For the past 30 years, research on the brain has advanced impressively. This work, from fields known collectively as the neurosciences, has expanded our understanding of the neural chemistry, physiology, and growth processes that support behavior, cognition, language, emotion, sociality, and their development. It has also cast considerable light on the nature of individual differences and relatable disabilities, from genetic to behavioral levels of analysis. As these areas of research have expanded, attempts to relate insights from the neurosciences to education have been numerous, although the quality of these attempts have been variable and often, perhaps, premature or overexuberant, as many have commented (e.g., Bruer, 1997; Goswami, 2006; Hirsh-Pasek et al., 2007; Willis, 2007). Nonetheless, of all the areas addressed by the emerging field of educational neuroscience, Varma, McCandliss, and Schwartz (2008) have suggested that the neuroscience of reading processes has proven the most impressive in its sophistication.

In this review of the neuroscience literature on reading, we briefly describe the current state of the science regarding neural correlates of acknowledged and potential reading processes and reading development. Specifically, we briefly review the neural correlates of decoding and language comprehension and relate such findings to current models of reading, reading instruction, and reading disability. We then discuss what neuroscience research might mean for researchers and practitioners in education. We conclude by suggesting that the field has a clear need for literacy education scholars who are knowledgeable about the
Neuroscience and Reading: A Review for Reading Education Researchers

Neural Correlates of Reading: An Overview

Studies of neural activation during reading can show us where and when reading processes occur in the brain. Neural imaging does not indicate that there are areas of the brain dedicated from birth to those reading processes; rather, most imaging indicates the anatomical result of development in response to successful instructional experiences. Thus, when brain images of struggling readers or nonreaders show different patterns of neural activation compared with competent readers, we cannot immediately determine from these data alone whether the difference is neurological/genetic or environmental/instructional. A reader with a genetically based neurological malformation preventing typical reading development may show the same atypical activation as a reader who did not receive quality reading instruction, a reader who received quality instruction but who was not developmentally ready for it, a reader who has linguistic and cognitive deficiencies because of limited early childhood language experiences, or a reader who has emotional problems due to an abusive home environment disruptive of his or her schooling. A brain chart, therefore, is not prima facie evidence for an innate deficiency.

The two most noted areas of brain research related to reading are correlational imaging studies that localize functional brain activity anatomically and correlational studies of neural activity that localize it in the time course of a reading event. A host of investigative technologies have been brought to bear in this work, and devising valid research designs is an ongoing challenge, as the sophistication of the facilitating technologies continues to advance rapidly. The results, too, are often highly variable and conflicting (Ross, 2010), and literacy educators should not get too caught up in the neophrenology—or less optimistically, “blobology” (Lieberman, 2006, p. 173)—wherein areas of dedicated function are mapped to precise locations in the brain.

More promising, brain imaging research may help alert us to disparities between the categories of reading subprocess demonstrated in the neurological research and those variously employed in models of reading (see examples in Ruddell & Unrau, 2004). As an example, a commonly employed phrase such as “sounding out the text” might suggest a singular text-to-sound decoding mechanism localized to a single brain area. However, brain imaging studies have demonstrated several quite distinct areas of the brain that are active during sounding out (e.g., sensory visual processing of letters and visual word forms, perceptual processing of speech sounds, speech motor processing, spatial orientation). That being noted, we cannot yet dependably match specific brain areas to categories of function that may be impaired in a struggling decoder (e.g., visual crowding of letters). Similarly, many areas of the brain are devoted to the processing of word meaning, syntax, and sentence-level semantics. Yet, imaging techniques are not at the point where we can identify a particular area as a potential locus of confound for a struggling comprehender.

At first, it might not be clear why anyone would even wish to do so. As a practical matter, there is no reason to employ multimillion-dollar brain imaging technology as a literacy assessment when much simpler and affordable behavioral assessments, coherently...
constructed and reasonably well tested for reliability and validity, are readily available. As a pedagogical matter, the ultimate objective of reading instruction is not to mediate brain activity or anatomy for its own sake but to facilitate the development of functional and assessable reading behaviors and remediate severe instances of dysfunction. Another objective is to foster an appreciation in students for the value of rewarding reading experiences, both individual and shared.

Conversely, the neuroscience research on reading and language processes suggests more generally that certain categories of function correlate with unique, if varied, activation of human brains. Models of decoding, comprehension, or reading that overlook any of these subprocesses, or stress some at the expense of others, may run the risk of failing to address the individual needs of developing or struggling readers, as some behavioral research already has suggested. We argue that the broader theoretical implications of neuroscience for understanding the vagaries and variability of literacy learning and development may prove of greater value for literacy education scholars than the still uncertain anatomical loci and biochemical processes of the brain.

Additionally, future work in educational neuroscience could lead to biomarkers for flagging future developmental and instructional difficulties in certain children, which could be helpful for providing those children with closer behavioral assessments and early interventions (Beddington et al., 2008; Goswami, 2009). However, as with any clinical assessment, guarding against false positives and premature tracking will be crucial for credibility. Early childhood is a notoriously pliant time, neurologically as well as behaviorally. Although the promise of biomarkers to confirm less precise behavioral assessments of cognitive or developmental difficulties is great, neuroscience is not yet at the point where it can help educators pick out particular subprocesses for intensive remediation of a struggling child. Given the immense functional variation of human brains and human beings, it is uncertain that it will ever do so in any but an ancillary fashion.

The anatomical localization of reading processes outlined in this review is based largely on hemodynamic correlation studies (i.e., studies of blood flow, glucose, or oxygen uptake in the brain) as biochemical correlates of neural activation, employing methods such as functional magnetic resonance tomography (fMRI) or positron emission tomography (PET). These studies do not, as is often misconstrued, provide a photograph of an individual brain in action. The colorful images are, in fact, statistical charts, indicating the difference between an experimental and a comparison condition averaged over a group of participants and trials. Because of the necessary use of subtractive methods between active conditions, the neural localization indicated in the charts are as much the result of the comparison condition chosen as the target condition being investigated (Caplan, 2004). In other words, the indicated result is the averaged difference between the two conditions, indicating the activity of the target condition relative to the activity of a selected comparison condition. Change the comparison condition, and you may well change the area of activation for a target behavior (e.g., Price & Mechelli, 2005).

