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The Brain Might Read That Way

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Research on how the brain implements reading has produced results of remarkable consistency, especially on the functional anatomy of single word reading. We examine the general features of this emerging knowledge and draw attention to the extent to which it converges with results from other methods of reading science in several areas: reading acquisition, reading disability, and the basic cognitive processes of reading. We also add perspectives not otherwise represented in this special issue by pointing to the promise of research in text processing and discussing the research on word reading across writing systems. The word reading network identified in alphabetic research does have a universal basis, but it also shows some accommodation to the writing system.

Reading begins when someone with certain knowledge views marks on a surface, intentionally made. The marks have to be the right kind—samples from a writing system—not drawings or arrangements of lines designed from marks outside a system of writing. And the "someone," to be a reader, has to know how this system works. And where does this knowledge reside? Like all human knowledge, it resides in the brain.

For some, this may be the end of the story about the neuroscience of reading. Researchers who have studied reading the old-fashioned way may feel that they are still trying to see its distant mysteries through a $75 Sears telescope while a new generation of scientists gaze through the Hubble space telescope to make startling new discoveries. However, feelings of telescope envy are entirely unwarranted. The fact is that until very recently researchers have known much more about the reading mind than the reading brain. The gap is closing, and now is the time to get acquainted with what is known about how the brain reads.

The new work, as represented by the articles in this special issue, does more than just fill in the areas of a schematic drawing of the brain. It connects with issues that

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have been central to the study of reading and language. Some of these connections are confirmatory. For example, they confirm that phonological processing is functional in the skilled reading brain, just as it is in the skilled reading mind. Other connections go beyond confirmation to suggest new understandings of some aspect of reading. From both types of connections, the substance of the science of reading is enhanced. In the sections that follow, we explain where we think these connections are especially interesting. We also try to fill in some parts of the story that received little or no attention in the articles, especially taking a universal (cross-writing systems) perspective and adding some observations on comprehending text. We frame our discussion within the basic research problems of reading science: the acquisition of reading skill, reading disability, and the cognitive processes of reading.

THE ACQUISITION OF READING SKILL

At the beginning, reading is different. The knowledge that makes the marks on the page special has to be acquired. How this knowledge is acquired has been reasonably detailed in a few ways (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). The child learns pieces of the system over time—the letters, fragments of orthography and mappings to phonology, and specific word forms readable from their spellings. Brain research adds to the picture by showing that cortical processing at the early stages of learning to read is not the same as the cortical processing of the skilled reader (Pugh et al., 2001; B. A. Shaywitz et al., 2002). Learning modifies brain functions in some systematic ways.

This learning assembles developing knowledge about the processes that engage the constituents of words—orthography, phonology, and semantics. Increasing skill is marked by the coordination of these constituents into a more integrated functional system of cortical structures. Neuroimaging research provides a surprisingly clear view of the reading circuit that develops with this learning. This circuit includes three major cortical regions: from back to front, (a) ventral (occipito–temporal), (b) dorsal (a temporo–parietal area, roughly corresponding to Wernicke's area), and (c) left frontal (Broca's area, the inferior frontal gyrus, and insular cortex). We characterize these regions rather broadly (each includes differentiated structures), and we caution against simple local mappings of functions to areas. However, the three regions are engaged in functions critical in reading: visual–orthographic processes in the ventral region; phonological decomposition in the dorsal region; and, in the frontal region, both phonological–articulatory processes (Fiez & Petersen, 1998) and semantic processes (Poldrack et al., 1999).

Although some important details are not settled, the general features of this word reading circuit emerge from convergent studies and quantitative meta-analyses (Fiez & Petersen, 1998; Jobard, Crivello, & Tzourio-Mazoyer, 2003; Mechelli, Gorno-Tempini, & Price, 2003; Price, 2000). Furthermore, the interpretations map onto important conclusions from reading theory and behavioral results. For example, in the distinction between sublexical (grapho–phonological) decoding and direct lexical lookup, the decoding mechanism seems to be supported by the left temporo–parietal region that includes Wernicke's area.

