

# What the Neurosciences can Tell Educators about Reading and Arithmetic A Review of Current Research

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## Abstract

Effective instructional methods are now an important national issue. We reviewed the current research techniques used in cognitive neuroscience and what is currently known about the neurocognition of reading and mathematics. We found that while the neurocognition aspects of reading and mathematics share common processes associated with language, certain aspects of semantics and comprehension are unique to reading and certain aspects of mathematics entail visual-spatial processing not observed during reading. We conclude that although significant advances have been made in the understanding of the underlying neurocognitive process in the last decade more research is needed before the neurosciences can make a direct contribution to instructional practice.

## Introduction

What serves as effective reading and mathematics instruction has been the subject of ongoing debate for a large part of the last century. Wholesale changes in curriculum have been instituted by political mandate, only to be revoked by public outcry (Jackson, 1997a, 1997b). An issue once discussed locally between teachers and parents is now debated by presidential candidates, and a scarcity of clear and definitive answers has spawned a national campaign to establish empirically what constitutes effective instruction (National Reading Panel, 2000). The inability of the educational research community to provide clear and convincing evidence has encouraged some to turn to the burgeoning field of cognitive neuroscience for answers. The aim of this paper is to provide educators with a conception of what cognitive neuroscience can contribute to this debate.

## Behavioral and Neuroscience Research

A funny thing happened during the unfolding of the cognitive revolution. The term "behavior" once used to emphasize the level of analysis in the Behaviorist tradition is now used to differentiate between conventional research in cognitive psychology and research in the neurosciences. Whereas most cognitive research in psychology involves the analysis of behavior (or the cognitive substrates from which

behavior arises), neuroscience research involves the analysis of neurons, neurotransmitters, genes, and something referred to as "activation." The outcome of this evolution in nomenclature is that cognitive psychology is now described as "behavioral" and cognitive research in the neurosciences as, well, "cognitive neuroscience."

This difference between behavior and neurons is relevant to this discussion in so much as education is concerned in large part with behavioral outcomes. When designing effective reading and math instruction we are interested in observable behavioral measures and student achievement. It is certainly legitimate to ask how knowledge about neurons is going to help us design curriculum. Our answer, honestly, is that it is not likely to ... at this point in time. However, that is not to say that neuroscience cannot help us understand how reading and calculation occur in the brain, and in fact, neurocognitive research in these areas has progressed significantly in the last decade. We believe that by building our understanding of these processes from the bottom up we will be able to eliminate some of the indeterminacy engendered by contemporary instructional theories. Beyond this, we find the study of how thought process occur in the brain fascinating and we hope you will as well.

We have organized this paper in a way that we feel is accessible for someone with little or no background in the neurosciences. We begin with an overview of research methods and brain anatomy. We then divide the paper into sections: one synthesizing the neurocognitive research in reading; another synthesizing the research in mathematics. We conclude with an analysis of the commonalities and differences between the two and close with comments on the possible implications for educational research.

## Research Methods in Neuroscience

There are several basic methodologies used in neurocognitive research. Each methodology has its own strength and weakness, and provides different information about neurological processes. While knowledge about individual technologies is not necessary for an understanding of neurocognitive

processes, we believe that it helps. In this section we provide an overview of the current techniques used in neuroscience research.

**Lesion Studies** Historically, our understanding of the neurological bases of cognition has come from case studies of individuals with head injuries or internal lesions caused by tumors or stroke. By observing which abilities are impaired and which are unaffected researchers have been able to localize particular cognitive functions to specific brain regions. Case studies such as these are generally referred to as lesion studies.

**Single Unit Studies** With advances in technology, early neuroscientists were able to measure the activity of individual neurons by inserting specialized electrodes into the brains of animals. By presenting animals with stimuli or having them perform tasks it was possible to determine which neurons would respond to what type of perceptual or cognitive activity. These single cell studies allowed researchers to localize cognitive functions and determine response times.

**Electrophysiological Studies** Researchers have also been able to measure neural activity non-invasively by placing electrodes on the surface of the scalp and recording the activity of large populations of neurons. These types of studies are called electroencephalography or EEG studies. EEG studies allow the comparison of different brain patterns depending on the type of cognitive activity that produces them. A special type of electroencephalography allows brain wave patterns to be time-locked with the onset of a stimulus providing researchers with the ability to observe both the time course of neural responses and to differentiate between cognitive functions. Because of their ability to measure neural activity in response to particular events these studies record what are called event-related potentials (ERPs) and are identified as ERP studies (Coles & Rugg, 1995). The most recent ERP technology utilizes a large number of electrodes (128) to also estimate the source of event-related potentials, but in general ERP studies are limited in their ability to localize cognitive function to specific brain regions.