Although results may indicate necessary areas of neural activation that exceed a particular, if conventional, signal–noise threshold, brain images do not provide a guide as to what would be comprehensively sufficient for a cognitive or behavioral function. Indications of localized activity may also indicate the particular degree of difficulty or familiarity of a task, which will vary between subjects and over trials, rather than the average baseline activity necessary for it, and the potential for meaninglessness is greater than appreciated by the nonspecialist (Bennett, Wolford, & Miller, 2009; Brown, 2007; Oakes et al., 2007). Finally, localized correlates of neural activity may indicate convergence zones for networks of necessary activation that may extend across the brain (Patterson, Nestor, & Rogers, 2007), which may be particularly true of complex or higher order tasks (Bennett & Miller, 2010). For instance, the simpler subprocesses involved in decoding are relatively easy to map to particular locations (e.g., visual processing in the occipital lobe) and, as a result, can be mapped as trajectories of typical sequence, of which some have argued, there are two, a dorsal for sounding out and a ventral for word form (Dehaene, 2009). By contrast, the more complex subprocesses in readers’ meaning construction seem to tap areas that process word meaning, syntax, semantics, text and narrative structure, tone, prior knowledge, emotion, and more in a multidirectional fashion and with great variability between subjects and readings (Boulinger, Hauk, & Pulvermüller, 2009; Hagoort, Hald, Bastiaansen, & Petersson, 2004; Patterson et al., 2007).

Lesion studies of stroke and accident victims, brain stimulation studies (e.g., transcranial magnetic stimulation), direct electrode assay studies, and imaging of functionally dedicated neural tracts (e.g., single photon emission computed tomography) have added to this anatomical data with ever greater detail and sophistication. However, hemodynamic studies typically span the neural activity of 2–3 seconds, which is an enormous amount of time for neural activity. For this reason, studies of direct electrical activity, known as event-related potential (ERP) studies, may be of more interest to reading process theorists, because they provide a more precise tracking of when in the time course of a reading certain correlates of reading subprocess occur. These studies, tracking either neural action potentials (i.e., cascades of membrane depolarization running
the length of thousands of neurons at a go; e.g., electroencephalography [EEG], direct electrode assays) or the fluctuation of electromagnetic radiation at different points across the scalp (e.g., magnetoencephalography [MEG]) can distinguish the timing of events with millisecond precision. Newer MEG techniques are also much more precise in terms of anatomical location, although many technical and interpretive challenges still persist. As with the anatomical data, the hope is that this time-course data may eventually enable the identification and location of distinct subprocesses in reading.

The following review of the neural correlates of reading is quite condensed. The research base in this area is not only relatively large but also relatively new, highly varied, and growing exponentially (Cabeza & Nyberg, 2000). Replication and meta-analysis are limited. We have therefore restricted our review to studies and findings illustrative of less controversial claims, with only occasional notation of exciting but uncertain evidence.

**Decoding Processes in the Brain**

What does the brain do when engaged in decoding or decoding-related processes? The simplest way to approach this question is to review imaging studies in which participants are given either real or nonsense words (i.e., unfamiliar letter strings that can be decoded; e.g., tegwop) and asked to read them. Early studies compared brain activation during single-word reading, using fMRI or PET, in comparison to brain activation in a resting condition with eyes closed. For example, Rumsey et al. (1997) used this experimental design with skilled adult readers and PET, whereas Brunswick, McCrory, Price, Frith, and Frith (1999) used this experimental design with skilled adult readers and fMRI. As might be expected, a very large number of brain areas are activated in such experimental designs. There is extensive activation bilaterally (i.e., in both hemispheres) in brain areas related to audition, vision, spatial and cross-modal processing, and spoken-language areas (e.g., posterior superior temporal cortex, occipitotemporal cortex, temporal and parietal areas, frontal cortex). Experiments using EEG that have contrasted real words and nonsense words, thereby keeping the visual–spatial demands associated with text processing constant and varying only whether the decoding target is a lexical word form or not, have shown that the brain responds differently to real versus nonsense words within one fifth of a second. This implies that lexical access (i.e., contact between the visual word form and its meaning) occurs very rapidly during reading. The speed of this differentiation has been shown to be similar for both children and adults across languages, suggesting that the time course of visual word recognition is very rapid (160–180 ms; see Csépe, Szucs, & Honbolygó, 2003; Sauseng, Bergmann, & Wimmer, 2004).

**Implicit Reading Tasks**

Comparing brain activity during visual identification of words compared with a subject’s having his or her eyes closed cannot tell us anything specific about reading or its development, which has led the field to develop the implicit reading task. Implicit reading tasks try to dissociate reading, as the making of meaning from strings of printed symbols, from the associated requirements of processing visual sequences of such symbols. The implicit reading task uses false fonts (i.e., meaningless hieroglyphic-type symbols matched to letters for visual features like the ascenders in the letters b, d, k) and asks participants to pick out target visual features, such as ascenders. Brain activity for this visual search task is then compared with the same task based on words (i.e., picking the number of ascenders in a word like bubble). In adults, such fMRI and PET studies (e.g., Price et al., 2003) have shown activation that is usually left-lateralized and focused on the occipitotemporal and posterior superior temporal cortices (see Figure 1; Price & McCrory, 2005). These left-hemisphere areas have hence been described as the core areas for letter identification.
in word reading. These areas are also active during spoken-language tasks (in the left superior temporal cortex) and visual tasks involving spoken language, such as picture naming (in the left occipitotemporal cortex).

Studies of children have generally supported the claim that a left-lateralized set of occipital and temporal areas are core to the word reading network. For example, Eden and colleagues used fMRI and the false-font task to compare brain activation during implicit reading in children and college students ages 7–22 years (Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003). First, the experimenters established that the 7-year-olds could perform the false-font task as competently as the college students, which was important, as the researchers hoped to attribute any changes in reading-related neural activity to developmental differences rather than differences in expertise. Comparisons of children with adults for word reading are always confounded by the inevitably greater familiarity that adults have with written words. Adults have read more words than children, and this experiential factor will be reflected in brain activation; the same difference in word reading experience affects comparisons between children with and without dyslexia. Turkeltaub et al. (2003) reported that adults performing the implicit reading task activated the usual left-lateralized sites, including the left posterior temporal and left inferior frontal cortices.

However, when they restricted their analyses to children below 9 years of age, the main area engaged was the left posterior superior temporal cortex. This neural area is also active when participants perform phonological tasks in the scanner, such as rhyme judgment. Turkeltaub et al. (2003) thus suggested that activity in this area could be the neural correlate of grapheme–phoneme translation. When they looked at changes in activation with age, they found that activity in left temporal and frontal areas increased, while activity previously observed in right posterior areas declined. This pattern was interpreted as showing that reading-related activity becomes more left lateralized with development.