With this view of the reading circuit, we can ask how it is acquired. It may be that learning to read progresses by first making the gateway region—the ventral region, where visual analysis of words takes place—responsive to graphic stimuli and then by establishing connections with other regions. Some cognitive models of learning to read (e.g., Ehri, 1991; Perfetti, 1992; Share, 1995) emphasize the acquisition of word representations through experiences that strengthen the orthographic specification of individual words. These experiences prominently include decoding words—associating pronunciations with letter strings while they are visually attended—thus supporting the establishment of an orthographic representation that can then be accessed more readily, through its spelling rather than through more effortful decoding.

One way to view the neuroimaging results is that they specify the cortical underpinnings of specificity and redundancy of representation (Perfetti, 1992). The ventral region supports lexical specificity, whereas sublexical (grapheme–phoneme) connections require the engagement of the dorsal region. An implication from the general theories, however, is that there is feedback from some phonological area, either the dorsal or the left frontal, to the visual areas that helps establish orthographic representations. Thus, at some point we should expect confirmation, modification, or disconfirmation of this hypothesis.

READING DISABILITY

One problem in reading science that should benefit directly from neuroimaging research is reading disability. The classic foundations of dyslexia were observations and speculations about neural organization that might lead to disordered reading. Orton's (1925) hypothesis that dyslexia was caused by incomplete lateralization attracted a focus to the brain basis of reading that endured through a long period in which research offered only studies of brain injuries and postmortem examinations to shed light on the brain states of individuals with dyslexia. Now functional neuroimaging brings a sharp tool to this problem. What does it tell us that is either new or confirmatory?

To put the answer in perspective, consider the extent to which favored explanations of disability have changed in 25 years. Frank Vellutino (1979), 25 years ago, argued forcefully against a prevailing view that dyslexia was a visual disorder and in favor of a verbal basis of dyslexia. By now the verbal hypothesis has been refined to the phonological deficit hypothesis, which, it is fair to say, has become the dominant (some might say "entrenched") explanation. The neuroimaging research, including articles in this special issue, joins the consensus by exposing some of the cortical correlates of phonological difficulties. (Some neuroimaging work seems to point to the visual–orthographic problems for at least some of those with dyslexia; Eden & Zeffiro, 1996).

The picture developed by behavioral studies is one of phonological deficits that span phonological awareness, phonological memory, word decoding, and even speech processes (Brady & Shankweiler, 1991; Stanovich & Siegel, 1994; Shankweiler et al., 1998). Sandak, Mencl, Frost, and Pugh (2004/this issue) suggested what brain research adds to this picture: Reading disability is marked by hypoactivity of the posterior dorsal and ventral regions of the reading circuit (Pugh et al., 2001; B. A. Shaywitz et al., 2002; S. E. Shaywitz et al., 1998). Sandak et al. further reported that skilled reading is associated with functionally correlated activity in the ventral and frontal regions, whereas low-skilled (young) readers and readers with impairment (both young and old) do not exhibit this pattern. This finding suggests a contrast between a skilled integrated word identification system and a less integrated set of components.

Another important idea is compensation. If one mechanism or knowledge source is deficient, other systems may get more involved. In the case of phonological deficits, for example, an increased reliance on semantics to support word identification has been proposed (Snowling, Hulme, & Goulandris, 1994). And what does neuroimaging add here? Sandak et al. (2004/this issue) reported that individuals with dyslexia may compensate by shifting reading processes to frontal and right hemisphere (RH) regions. Such shifts may imply an appeal to general purpose resources associated with executive control and memory. The picture is sharpened by training studies that suggest that phonological training leads to increases in left dorsal activity (McCandliss et al., 2001; Simos et al., 2002; Temple et al., 2003).

The double deficit hypothesis (Wolf, Bowers, & Greig, 1999) emphasizes the possibility that some children have problems beyond phonology, a second deficit in generalized rapid naming that includes nonlinguistic stimuli. Although the strong association of slower naming with reading problems is usually observed, the interpretation of the naming deficit has not been clear. For example, the fact that stronger associations are observed for alphanumeric stimuli, compared with colors or objects, suggests the possibility that the naming effect is mediated by experience with linguistic stimuli (include digits) or by perceptual factors shared more by letters and digits than other stimuli.