**PET and fMRI** In the last two decades, advances in neuroimaging technology have allowed researchers to localize activation with high spatial resolution non-invasively. The earliest of these technologies was Positron Emission Tomography (PET), which uses a radioactively labeled substance to measure blood flow in the brain (it has been shown that blood flow is highly correlated with neural activity). More recently Magnetic Resonance Imaging (MRI), which is normally

used to develop anatomical images, has been adapted to measure blood flow by detecting changes in the amount of oxygen present in the blood. This latter type of MRI is called fMRI, the "f" standing for functional. Both PET and fMRI produce high resolution images showing which regions of the brain are active during cognitive tasks. While PET and fMRI have good spatial resolution (approximately an eighth of an inch), they lack the temporal resolution of ERPs; ERPs are accurate within several thousandths of a second, while PET and fMRI are generally limited to a period of two or three seconds.

**New Technologies** In the last ten years a new neuroimaging technology advance has combined the temporal resolution with improved spatial resolution. Magnetoencephalography or MEG produces images of neuronal activation by measuring the strength of the magnetic fields generated by populations of neurons. This ability permits non-invasive imaging of the brain temporally within a thousandth of a second and spatially within approximately an inch depending on the number of sensors used in a particular device. Researchers are currently trying to combine fMRI and MEG to achieve both high temporal and high spatial resolution (Dale, et al., 2000). Another new technology allows researchers to create transient artificial lesions which temporarily disrupt neural activity. Transcranial magnetic stimulation (TMS) does this by using a localized magnetic pulse to simultaneously simulate a population the neurons in a localized area preventing them from performing their normal neurological functioning (Walsh & Cowey, 2000). TMS allows researchers to test hypotheses about specific areas in the brain (within approximately an eighth of an inch). TMS also has reasonably good temporal resolution, roughly around one second. However, unlike PET and fMRI TMS does not allow for unrestricted exploration because the small area impacted by TMS stimulation requires a priori hypotheses for the interpretation of results.

**Summary** To summarize, different types of neuroscience studies provide different types of information. Lesion studies, PET, fMRI, MEG, and TMS help to localize cognitive functions to particular regions of the brain with varying degrees of resolution. EEG and ERPs allow us to compare the types of waveforms generated by various cognitive tasks. ERPs, MEG, and TMS allow us to specify the timing of events as they occur in the brain. While localization and timing provide an immensely greater understanding than we had thirty years ago, the future of neurocognitive research may lay beyond the localization and timing of cognitive activities. A complete understanding of how thought processes occur in the brain may require the

analysis of how different processes interact. Researchers are just beginning to use statistical methods to observe the dynamic patterns of interaction between active regions. Thus, in the future much of our understanding of cognitive processes may require an analysis of the interactive dynamics of thought processes (Horwitz, Friston, & Taylor, 2000; McIntosh, 1999, 2000), however there is still a lot to convey about what we have learned in the last ten years.

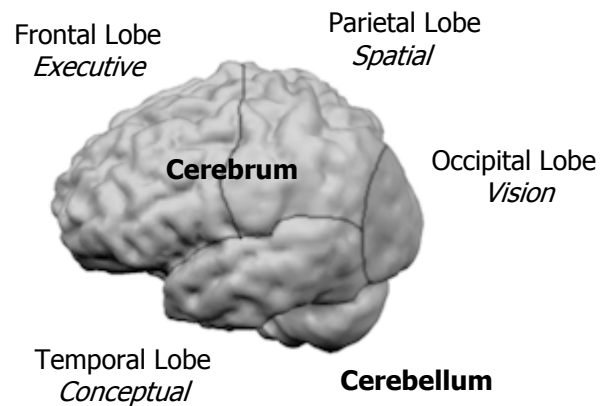
### Basic Brain Anatomy

While it is possible to gloss over methodologies, a fundamental understanding of basic anatomy is required to make sense of neurological research. This is because much of contemporary neurocognitive research involves identifying the locations of particular cognitive functions. We have tried to minimize the amount of detail required so that you need not have memorized Brodmann's areas (a map of the brain based on cytoarchitecture), Talairach coordinates (a standardized coordinate system for identifying locations in the brain in three dimensional space), nor the names of gyri and sulci. However, in order to be able to understand where things are occurring in the brain knowing which lobe is which will help considerably.