The Visual Word Form Area

The left occipitotemporal cortex is involved in object recognition and is an area of interest in research on decoding, because it has been suggested to house a word form area. This area is in essence a part of the visual cortex specialized for recognizing print, although there is some debate about this (see Démonet, Thierry, & Cardebat, 2005; Price & Devlin, 2003; Price & Mechelli, 2005). Labeled the visual word form area (VWFA), this neural region shows activity whenever printed words are shown to the adult brain, even if the words are only shown in the left visual field, which means that they first activate visual areas in the right hemisphere (see Cohen & Dehaene, 2004). The VWFA is also active when children are shown printed words.

However, expertise clearly plays a role in brain activation, as the VWFA becomes more active as children get older and become better readers (Pugh, 2006). Pugh and others have suggested that the amount of activity in the VWFA is the best neural correlate that we have of reading expertise. However, the VWFA is also active when shown nonsense words, which suggests that it is not purely an area responsive to word forms. Rather, it appears responsive to any sequence of printed letters. Nevertheless, activity in the VWFA increases when orthographic strings are more familiar, such that nonsense words that contain large fragments of real words elicit greater brain activity. Again, this supports a role for expertise in print–sound connections in modulating this brain activation, and as might be expected, the VWFA shows reduced activation in developmental dyslexia (e.g., B. Shaywitz et al., 2002).

Recently, a number of developmental studies have analyzed how neural activity in the VWFA tunes itself to print and becomes specialized for letter strings that are real words. In a study conducted in Switzerland, Maurer, Brandeis, and their colleagues (e.g., Maurer, Brem, Bucher, & Brandeis, 2005; Maurer et al., 2007) followed longitudinally, from the very beginning of learning to read in German, a sample of children who either were at risk for developmental dyslexia or had no risk for it in terms of family history. The researchers used EEG to measure millisecond-level changes in the electrical activity associated with the recognition of word forms. The task was to detect the repetition of either real words or meaningless symbol strings. As noted earlier, the brain registers a difference in activity to words versus nonsense words by about 160–180 milliseconds after the letter string is presented, hence the N170 (i.e., a negative deflection in brain electrical activity approximately 170 ms after stimulus onset) was the main measure of word-specific neural processing. Brain activity was recorded in kindergarten, before the children had received any instruction in reading, and again in second grade. Before any reading instruction had commenced, the children did not show an N170 to printed words, despite having considerable knowledge about individual letters. After approximately 1.5 years of reading instruction, the typically developing children showed a reliable N170 to words, described by the authors as evidence for a coarse tuning to print. The children at risk for dyslexia showed no significant differences in their brain activation compared with control children during the kindergarten measurements, but they did show a significantly reduced N170 to word forms in second grade. This response was reduced rather than absent. Maurer et al. (2007) suggested that the
reduced N170 response was a clear neural correlate of a visual word-processing deficit.

**Integrating Letters and Sounds**

Since we know from behavioral work that visual word recognition is not a purely visual task, imaging studies showing neural activation when letters are associated with speech sounds are also required to interpret this word–symbol string difference. Blomert, Blau, and their colleagues have been carrying out a series of such studies using fMRI with adults who read in Dutch. For example, Blau, Van Atteveldt, Formisano, Goebel, and Blomert (2008) asked participants to decide whether they heard the vowel sound /a/ or /e/ in a forced-choice auditory task using degraded stimuli, to avoid ceiling effects. Participants either heard just the speech sounds or heard the speech sounds in the presence of visually presented letters. The letters were either congruent (e.g., letter A for sound /a/) or incongruent (e.g., letter A for sound /e/).

Participants were significantly better at recognizing the target speech sound in the auditory–visual condition compared with the auditory-alone condition for the congruent letters, and significantly worse for the incongruent letters. The fMRI data showed that brain activity in the auditory–visual condition differed in speech recognition areas of the brain and not in occipital areas, such as the VWFA. When the letters were congruent with the speech sounds, activity increased, and when the letters were incongruent with the speech sounds, activity decreased. However, an area very close to the VWFA was activated for sound /e/.

Similar studies with children would be of interest in helping to pinpoint where, or perhaps when and where, neural activity correlated with letter–sound integration is situated. Meanwhile, Blau and colleagues have used the same task with adults with dyslexia and shown that incongruent letter–sound pairs (e.g., A and /e/) do not suppress neural activity in these speech-processing areas compared with the auditory-alone condition. The adults with dyslexia showed an enhancement in processing for the congruent condition (i.e., A and /a/), however, although it was weaker than in controls. Therefore, imaging data have shown similar neural processing in this task in typically reading adults and adults with dyslexia when letters and sounds are congruent, with decreased activity accompanying decreased decoding skill. Letter–sound integration as indexed by this particular neural correlate is, however, different in dyslexia, such that when letters and sounds do not match (e.g., A and /e/), incongruency does not change activity in this brain region for adults with dyslexia. This might be expected given the behavioral phenotype, but it is nonetheless interesting.

**Time Course of Activation During Decoding**

The neuroimaging studies discussed so far have shown systematic correlations between visual and auditory brain areas and word decoding, which will not be surprising to educators. However, one area in which neuroimaging has the potential to go beyond the correlations expected from behavioral studies is the measurement of the time course of activation. The sequence in which different brain areas become activated during reading is of interest, given different developmental models of how decoding skills become established. Such sequential information enables a test of developmental stage theories, such as the assumption that there is an early logographic stage in visual word recognition (Frith, 1985). In the logographic stage, it is assumed that holistic visual stimuli are associated with whole spoken words in the same way as familiar symbols like £ and $ are associated with the spoken words pound and dollar. If children can really go directly from print to meaning without recoding the print into sound first, then we might expect that neural structures active when viewing text and understanding meaning should show activation in very young readers, whereas neural structures that are active during phonological recoding should not.

Although imaging methods can track the time course of the activation of different neural structures, such methods are not easy to use with children, and relevant studies are currently rare. One technique, magnetic source imaging (MSI), depends on a combination of MEG and MRI (Simos et al., 2005). MEG measures the tiny magnetic fields generated by the electrical activity in the brain, rather than the electrical activity itself, and combines this information with MRI scans to localize the activity. The magnetic fields are tiny, estimated to be one billion times smaller than the magnetic field generated by the electricity in a lightbulb, and the technique is very expensive. Nevertheless, Simos and colleagues were able to conduct a longitudinal MSI study of 33 English-speaking children, measuring brain activity at the end of kindergarten and again at the end of first grade. The children completed a letter–sound task (i.e., the child saw a letter and had to produce its sound) and a simple nonsense-word reading task, based on easy items with many analogies (e.g., lan).