Misra, Katzir, Wolf, and Poldrack (2004/this issue) provided some important results to help clarify the interpretation of rapid naming. In their imaging study, they found overlapping activation for letters and objects in the ventral region of the reading circuit—an area that either includes the putative visual word form area or is just medial to it. This region is implicated in several tasks of naming and imagery where visual-to-verbal mapping is required (Price & Devlin, 2003). Thus, one conclusion appears to be that the mapping of orthography to phonology has its roots in the ventral region of the reading circuit.

COGNITIVE PROCESSES IN READING

Our theories of reading are partly about when things happen. This is because when things happen is important for explaining causal links between cognitive states and processes. For example, is phonological recoding the necessary step to the meaning of a word? Not if phonological recoding were found to occur only after semantic access.

More generally, when the eyes fixate on a word during reading of a text, a sequence of cognitive events unfold in very rapid succession. These events are frozen in discrete, if overlapping, cognitive descriptions: visual processing, orthographic form processing, phonological processing, semantic processing, syntactic processing, and text integration. Considering the brain provides a reminder that such descriptions might be too rigid to map in a simple sequence onto what the brain is doing over the 200 to 300 msec or so before the eyes move onto the next word. Although the orthographic, phonological, semantic, and syntactic processing of a word in actual reading might take 200 to 400 msec, the brain does not wait this long before telling the eyes to move on. The decision to move the eyes must be made within about 100 msec if the eyes are to be on another word by 300 msec. This fact complicates explanations of how a not-yet-completed recognition of a word can lead to an eye movement (Reichle, Rayner, & Pollatsek, in press).

Detailed theories of reading must include the timing of word reading events, and current functional magnetic resonance imaging (fMRI) methods cannot provide this information. A picture of activation in the ventral region is acquired over a time span that exceeds the time needed for word identification several times over. For temporal information, we need event-related potentials (ERPs) and magnetoencephalography (MEG). Salmelin and Helenius's (2004/this issue) interesting review of research using these electrophysiological methods provided timelines for word identification events and associated skill differences. A visual processing stage over the first 100 msec gets things going, independent of reading skill. The next event, which distinctly reflects the processing of letter strings, is where skill differences emerge. Low reading skill is associated with letter-string-processing problems between 150 and 170 msec in the left occipito–temporal boundary region (a bit posterior compared with regions identified in positron-emission tomography [PET] and fMRI studies).

One puzzle to be resolved is that the MEG–ERP studies have shown this 150- to 170-msec processing shift to be associated with letter strings generally, rather than words and pronounceable nonwords, as reported in the fMRI and PET studies. The coarse time window of fMRI and PET imaging methods misses a point at which a letter string is processed in the visual area regardless of its wordness. If so, we should see some differentiation of wordlike and nonwordlike letter strings within a few milliseconds. The larger picture, however, is that prelexical processing of orthographic information appears to be the component most related to reading skill. Whether this conclusion fits comfortably with the phonological conclusion in the fMRI publications remains to be seen. In any case, ERP and MEG are the tools most likely to sort out the unfolding of these extremely rapid and interlocked processing events.

ERP and MEG time course data are useful not only for the early events of word identification but also for later syntactic and semantic processing. The N400, which peaks about 400 msec into the viewing of a word, is observed when a word is read in context and is larger when the word does not fit with the preceding context. Its interpretation is expressed in various ways, but the concept of semantic integration difficulty captures its significance reasonably well. The experiments summarized by Salmelin and Helenius (2004/this issue) show skill differences in the latency of the N400, which begins at about 200 msec for skilled readers and at about 300 msec for less skilled readers. If we put these observations together, we see processing weaknesses that cascade for the less skilled readers, beginning within the first 150 msec with letter string processing and followed by a sluggish (but clearly present) response to the meaning of the word as it relates to its context.

An intriguing fact is that the cortical generator for the N400 includes one of the regions (left superior temporal) found to be underactivated for individuals with dyslexia in single word processing. Yet this region is activated for less skilled as well as skilled readers when the word is part of a sentence. This is the paradox of context: The greater context dependence of low-skilled readers for basic word identification is coupled with a reduced ability to actually use it effectively (e.g., Perfetti, Goldman, & Hogaboam, 1979).

