI data can be used to assess functional connectivity in the developing brain through a variety of analysis techniques, including correlations, Grainger 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 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 ERP 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). Although 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 studying the writing brain early in development.

Development of the Writing Brain

Similar to the ever-changing platforms in our computer technology, the developing brain supporting writing undergoes continual change, in part because of genes that regulate neural migration, neural development and function, and protein production, and in part because of interactions between the brain and environment of the developing child (Berninger, 2015, chap. 7). In a groundbreaking longitudinal study using MRI, Giedd and colleagues (1999) 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 taught to infants and very young children, longitudinal research using EEGs and ERPs has shown that processes known to underlie letter and word perception may have their 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. The ERPs also predicted letter knowledge and phonological skills prior to school age and phoneme duration perception, spelling, and reading speed in second 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) showed with concordant ERP and fMRI in nonreading kindergarten children that print sensitivity for fast (< 250 milliseconds) 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

etworks for Visual Word Forms as Well Graphomotor Planning

is well established that a network of brain regions is activated when written words and eir letters are processed in literate adults e.g., Cohen et al., 2002). This system of regions includes the left fusiform gyrus, hich is sometimes referred to as the “visual ord form” area, left superior temporal gyrus/supramarginal gyrus, and left inferior frontal gyrus. However, because the left fusi- rm gyrus responds differently depending n 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 rthographic coding area. Of note, consistent with the results for early childhood, e posterior fusiform (near the back of the rain) has been shown in direct recording on e 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 8.1) (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.

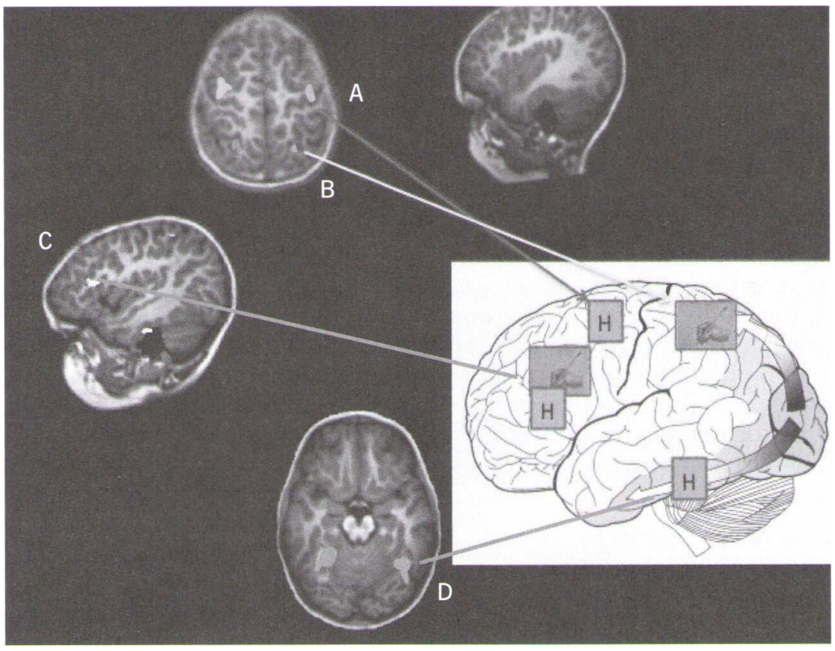

FIGURE 8.1. Brain regions that are more active during letter perception after printing experience than typing experience and visual-auditory practice: A. Precentral Gyrus and Premotor region, B. Inferior Parietal Lobule, C. Inferior Frontal Gyrus and ‘Exner’s Area’, D. Fusiform Gyrus.

Role of Writing Experience in Visual Perception for Children

James (2010) trained two groups of preliterate 4- to 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 8.1). 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- to 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 more active 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 8.1).

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 the 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.

The premotor activations seen in these studies could be reflecting the recruitment of a premotor region referred to as "Exner's area" (middle frontal gyrus; see Roux 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 involved in both spelling and reading (Purcell, Napoliello, & Eden, 2011; Purcell, Turkeltaub, Eden, & Rapp, 2011).

ng Letters versus Observing Others e 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 whether 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 t (1) printing practice recruits the letter/reading processing network more than does ing/hearing letter names and typing and ing letters; and (2) learning to write must olve self-production of printing—that is, riting is essential for developing the net orks involved in letter processing.