A total of 33 children were studied, and half the group (16 children) were thought to be at risk of developmental dyslexia. This high-risk group showed significantly delayed neural activity in response to both letters and nonsense words in kindergarten in the occipitotemporal region, showing activation on average after 320 milliseconds compared with 210 milliseconds.
for children who were not at risk. The high-risk group also showed atypical activation in the left inferior frontal gyrus when performing the letter–sound task. For the high-risk children, the onset of neural activity in this region actually increased, from 603 milliseconds in kindergarten to 786 milliseconds in first grade. The typically developing children did not show this processing time increase. Comparing the onset of activity of the three core neural networks for reading, Simos et al. (2005) reported that low-risk children showed early activity in left occipitotemporal regions, followed by activity in temporoparietal regions, predominantly in the left hemisphere, and then bilateral activity in inferior frontal regions, which were also active during the production of speech. In contrast, high-risk children showed little differentiation in terms of the time course of activation between the occipitotemporal and temporoparietal regions. Nevertheless, temporoparietal activation is usually correlated with recoding print to sound, questioning the necessity of an early logographic stage in the development of decoding skills.

Analyses of Brain Structures
Another method for exploring how different neural areas are related during word decoding is to analyze structural differences in the neural areas known to be important for reading words. One available method, diffusion tensor imaging (DTI), can be used to measure white matter tracts, the “information highways” of the brain; white matter is the axons connecting different neurons in the brain and appears white because of the fatty myelin sheaths that speed up electrical signal transmission along the axons. In DTI, the diffusion of water in brain tissue is measured, enabling axonal fibers to be tracked, because water diffuses more readily along the orientation of these fibers than in other directions.

Niogi and McGanding (2006) used DTI to study white matter tracts in 31 children age 6–10 years, 11 of whom were reading impaired. The children were also given standardized measures of reading, such as the Woodcock-Johnson word identification and word attack subscales. White matter integrity (i.e., axonal coherence and density) in two regions of the left temporoparietal cortex, the superior corona radiata in the left temporal lobe and the centrum semiovale, was correlated with performance in the word identification task. Therefore, the microstructure of white matter in these regions was correlated with individual differences in word reading. There was no similar correlation for homologous areas in the right hemisphere, and the relationships remained significant even after controlling for working memory, age, and nonverbal I.Q. in multiple regression equations.

Longitudinal investigation of the development of the microstructure of these areas could throw light on which developmental factors promote this structure–function relationship. Although such studies are not yet in the literature, we will mention one recent connectivity study notable for its ingenuity, which also illustrates how correlations, even correlations between brain structure rather than function (i.e., neural activity), are very far at present from throwing light on developmental mechanisms.

Carreiras et al. (2009) compared Colombian “guerrillas” (p. 983) reintegrating into Colombian society and belatedly learning to read as adults (i.e., late literates) with carefully matched adult illiterates, who had never learned to read in spite of having grown up in more typical social contexts, as well as typically reading adults (i.e., early literates). In this study, the structural brain differences shown using MRI and DTI between the late literates relative to the illiterates contradicted the classical version of the neural model of word reading, which assumes that information flows from the visual areas of the brain to the speech-related areas when visual word forms are encountered. Instead, the authors found that the angular gyrus, a classical spoken-language area, modulated dorsal occipital activity (i.e., the activation patterns suggested that spoken language areas controlled the amount of activation in visual areas). Carreiras and colleagues suggested that the oft-reported reduction in gray matter in the left temporoparietal areas in developmental dyslexia and associated reduced neural activity may be completely linked to reading expertise and have nothing to do functionally with having developmental dyslexia.

Synthesis
At present, there are still relatively few neuroimaging studies of word decoding by typically developing children. There are more studies of word decoding by children with dyslexia, but these have only been mentioned in passing here, as there are many difficulties in linking neural activation levels in these children with word reading per se. Nevertheless, there are some very consistent patterns of correlation in the neuroimaging studies of decoding that are available. Word processing appears to correlate with left-hemisphere activity. There is more neural activation in the left temporoparietal and occipitotemporal areas as reading skill increases.

The studies discussed earlier suggest that these correlations depend both on developing visual expertise (i.e., experience with the special visual stimuli that are words) and developing skills in letter–sound integration. When children have to read words aloud, there is also left-lateralized activity in the frontal areas of the brain that are associated with speech production and possibly articulatory codes, even when speech is not overtly produced in the scanner. None of these studies can as yet give us insights into developmental causal mechanisms. Nevertheless, the careful documentation of the neural networks that are active during decoding,
their connectivity, and the time sequence of their activation are important first steps in using neuroimaging techniques to ask educationally relevant questions.

**Language Comprehension Processes in the Brain**

To date, most efforts at educational neuroscience matching neuroscience research to reading education have focused on brain processes and structures related to decoding instruction and its impairments, as in dyslexia (e.g., Nevills & Wolfe, 2009; Shaywitz, 2003). This contrasts greatly with the nature of scholarship on reading and literacy education in general, in which an emphasis on comprehension, as well as learner motivation, sociocultural context, identity, and other factors, is well developed (e.g., Allington, 2008; Hagood, Alvermann, & Heron-Hruby, 2010; Hall, Burns, & Edwards, 2011). For the larger reading education field, then, educational neuroscience literature reviews that omit available research on language comprehension and other global processes fail to address many issues typically treated in literacy scholarship. More important, they fail to paint a comprehensive picture of the neuroscience research on reading. Attention to how comprehension is understood by neurolinguists demonstrates the possible value of this work.

Aside from vocabulary knowledge and cognitive strategies for content understanding, what reading education scholars and teacher educators presume language comprehension to entail is less than clear. Where the term comprehension is not circularly defined as understanding or meaning-making, it is typically defined by the nature of what researchers can dependably measure. In essence, comprehension becomes what comprehension tests test, but the underlying subprocesses that present difficulties for struggling comprehenders/readers are often poorly articulated (cf. Lesaux & Kieffer, 2010). Syntax and semantics are alluded to irregularly and with great definitional variation (e.g., Common Core State Standards Initiative, 2010a).

English language arts instruction, in addition to word study, typically emphasizes instruction in the rules of grammar, as well as style and, to a lesser extent, the nature of genre, tone, and discourse. Yet, the tracking of sentence- and paragraph-level semantic analysis, apart from syntax, is weak to nonexistent in most reading assessments (e.g., Common Core State Standards Initiative, 2010b) and even in scholarship on the importance of language ability in literacy (e.g., Dickinson, Golinkoff, & Hirsh-Pasek, 2010). Attention by reading researchers and teacher educators to how neuroscientists parse the floating signifier of language comprehension may provide a fuller map of necessary comprehension subprocesses.