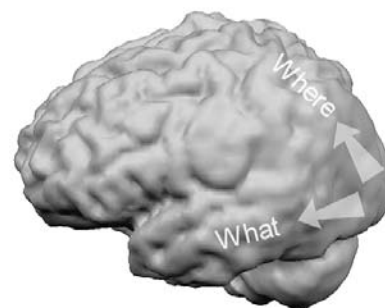
**Cerebrum and Cerebellum** At the global level the brain consists of the cerebrum and the cerebellum. The cerebrum comprises the largest portion of the brain and the cerebellum lies below and to the rear of the cerebrum. The cerebrum is comprised of two distinct hemispheres which are connected via several communications pathways. These hemispheres are basically symmetric, although they are thought to be differentiated by the types of functional tasks they perform. These functional differences are sometimes characterized as analytic (left) vs. holistic (right), but more recently it has been theorized to reflect a difference in the spatial frequency processing of information; high frequency (left) vs. low frequency (right; Gazzaniga, Ivry, & Mangun, 1998). The cerebellum (which also comprises two hemispheres) is commonly associated with the control and coordination of rapid movements and equilibrium. Traditionally, the cerebellum has not been associated with higher level cognition, although this perspective is changing (Fulbright, et al., 1999).

**Lobes of the Cerebrum** At the next topographical level, both hemispheres are divided into lobes. A lobe is essentially an area that is physically separable from other lobes. Lobes in one hemisphere are mirrored by complementary lobes in the other hemisphere. There are four lobes in the cerebrum: frontal, temporal, parietal, and occipital. In a very general sense lobes

can be categorized by the type of cognitive function they perform: frontal/executive control, temporal/conceptual, parietal/spatial, and occipital/vision (Figure 1). In addition to the functional differentiation by lobe, it is also hypothesized that there are two basic visual information streams in each hemisphere (Ungerleider & Mishkin, 1982). Both streams originate in occipital lobes where vision is processed. The dorsal stream projects into the parietal lobes and processes information dealing with "where" objects are located. The ventral stream projects into the temporal lobes and processes information dealing with "what" objects are (Figure 2).



**Figure 1: Global Topology of the Brain.** The major component of the brain is the Cerebrum which is made up of two hemispheres each of which contain four lobes. The four lobes are associated with general cognitive functions identified in *italics*.

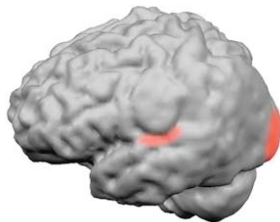


**Figure 2: What and Where Pathways.** Information about object identification travels from the occipital lobe through the ventral pathway to the temporal lobe. Visual information relating to location travels through the dorsal pathway to the parietal lobe.

**Localization** The question of where specific cognitive processes are located in the brain is the focus of a large segment of the current research in cognitive neuroscience. Much of what is reported in this paper will concern how functions are functionally segregated

and localized to particular regions, but it is important to note that how "local" particular functions are is a matter of ongoing debate (Cohen & Tong, 2001). It is our opinion that while it cannot be denied that cognitive activities in the brain are distributed, interactive, and sometimes overlapping, it is still possible to state that specific functional aspects of cognition tend to activate specific regions in the brain. Knowing where these regions are and understanding their dynamics helps us interpret cognition at a behavioral level of analysis.

**Primary Auditory and Visual Areas** There are two areas in the brain that are important for understanding the localization of reading in the brain. The first are the primary auditory areas that are located in the temporal lobe behind the ears. These areas are the where the initial processing of sound and language occurs. Although, the primary auditory areas are not noticeably active during reading, it is important to keep in mind their location in relation to phonologic and semantic processing. The primary visual area is located in the rear most portion of the occipital lobe. It is in this location that the processing of visual information begins. Because of close relationship of language and reading many common areas are activated when processing language or during reading. As we will see one general pathway for reading progresses from the primary visual area along the "What" pathway (ventral stream).



**Figure 3: Primary Auditory and Visual Areas.** The primary auditory area is located in the temporal lobe and the primary visual area is located in the parietal area as identified by the areas marked in red.