One might expect that other skill differences in temporal indicators associated with syntactic and text processing events will also emerge. The question would be whether subsequent "down stream" problems have their origins in the initial 150-msec letter–word processing. Certainly things will be simpler if researchers can understand cascading, multiple indicator, processing problems as having a single early origin. *Asynchronous word processing*, the failure of processing events to have been completed in time for subsequent events to use their output, may characterize unskilled reading (Perfetti, 1985), and indeed such asynchronies are detected with ERP studies of dyslexic reading (Breznitz & Misra, 2003). It is important to recognize, however, that the discovery of a single early indicator of a word-processing problem does not mean that there is a faulty mechanism. The processes of word reading rest on multicomponent knowledge about words, and we think it is this knowledge that is the source of word reading problems.

READING BEYOND THE WORD

Word reading, as we have noted, can be traced from events early in visual processing through at least some of the semantic processes that integrate the word with the text. Neuroimaging research has produced much more information about word reading than about sentence and text comprehension, mirroring the imbalance in behavioral research. Reading beyond the word brings processes of meaning and reference, syntax, and text integration into central focus and requires as well the support of cognitive resources (e.g., working memory) that are not as much in play in word identification. This added complexity has been confronted in behavioral research and increasingly in neuroimaging research, where the complexities are even more challenging for experimental designs. Caplan's (2004/this issue) article brought out key issues in sentence-level processing, in particular.

Because reading ability is dependent on language ability, one should observe shared processes and common cortical resources across language modality. Syntactic processes are not about reading only but about language. Moreover, syntactic processes depend on processing resources (working memory) in a way that complicates explanations of their role in comprehension, including whether faulty syntactic processing is a possible cause of comprehension difficulty. Nevertheless, the brain does appear to have some specific machinery for syntax as shown by the large body of evidence implicating left inferior frontal regions that include Broca's area. Research that parametrically manipulates processing load, as Caplan's (2004/this issue) research did, has a chance to identify the more syntactically specific aspects of the process of sentence comprehension, separately from its semantic correlates and its dependence on processing resources.

Again, ERP and MEG methods, because of their time sensitivity, are helpful in this theoretical task. Processes have different time courses as well as different regions of cortical responsibility. For example, the N400 signature for semantic processing is not sensitive to syntax. Syntactic violations, however, can produce both a later occurring positive shift (P600; Osterhout & Holcomb, 1992) and an earlier occurring negative shift in left frontal regions (Friederici, Hahne, & Mecklinger, 1996).

There is less neuroimaging work beyond syntax, and none of this research is represented in the articles in this special issue. However, integrating information across sentence boundaries and drawing inferences are important in reading comprehension, and interesting results have begun to appear from fMRI and ERP research. For one, it appears that any assumption that the RH is idle during language comprehension has to be abandoned. When readers attempt to comprehend texts that require inferences, as most texts do, the RH has a role (Beeman, Bowman, & Gernsbacher, 2000; Mason & Just, 2004). Another important development is that ERP research shows that the N400, the signature for semantic processing, is sensitive to text processes (St. George, Kutas, Martinez, & Sereno, 1999). The N400 can even expose the reader's attempts to integrate a word at the beginning of a sentence with information from the previous sentence (Perfetti et al., 2003).

It is important for us, as researchers, to remind ourselves that simple word identification occurs during reading within a discourse context. Furthermore, some of the word processes that are required by discourse, for example, mapping a word to a previously introduced referent, may occur within 240 msec of word processing (van Berkum, Brown, & Hagoort, 1999), barely beyond the time frame of orthographic processes. The early visual, graphic, and phonological processes should be similar for discourse and isolation. However, as suggested by some of the results of Salmelin and Helenius (2004/this issue), slightly different, perhaps compensatory, brain resources can be applied in the discourse context. One of the real potentials for ERP and MEG methods is exposing what happens over the course of word identification within a discourse context.