**What’s in a Word?**

In the neurolinguistic research base, comprehension is presumed to begin with relating an identified word form to its possible meanings through association as an item of vocabulary. As a result, research on word form recognition, morphological analysis, and word meaning, or semantics at the single-word level, is abundant (see the review in Osterhout, Kim, & Kuperberg, 2006). As already noted, word form identification may correlate with activity in the left inferior temporal-occipital area along the fusiform gyrus.

The relationship of word identification ability to comprehension is now well known, but the relationship of word identification to subprocesses for identifying association patterns of spelling, sound, and meaning is ongoing. Building on Perfetti’s lexical quality hypothesis (Perfetti & Hart, 2002), which asserts that the quality or abundance of networks of associations with a word is a correlate of comprehension of the text, Balass, Nelson, and Perfetti (2010) asked participants in an ERP study to make meaningful judgments about newly learned, familiar, and unlearned words. This was done in three different conditions: orthography to meaning (i.e., no phonology), wherein the participants needed to learn the spelling and meaning of rare words; orthography to phonology (i.e., no meaning), wherein participants needed to learn the spelling and pronunciation of rare words; and phonology to meaning (i.e., no orthography), wherein participants needed to learn the pronunciation and meaning of rare words. After being tested to demonstrate their knowledge of these new words, subjects were given a semantic-relatedness judgment task, matching related and unrelated words, for rare words, known words, and unknown words not included in the previous learning task. ERP measurements were taken to determine novelty effects (P600) and meaning effects (N400).

The results suggested that the degree of word knowledge, specifically phonological, orthographic, and semantic knowledge, at the time of word learning influenced subsequent recognition of the word in new contexts, a finding with implications for vocabulary instruction. Although there were no comprehension differences in the behavioral data, the ERP data found the orthography–meaning condition produced a more powerful recognition effect than the orthography–phonology and phonology–meaning conditions. This is significant for vocabulary learning, because incremental knowledge development about a word over time relies on recognizing past encounters with the word.

To study the role of morphological processing, Bozic, Marslen-Wilson, Stamatakis, Davis, and Tyler (2007) used fMRI to examine areas of activation by contrasting priming of word pairs that shared either an opaque morphological relationship (e.g., archer, arch) or a transparent morphological relationship (e.g., bravely,
brave) with meaning only (e.g., stop, halt), form only (e.g., catalog, cat), and identity-priming (e.g., cat, cat) word pairs. The results suggested that morphological analysis is a subprocess involving left frontal areas of the brain distinct from word form recognition or word meaning identification processes located elsewhere. This finding may be of potential significance for educational research on vocabulary instruction considering the role of morphological analysis in word identification.

Word meaning has commonly been correlated with activation in the left medial, superior, and superior posterior temporal areas. In the early work along these lines, it was prematurely claimed that particular categories and classes of word meanings could be located in distinct areas of the left temporal lobe. With each new category studied (e.g., tools, machines, buildings, domestic animals, farm animals, wild animals), strong claims were made for distinct areas of activation. There seemed to be no end to the possible categorical distinctions that could be mapped, assuring a steady stream of such studies. However, eventual follow-up work found a lack of replication for these findings, indicating (a) individual but perfectly functional differences in localization, (b) a lack of clarity in the notion of encoding in the brain, and (c) overconfidence in the reliability of the early imaging techniques (Heim, 2005). Periodic improvements in imaging precision have inspired similar claims regarding localization in the temporal lobe and elsewhere, but unless well replicated, they should be taken with caution (Ross, 2010).

Occasionally, words must be parsed in terms of their syntactic or semantic function before they can be definitively identified or sounded out correctly as words (e.g., the noun or verb form of progress, the present or past tense verb form of read). Reading researchers already know that word processing is highly adaptive on behalf of comprehension satisfaction, and strict linearity of processing is absent, even at the word form level. Neuroscience studies have confirmed that syntactic and semantic processes can have a top-down effect on word meaning processes, and this effect may play a variable role even for words that are not ambiguous (Kuperberg, 2007). These results indicate that models of language that assume language meaning derives only from word meanings linked with grammatical markers are inadequate for representing authentic language processing (Boulenger et al., 2009; Friederici & Weissenborn, 2007; Hagoort & van Berkum, 2007; Kimrodt et al., 2009).

More current work has suggested that areas across the brain dedicated to basic sensory, motor, emotional, analytic, or social processing converge in the left temporal lobe for word meanings (Frishkoff, Perfetti, & Westbury, 2009; Patterson et al., 2007). For instance, verbs that indicate physical actions activate areas in the motor or premotor cortex that link to categorical identification and word representation convergence zones in the left inferior anterior temporal area (Willems, Hagoort, & Casasanto, 2010).

Syntax and Semantics

Research on vocabulary has been complemented by a substantial body of studies on syntactic processing (i.e., identification of grammatical function, grammatical interrelationship of words in a clause or sentence) and semantic processing (i.e., identification of indicative intention of words, phrases, and idioms, and their intentional relationship at a clausal, sentence, or passage level). The anatomical areas and time-course involvement of these two general domains appear distinct, yet overlapping, and much more work on these processes can be expected. It could be that the traditional distinction between these domains is not easily disentangled at the level of neural function.

Typically, syntactic or semantic anomalies are used in comparisons to distinguish the relevant neural correlates. For instance, semantically anomalous sentences (e.g., “When peanuts fall in love . . .”) elicit an exaggerated N400 signature, a peaking of negative charge approximately 400 milliseconds after the lexical anomaly, in the central parietal region (van Berkum, Hagoort, & Brown, 1999; see the review in Kutas, Van Petten, & Klunder, 2006). By contrast, anomalous syntactic structure elicits an abnormal early positive charge in the left anterior region, followed by an exaggerated P600 signature, a peaking of positive charge 600 milliseconds after onset, either in the central parietal region (Friederici & Kotz, 2003; Friederici, von Cramon, & Kotz, 1999), as with the N400, or in more anterior (i.e., frontal) areas of the brain (Osterhout et al., 2006). These unique time-course signatures suggest that semantic and syntactic processing of anomalies are neurologically distinct operations. The research further suggests that semantic and syntactic processing of correct or typical sentences is similarly timed (Kaan, Harris, Gibson, & Holcomb, 2000). In other words, ERP studies indicate that on a word-by-word basis, early brain activation is for word and morphosyntactic identification, followed at the N400 by semantic identification and at the P600 by a sentence-level syntactic recheck (Friederici & Kotz, 2003).