### Reading

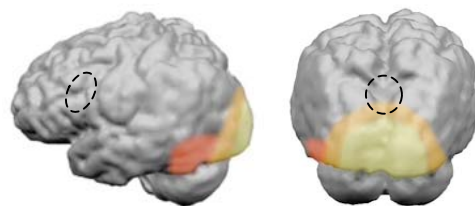
Interestingly, the investigation into the neurological bases of reading has been guided more by the study of linguistics than by disciplines more commonly associated with reading research such as discourse comprehension. Neuroscientists approach reading from the perspective of orthographic and phonological analysis, syntax, and semantics (Perfetti, 1999); whereas traditional reading research has dealt with different levels of analysis such as surface-code, textbase, and situational models (Graesser, Millis, & Zwaan, 1997). This discrepancy is not surprising given that neurological research is searching for the underlying components of reading and discourse

research has had a more behavioral focus. Here in our description, rather than rely on traditional theoretical formulations of reading, we will try to structure our account of the neuroscience of reading chronologically as it occurs in the brain. We will begin with the processing of visual stimuli, the formation of words and interpretation of words, the parsing of sentences, and the comprehension of passages.

A word of caution is prudent before we proceed. In order to provide a comprehensive overview, our summary of the research literature involves a degree of synthesis and interpretation. Studies vary in their level of analysis: words, sentences, and passages; in their methodology: lesions, ERPs, fMRI, and MEG; and in the types of experimental and control tasks used. Although we believe our synopsis is veridical, individual researchers might object that at some points we favor one study or theoretical perspective over another. This may well be true, but we will try to qualify our interpretations when we feel it is important.

### Visual Processing

It takes approximately 80 milliseconds<sup>1</sup> (ms) for the image of a written word to travel from the eye to the occipital lobes. It is in this region that information about the orientation of the lines and curves making up letters will be processed (Clark, Fan, & Hillyard, 1995). This type of elementary orthographic (word form) processing occurs in both hemispheres (bilaterally). As processing proceeds to the recognition of letters and graphical symbols activation spreads from the primary visual area to adjacent areas bilaterally (see Figure 3; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). This process occurs in the range of approximately 120 to 150 ms. It is interesting to note that the amount of time required for this process is bounded by the length of time that the eyes typically stay fixed at a single point while reading a sentence. In other words, the brain is already processing the lexicographical information necessary to compute where to look next in the sentence within 150 ms (Serenó, Rayner, & Posner, 1998).



**Figure 4: Initial areas activated during reading.** The yellow region indicates the primary visual area associated with the processing of lines and curves and is first activated ~80-100ms as viewing a word. The

<sup>1</sup> A millisecond is a 1000<sup>th</sup> of a second. For example, 100 milliseconds would equal a tenth of a second.

orange area is the secondary visual area that processes basic orthographic information activated at ~100-150 ms. The red area is the putative location of the visual word form area and is activated beginning ~150 ms after presentation. The dashed oval indicate an interior area in the frontal lobes associated with attention and is activated at ~170 ms.

Following the activation of areas associated with the recognition of letters, a region identified as the *visual word form* area is activated in the lower posterior portion of the temporal lobe in the left hemisphere (Cohen, et al., 2000). It has been shown that different types of information are routed into alternate hemispheres. For example, information about human faces activates an area in the right hemisphere and, as we have said, words activate an area in the left hemisphere (Khateb, et al., 2001; Schendan, Ganis, & Kutas, 1998). This shift in activation indicates a predisposition for reading and language processing to be lateralized in the left-hemisphere in most individuals (over 96% of humans are left-hemisphere dominate for language). Exactly why language is left lateralized is unknown. Different theories have postulated the cause to be due to evolutionary development; morphological relations between neurons; structural differences in the skull; or to the lateral differences in frequency analysis cited above (Gazzaniga, et al., 1998). The fact that language is left lateralized does not imply that activation does not occurs in the right hemisphere, only that the majority of activation occurs in the left; and that lesions in the left hemisphere cause profound defects in language processing and reading, while lesions in the right hemisphere do not normally have a significant impact.

**Initial Processing in the Frontal Lobe** At approximately the same time that activation occurs in the word-form area ERP signals appear to emanate bilaterally from areas in the frontal lobes associated with attention (Abdullaev & Posner, 1997; Ivanitsky, Nikolaev, & Ivanitsky, 2001; Snyder, Abdullaev, Posner, & Raichle, 1995). As processing progresses there appears to be interplay between regions on the left side of the frontal lobe and posterior regions of the left side of the lower parietal lobe and areas of the left temporal lobe. This interaction has been hypothesized to represent frontal control and coordination of activation of posterior representations (Miller & Cohen, 2001; Owen, 1997). In relation to reading, these posterior representations would store lexical, semantic, and phonological information.