UNIVERSALS IN READING

Because the human brain is approximately universal, studies of functional neuroanatomy can test the hypothesis that the process of reading words includes universal processes (Perfetti, 2003). Within the family of alphabetic writing systems, some uniformities across shallow and deep orthographies have been observed in the word reading network (Paulesu et al., 2001). The universal hypothesis requires research across writing systems, however. Research by Chee and Tan and colleagues suggests that reading words in Chinese makes use of the same word reading network as identified in research on alphabetic reading (Chee, Tan, & Theil, 1999; Tan et al., 2000; Tan et al., 2001).

However, this simple picture of universal brain areas may require modification.[1] First, fMRI studies can miss temporal processing differences that might lie beneath the observed shared regions. With ERPs, Liu and Perfetti (2003) found that Chinese–English bilinguals showed a different pattern for English and Chinese word reading during the first 200 msec, with a left occipital pattern for English but a bilateral pattern for Chinese, suggesting more RH visuospatial analysis for Chinese characters. Second, several fMRI studies have demonstrated that additional brain regions (beyond the alphabetic word network) are involved when Chinese readers read characters (Tan et al., 2000; Tan et al., 2001). These additional areas of the brain (left middle frontal and posterior parietal gyri) support the processing and maintenance of spatial information processing and coordination of cognitive resources. Tan et al. (2001) suggested that these areas may function because of the spatial representation required by Chinese characters and their connection to a syllable-level phonological representation. Furthermore, Tan et al. (2003) found that when Chinese readers read English, these Chinese-specific areas are also activated.

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[1] An analysis of seven recent studies of Chinese character and Japanese Kanji reading (Bolger, 2003) indeed revealed consistent activation of the network identified in alphabetic system research. However, it also showed differences. Chinese produced substantial bilateral activation in ventral visual regions, and both Chinese and Kanji experiments showed little or no activation in the left superior posterior temporal gyrus, where alphabetic research shows activation usually interpreted as supporting phonological processing. Chinese character reading showed stronger activation in bilateral striate and extrastriate regions and in left dorsal lateral prefrontal cortex.

This leads to the intriguing hypothesis that the brain not only makes some accommodation to the writing system but also applies its acquired processing functions to a new system. Recent ERP studies of English-speaking adults learning to read Chinese point to orthographic learning effects within 200 msec of exposure to a word (Liu, Perfetti, & Wang, 2003). In these studies, the pattern of activation in occipital areas for the learners was similar to the bilateral pattern for Chinese speakers observed by Liu and Perfetti (2003). This suggests that the visual form of a writing system might make a difference in the early stages of processing for learner and expert alike.

Although the picture on universals is incomplete, results may suggest a general conclusion of universality plus accommodation. Because word reading involves orthographic, phonological, and semantic processes that are part of all reading, one should expect the brain to support these processes in a universal way, but only to the level allowed by universal details. Important differences exist in the details of how writing systems work, especially in how units of orthography map onto units of phonology. One should not be surprised that these details make a difference in the brain.

GENERAL CONCLUSION

Research on how the brain reads has produced impressive progress and joins the advances in behavioral research to strengthen the science of reading. There is a remarkable convergence on the functioning of a cortical network that supports word reading, although it is incomplete in both its neuroanatomical details and its functional interpretation. The increased complexity of reading above the word level is a challenge to functional brain research just as it is to behavioral research, but even here there has been significant progress.

Much of this progress has been made through neuroimaging procedures (fMRI and PET) that provide detail about brain locations. However, for researchers to shed light on the cognitive events that occur rapidly during word reading, time-sensitive measures such as ERPs and MEG are essential. The space-location and time-location methods are complementary partners in a better understanding of reading.

Assumptions about a universal reading brain may require some qualification. The word reading network identified by the alphabetic research does have universal features. However, the research in nonalphabetic systems suggests that there is accommodation to specific writing system features.

There is still a lot to be learned about how the brain implements the cognitive processes of reading. As our title suggests, a plausible story is emerging. We won't be surprised to learn that parts of the story turn out to be wrong, but we dare not say that the brain doesn't read that way.[2]

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[2] Our title echoes *The Mind Doesn't Work That Way*, Jerry Fodor's (2000) answer to *How the Mind Works* (Pinker, 1997). We find it difficult to be really sure about how things work, both minds and brains.

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