Such findings can support linear theories of syntactic processing (e.g., Friederici, 2002), although alternative distributed processing theories have been suggested (e.g., Hagoort, 2003) and supported by studies (Cooke et al., 2006; Hald, Bastiaansen, & Hagoort, 2006). Other studies suggest that traditional notions of syntax and semantics are ill matched to the processing indicated by ERP evidence, and alternative explanations of meaning elaboration are required to make sense of the data (Kuperberg, 2007). In spite of the uncertainties, timing of process is clearly of importance (Perfetti & Bolger,
2004), and when matched to more spatially precise imaging techniques, such as the newer MEG or fMRI techniques, ERP methods may give a more reliable indication of the order and structure of cortical processing of texts during comprehension (Heim, 2005).

As a result of hemodynamic research, syntactic processes have been found to dependably associate with activity in the left frontal gyrus, or Broca’s area (Sakai, Noguchi, Takeuchi, & Watanabe, 2002). Semantic processes are more variably located, depending on whether they are at the word level (posterior superior temporal and temporal-parietal areas; e.g., Wernicke’s area and related basal language areas, such as the supramarginal gyrus and temporal sulcus, as well as in left inferior frontal areas, at least for articulatory rehearsal; Rogalsky, Matchin, & Hickok, 2008), sentence level (left inferior frontal areas proximal to Broca’s area), or text/discourse level (more distributed frontal and parietal areas depending on task complexity or degree of abstraction; Binder, Desai, Graves, & Conant, 2009).

These areas of dedicated activation in response to syntactic and semantic demands develop over time in individually variable ways, possibly as a result of differing experience. Berl and colleagues (2010) used fMRI to study the effects of task, age, neuropsychological skill, and posttask performance in the reading versus listening of developmentally appropriate paragraph-length texts by subjects ranging from early childhood through preadolescence. The researchers found a consistent activation across ages and modality (i.e., reading, listening) in the left superior temporal sulcus, dubbing it the “comprehension cortex” (p. 115) because of its involvement in lexical-level syntactic and semantic tasks.

However, they also noted developmental differences in text-comprehension processing, with younger children demonstrating a more diffusely distributed activation pattern in response to comprehending written text. These areas of dedicated activation in response to comprehending written text included the right temporal pole and right cerebellum. Older children and adolescents showed increased activation in the left inferior frontal cortex while listening to stories, suggesting an increased recruitment of this area for more structurally complex texts, and this activation correlated positively with comprehension results. Reading was shown to require activation across a greater number of cortical areas than listening (see Figure 2; Berl et al., 2010), including the right temporal and right inferior frontal lobes, possibly suggesting that children require this additional activation to handle the more difficult semantic structures of written texts in meaning construction (cf. Yeatman, Ben-Shachar, Glover, & Feldman, 2010).

The Role of Emotion in Meaning

Emotional valance would seem to be integral in tracking the meaning and/or meaningfulness of language and what it represents, and the neurolinguistic literature supports this (Ferstl, Rinck, & von Cramon, 2005; Havas, Glenberg, & Rinck, 2007), with corresponding neural activity found in the anterior temporal and inferior prefrontal areas adjacent to the orbital-frontal cortex. These cortical areas are known to develop early in childhood for affect regulation and socioemotional response (for introductions to social neuroscience of early childhood, see Cosolino, 2006; Schore, 1994). They connect to subcortical areas in the basal ganglia that comodulate the endocrine system, and thereby the individual’s emotional state, and are closely tied, both neurologically and hormonally, to subcortical areas involved in memory formation and its reconstruction, such as the hypothalamus. There is also a fair degree of overlap between areas of the brain for both emotional control and semantic memory (Binney, Embleton, Jeffries, Parker, & Ralph, 2010).

It should be acknowledged that the neurological basis for the relationship of emotion and sociality to language comprehension development is not yet well understood theoretically (cf. Immordino-Yang & Damasio, 2007). Nonetheless, these subcortical areas, and loci in the orbital-frontal and anterior temporal cortices, may prove a crucial link between language and meaning and could provide another front in the growing appreciation for the importance of early childhood social, emotional, and language development for subsequent literacy achievement (Beaucousin et al., 2007; Kuhl & Rivera-Gaxiola, 2008).
Higher Order Cognitive and Discourse-Level Processes in Reading

Research is accumulating on the neural correlates of text genre identification, action tracking, processing of expository and narrative text structures, determining the appropriateness of tone or trope (e.g., irony, metaphor), identification and processing of idiom, and the use of appropriate discourse forms (for an intriguing review of some of these processes, see Perfetti & Frishkoff, 2008). For instance, the importance of basic cognitive functions, such as inference in relating textual information to prior world knowledge, is treated at some length (Fries, Rutschmann, Raabe, & Schmalhofer, 2008; Mason & Just, 2010). Executive skills in text tracking (Sesma, Mahone, Levine, Eason, & Cutting, 2009) and the reader’s analysis of metaphor (Mashal, Faust, Hendler, & Jung-Beeman, 2009) are additional examples of such work.

Making meaning from decoded text symbols lacks much of the contextual information provided by auditory processing during speech by tracking facial movements to help identify ambiguous phonemes, as in the McGurk effect (Beauchamp, Nath, & Pasalar, 2010), or integrating the semantic content of hand gestures (Dick, Goldin-Meadow, Hasson, Skipper, & Small, 2009). Still higher order context effects, such as those associated with linguistic environment, appear to have a developmental, not just functional, effect on language comprehension processes, particularly regarding syntax and higher order semantics and idioms (Raizada, Richards, Meltzoff, & Kuhl, 2008). All of these issues will likely become important as educational neuroscience further explores the effects of home and classroom discourse participation on language development.

Neuroscience research on the processing of text content in terms of subjects’ prior knowledge is in its infancy; as an example of this research, Speer, Reynolds, Swallow, and Zacks (2009) have suggested that processing scenes and actions described in narrative texts involves sensory and motor processing areas of the brain. The importance of prior knowledge for text comprehension is well documented, with a distinction being made between declarative and procedural knowledge, and between prior knowledge of the world and prior knowledge specific to language (e.g., prior knowledge of vocabulary, prior knowledge of dialect- and discourse-specific syntactic and semantic patterns, prior knowledge of domain-specific discourses and genres). There is the possibility that, insofar as this prior knowledge of language or even of social protocols is the result of overlearned and thus automated pattern recognition (e.g., syntactic and idiomatic pattern recognition), it would be more appropriately categorized as a form of developed skill rather than as explicit knowledge. (Rule application models of language processing blur this distinction.) Still, the difference between prior knowledge that is specific to language comprehension rather than content comprehension is worth noting.