Functional Connectivity in Very Young Writers

Functional connectivity analyses can be ed to assess regions of the brain that are coactivated 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 (associated with fine motor skills), 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 coactivated 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, submitted). 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 PreK–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 et al., 2011). Richards et al. (2009) also found that, during a finger sequencing task that 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-Koene and colleagues (see Roeske et al., 2009) 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 milliseconds 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 millliseconds 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 the ears, and one involved in regulating energy production (blood oxygenation of glucose), which may be inefficient in those with genetic variants.

McNorgan, Awati, Desroches, and Booth (2014) 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 judgmen 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) crossmodal (audio and visual). Regression analyses of the relationships between pairs with overlapping orthography and phon ogy and only overlapping phonology re licated prior findings by this group that planum temporale higher level written word skill was correlated only with cross-modal processing for known words. Such kno written words are often referred to as word-specific spelling, which integrates phonological, orthographic, and morphological cod and their connections to semantic represe tations (vocabulary meaning), and was persisting developmental difference at fifth grade between those with and without dysgraphia (Berninger & Hayes, 2012). Th 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 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 Niedo, Abbott, and Berninger (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 disab ity (OWL LD); see Silliman and Berning (2011).

Idea Generation

Berninger et al. (2009) analyzed idea generation during scanning before composing oue the scanner and compared it to the rest ndition during scanning. Results showed t typically developing writers recruited a rger network of brain regions, including ons previously associated with specific spects of cognition, language, and executive functions, working memory, motor anning, and timing. But those with dysaphia showed a different pattern of acti-tion, including more regions in back than ntal cortical regions as well as different ations within BA 46, a frontal region sociated with working memory. The cur-t connectivity work on idea generation comparing the default network for self-erated thinking at rest and the strategic twork for composing on a topic given by e researchers during scanning but written out subsequently outside the scanner.

ems Approach to the Writing Brain

cent research on writing at the University Washington is exploring applications of paradigm shift in neuroscience to the tilevel connectome of the human brain g., Sporns, 2011, 2012) to the writing ain. Fair et al. (2009) have shown that ges in these neural networks can inform elopmental changes in brain–behavior tionships.

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dwriting

mes and Gauthier (2006) determined psyophysical thresholds for adults given the of identifying letters presented in visual , which varied in amount across trials, a computer screen. Subsequently, letters re presented near threshold, and partici-s were required to identify the letters e they wrote a letter or drew a simple pe at the same time. The rationale was if letter perception invoked a motor n specific to that letter, then writing a erent letter or simple shape would interwith letter perception, but if the same er was written and perceived, then no rference would occur. Results from this ly demonstrated that letter perception holds were raised (worse performance) when participants wrote a different let- from that perceived, or drew a shape. The results suggested that motor plans specific to individual letters are invoked during letter perception and that 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) and 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 the left inferior parietal lobes in older students for the nonconflicting 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 a review of brain changes over ages in the 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 et al., 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. Research by James and colleagues 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 acquisitio However, brain activation of both the premotor cortex, involved in motor planning and sequential finger movements, and the left fusiform gyrus, involved in orthograp 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 childho 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).

- **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 for (heard and spoken words), orthographic word forms (viewed and written word 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 lea how to integrate phonological coding 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, chaps. 4, 5, 6, and companion websites).

- **Key Idea 3: Multicomponent working memory supports the multileveled, multiple-language systems involved in writing.** Brain and behavioral research has shown that a working memory system, which includes these multiple components, supports written language learning (1) storage and processing units for orthographic, phonological, and morphological word forms and syntax for accumulating words; (2) loops that integrate internal codes and output units through hand by mouth; and (3) 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 the written expression of ideas and the multiple levels (subword, word, syntax, and text) within each of these language systems that 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 producing insights into how these multileveled, 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, Swanson, & Griffin, 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 & Niedo, 2014; Arfé, Dockrell, & Berninger, 2014).

- **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, 2009). 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 (Peverly, 2006; Peverly et al., 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).

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 et al., 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 (1) interdisciplinary research on the developing and learning writing brain, and (2) more writing educators and researchers on the interdisciplinary research team to design the research and interpret and disseminate the findings.

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