Also worth noting is the distinction between the tapping of developed processing skills and long-term memory with working memory’s role in the construction of situation models from text. The construction of summary memories of a passage for retelling, for instance, requires the compression of details on the basis of significance. Lillywhite and colleagues (2010) used fMRI to contrast subjects’ processing of passages read to them repeatedly and found a marked difference in neural activation between the first and subsequent hearing of the texts. The neural activation between the iterations of the passages extended from chiefly auditory and language comprehension areas in the initial reading to include areas in the frontal, parietal, and subcortical areas during subsequent readings, suggesting areas for modeling, memory, and recognition processes beyond basic language comprehension processes. When the analyses were extended to subjects’ retelling or summarizing of the text, a strong correlation was discovered with activity in the right parietal cortex, suggesting its role in discourse representation.

Such discourse processing research may be of interest to reading professionals. However, it is rarely the case that the term discourse in neurolinguistics means what it does in psycho- or sociolinguistics (e.g., Gee, 2008), sources that have been highly influential in reading education scholarship. For the relevant neurolinguistic research, discourse is simply extended, usually narrative, text, with all of the micro- and macrostructural elements of such texts intact (e.g., Lillywhite et al., 2010). The point of such research is to determine the neural activity that correlates with the processing of such features and, as a result, determine whether structure-related categories of mental process have a tangible neural signature.

For instance, Yarkoni, Speer, and Zacks (2008) used fMRI to distinguish sentence-level comprehension processing from passage-level comprehension processing. Presuming that the reading of a narrative requires the building of mental representations of the narrative, which are then employed constructively to process subsequent narrative elements, they tracked the reading of cohesive narratives contrasted to paragraphs comprised of unrelated sentences. They found that similar areas of the brain were involved for comprehending the content of sentences, but distinct areas were tapped for the processing of the situation model, with the posterior parietal cortex implicated in the construction of such models, and anterior temporal areas implicated in their maintenance. Taking a different approach, Whitney and colleagues (2009) explored the distributed neural network underlying story comprehension. They contrasted the processing of sentence boundaries with content-substantive narrative shifts and were thereby able to demonstrate the
role of the medial parietal cortex in narrative structure comprehension, and the apparent role of the precuneus and posterior cingulate in updating story representations. The role of the precuneus, tucked into the medial parietal fissure, for higher order processing is particularly intriguing, given its potential contribution to self-awareness and self-monitoring (Cavanna & Trimble, 2006).

As literacy scholars have long appreciated, reading is more than just the mental processes inside the head of a reader. Social, linguistic, and cultural factors all play a role both during a reading event and in reading development over time. Current developmental science has suggested that these contextual factors do not just happen to a reader but are aspects of a developing child’s social and cultural environment, a symbolic landscape that the child learns to appropriate, represent, and negotiate in a generally functional and eventually strategic fashion (see the reviews in Eisenberg, 2006). Insofar as a reader perceives and responds, mentally or behaviorally, to representational elements of his or her sociocultural landscape, there will be correlated neurological activity and development to study (e.g., monitoring the intentions of others as distinguishable from physical causality; Mason & Just, 2010). The neurological correlates of such perceptions and responses are the focus of study for researchers in developmental cognitive neuroscience, the neuroscience of affect regulation, personality neuroscience, and social neuroscience.

Synthesis

The anatomical areas of the brain that correlate with the foundational language comprehension functions (i.e., vocabulary, syntax, semantics) are more active in the left hemisphere of the neocortex, although homologous areas in the right hemisphere are typically activated as well, especially for reading, possibly for related but distinct discourse processing or textual representations (Perstl, Neumann, Bogler, & von Cranon, 2008). Higher order comprehension processes and strategic analysis involve a much more distributed set of brain loci. The neuroscience work on comprehension is far more variable than that on decoding processes and would seem to range over a more extended set of subprocesses.

The ERP time-course studies of syntactic and semantic processing during text comprehension in competent adult readers have indicated that syntactic processing begins in the left frontal and anterior temporal lobes with phrase-structure monitoring at approximately 150–250 milliseconds (Segalowitz & Zheng, 2009), expanding to verb–subject or syntactic/thematic processing around 300–350 milliseconds in the left inferior gyrus, an assessment of the semantic intention within the sentence at approximately 400 milliseconds (Marinkovic et al., 2003), and culminating, especially in cases of more complex syntactic structures, with a syntactic recheck or incongruity/novelty effect, peaking at approximately 600 milliseconds (Hagoort, 2003). Integration of syntactic and semantic processes occur at approximately 400–600 milliseconds (Friederici & Weissenborn, 2007). More global-level processing of text features occur subsequently. Although anatomical localization of these events in time-course studies does not always precisely match that suggested by the functional anatomical studies, both types of studies are in agreement regarding the distinctive nature of word meaning, syntax, and semantic processes.

There is great theoretical uncertainty about the role these various subprocesses play, and clearly the role would vary depending on the nature of the text, the culturally specific representational system employed, the purpose and context of the reading, and the ability and educational level of the reader. For these reasons, constructing more ecologically valid studies of brain activation during comprehension would be helpful. In future, this work may require a more substantial contributory role from educational researchers than they have played in the past.

Issues in the Educational Neuroscience of Reading

Methodological Issues in Neuroscience Research

Recent technological advances in the neurosciences have been rapid, and the number of cognitive neuroscience studies has expanded exponentially (Cabeza & Nyberg, 2000). Nevertheless, the majority of imaging findings are less than a decade old and are thus unreplicated. Meta-analyses are scarce (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008). Because of the novelty of the technological advances, many brain imaging studies are often as much about a method’s appropriate use, research design, and implementation as they are about the object of investigation, which has made for some engaging debates within the neuroscience literature. At first blush, reading education researchers may find these debates impenetrably technical.

Yet, most of the critique revolves around the fundamentals of research design and the logic of interpretation, issues with which well-prepared literacy researchers are familiar. Debates about such conceptual fundamentals as the difference between necessary and sufficient conditions, between correlation and causation, between reliability and validity, between constrained and unconstrained variables, and the use of circular reasoning and other fallacies in research design and interpretation have all made appearances in the history of reading research. Literacy researchers will find these familiar motifs evident in the critical neuroscience literature as well.

Among the technical and interpretive concerns recently treated, Vul, Harris, Winkielman, and Pashler
(2009) noted that correlations in brain imaging studies may be seriously overstated. Bennett, Wolford, and Miller (2009) noted that the reliability of brain–behavior correlates varies widely depending on the type of behavior being correlated, and reviewed many of the challenges that remain regarding reliability in brain imaging studies. One possible issue has been inadequate attention to the need for multiple comparisons correction, given the extensive number of calculations between conditions required in neuroimaging techniques (Bennett, Baird, Miller, & Wolford, 2009). Other methodological issues have been suggested as well (see Brown, 2007; Oakes et al., 2007). All of this should caution educators and educational researchers from taking any particular brain study finding at face value, particularly when disseminated through the popular media, let alone as a definitive form of evidence for a reading program, method, policy, or theory.

Conceptual Frameworks for Bridging Neuroscience and Reading Research

At present, there is an emerging interdisciplinary neuro–cognitive perspective that is seeking to integrate brain, cognitive, social, and cultural perspectives on learning and activity (Fischer, Bernstein, & Immordino-Yang, 2007; K. Hall, Goswami, Harrison, Ellis, & Soler, 2010; Varma et al., 2008). Neuroscience research, research on educational processes, and research on learning can be mutually informing. For example, recent advances in neuroscience link directly to long-standing models in cognitive educational psychology, enabling the rigorous analysis of such models from a new evidence base.

Unfortunately, the computational-brain framework is the one most often garbled in the popular media and brain-based education materials. At the same time, an alternative theoretical framework is emerging that is organic rather than mechanistic, biological rather than representational, built on the motif of learning as physiological development, and powered by the biocological dynamics of organisms as agents growing functionally in response to their ecological contingencies, environments to which they adapt through behavioral, developmental, epigenetic, and even evolutionary processes (e.g., Mareschal et al., 2007). The awareness of complex dynamical effects over time is certainly relevant to research in literacy education, particularly to research from a sociocultural perspective and models of situated cognition. Other theoretical frameworks are also possible (see Meltzoff, Kuhl, Movellan, & Sejnowski, 2009). Given the relatively advanced state of educational neuroscience on reading, literacy education seems to be an ideal field within which to forge and field-test new theoretical frameworks informed by neuroscience for educational policy, theory, and practice.

Topical Focus and Level of Analysis

Remembering that research is about what it is about and not something else is almost too obvious to elaborate on, yet this fundamental observation has already been underscored by cognitive and neuroscience researchers alike (e.g., Bruer, 1997; Hirsh-Pasek et al., 2007). If we require research-based evidence on effective classroom practices, we should first attend to the copious research on effective classroom practices. If we are dissatisfied with this research, or the implications of its findings, we ought to attempt to improve on it. There is a kind of natural hierarchy to what kind of research is most relevant to a problem, and research on the problem itself should come first. Cognitive and social aspects of learning should probably come next, with cognitive neuroscience and educational neuroscience playing a more distant role. Yet crucially, all of these research perspectives will eventually be important in achieving a full understanding of, for instance, the efficacy of classroom practices. All of these different levels of analysis and explanation have mutually supportive roles to play in an integrated understanding of how to improve classroom practices for literacy development. Reduction of cause to a single level of analysis when researching the complex nature of bioecological systems is unwarrantable and unlikely to be helpful for finding connections to efficacious educational practice.

The reading education research base, taken at large, indicates that the answer to the simplistic question What works? is, it depends—on student variability, teacher efficacy, material resources, curricular objectives, and numerous other contextual factors. As experienced teachers know, no method will work for everyone in a given class, and nothing works for anyone all the time. Given that, the question should probably be rephrased as, What works for particular kinds of students, under particular circumstances, to particular ends, with particular dependability? Yet, neuroscience also offers us methods for studying these questions within an educational context. Neuroscientists are trying to achieve an understanding of how learning occurs at neurosystemic, neurocognitive, neurochemical, and neurogenomic levels of analyses. At these levels of analysis, learning will depend on physiological processes that may come to be phrased as general laws of learning. As we discover what these processes are, we can then use them to examine learning at the physiological level in response to various contexts and situations of learning. It is critical to be aware that neuroscience will not replace understandings arising from social science. Rather, neuroscience can complement the understandings derived from educational research.

Research from ancillary domains, when coherently theorized as pertinent to classroom evidence, can be very illuminating and help us expand or reframe our
thinking, as the history of reading education research has suggested (Alexander & Fox, 2004). As more is understood about the neurological processes and development that correlate with reading and its instruction, educational neuroscience on reading processes will likely begin to influence our theoretical constructs about reading education across the life span and, thereby, inform public discourse and policy formation. It therefore would be helpful if reading education scholars developed expertise in the research, philosophy, and limitations of neuroscience, and the developmental sciences more broadly, to help inform the public debate.

**Biology and Complexity**

Current life science has provided us with a much more complex understanding of developmental processes than popular views of genetic determinism may suggest. Physiological and genetic propensities are realized through interaction with an environment, be it nucleic, biochemical, cytological, systemic, organic, or symbolic (Gottlieb, 2007). Given the severely limited number of genes in the human genome that distinguish us from other species, much of the necessary information for behavior and learning is not actually encoded in the genome, but off-loaded in the environment in which the genome has historically and developmentally functioned; the same also may be true of the putative need for the knowledge representations required for adaptive behavior (Clancey, 1997; Hendriks-Jansen, 1996).

This insight lies at the heart of the promise of neuroscience for literacy education. Literacy educators are creating the contexts within which children’s brains develop, enabling them to perform increasingly demanding reading tasks and develop capacities for comprehension, understanding, and lifelong learning across many situations and domains. Reading and literacy development involve relationships among social, cultural, biological, cognitive, and developmental processes. The need to incorporate all research perspectives in constructing optimal policy and pedagogy means that the impact of bringing neuroscience into the traditions in reading education and literacy research may be profound.

As we hope we have made clear, the potential of neuroscience to help expand our understanding of reading processes, their development, and their occasional dysfunction is profound. We hope that our review of the research provides a helpful overview of the terrain and the issues confronting any attempt at an interdisciplinary conversation between literacy education research and neuroscience research. A successful interdisciplinary conversation could helpfully address many questions about literacy and its instruction and development. Until such time as knowledgeable literacy education scholars prepare themselves to engage in such a conversation, the full promise of the biological sciences for analyzing educational issues will remain obscure.

**Notes**

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