## Words

**Early Word Processing** As the processing of a word progresses from the visual word form area it moves into areas of the posterior temporal lobe associated with

lexical-semantic functions and into the boundary area between the temporal and occipital lobes hypothesized to be related to the integration of orthographic, phonological and lexical-semantic information (Pugh, et al., 2000). The exact timing of processing is unclear and it is possible that events might occur either simultaneously or sequentially. However it is known that very early in processing effects (ERPs) of lexical features of words are already detected. Thus, differences in distinguishing between words and non-words occurs between 100 and 130 ms; differences between words that occur frequently and those that appear infrequently can be observed 130 and 160 ms; and detectable difference in whether words conform to standard rules of English pronunciation (regularity vs. non regularity) occur between 160 and 175 ms (Serenio, et al., 1998). These features that might be classified as lexical and phonological analysis are already occurring very early. Soon after, at approximately 250 ms, semantic effects can be observed in the superior temporal region (Helenius, Salmelin, Service, & Connolly, 1998).

**Frontal Lobe Activation** At approximately the same time that early lexical effects related to word recognition are occurring in the posterior portion of the brain, activations are beginning to appear in lateral areas of the left frontal lobe known to be related to later semantics, phonological, and syntactic processing. This initial processing may be related to establishing the meaning of a word, performing a orthographic to phonological translation, or determining the syntactic category of a word, but although we know where this activation occurs and its approximate onset (220 ms), the interaction between frontal and posterior areas is not known.

## Sentences

A large portion of the neuroscience research of reading has involved the analysis of word processing; recently more focus has been placed on sentences. Analysis at the sentence level adds several important dimensions: syntax, semantics, and comprehension.

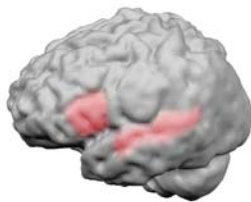
**Syntax** In relation to linguistics, the most predominant dimension has been syntax (Hagoort, Brown, & Osterhout, 1999). According to linguistic theory, syntax plays a role in assigning words to grammatical categories, disambiguating semantics, and building an internal representation. During the process of sentence parsing, traditional linguistic theory has postulated the existence of an intermediate representation between the surface structure of a sentence and its internal representation. Exactly how well this model corresponds to neurological processes has been one of the questions addressed by neuroscience research.



**Figure 5: Early Activations in Frontal and Posterior Regions** Areas shown in pink indicate the approximate locations of areas hypothesized to be active during early word processing at ~220 ms.

Imaging studies have found an area in the left lateral frontal lobe to be most commonly associated with syntactic processes (Dapretto & Bookheimer, 1999; Indefrey, Hagoort, Herzog, Seitz, & Brown, 2001; Kang, Constable, Gore, & Avrutin, 1999; Sakai, Hashimoto, & Homae, 2000). Other studies have also found that in addition to this frontal lobe area an upper region of the left temporal lobe is also activated (see Figure 6; Crozier, et al., 1999; Friederici, Wang, Herrmann, Maess, & Oertel, 2000).

In terms of chronology there appears to be three time periods that are important for syntactic processing. The earliest occurs between 100 and 300 ms and appears to be related to word category processing (parts of speech: articles, nouns, verbs, etc.). A second period occurs from about 300 to 500 ms and seems to be related to automatic processing of phrase structure violations. A third period occurs after 500 ms appears to involve more attentional phrasing, and an integration of lexical-semantic and phrase structure information (Friederici, et al., 2000; Hahne, & Friederici, 1999).

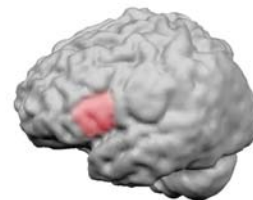


**Figure 6: Syntactic Processing** The areas highlighted above have been found to be associated with syntactic processing.

Some researchers have theorized that word classes may be localized to particular locations in the brain (Pulvermuller, 1999) and while there is some evidence that exists that shows that different areas in the frontal lobes process nouns and verbs (Shapiro, Pascual-Leone, Mottaghy, Gangitano, & Caramazza, 2001), other researchers have question if such differences in location exist (Tyler, Russell, Fadili, & Moss, 2001).

**Phonology** Much of the research investigating phonology in reading has centered around the issue of whether there are two routes used in word processing or just one. A dual route hypothesis has been proposed based on differences between subcategories of dyslexia. Surface dyslexics can read pseudo-words (words that adhere to pronunciation rules, but are not in the lexicon), but have trouble reading irregular words (words that violate pronunciation rules). Phonological dyslexics on the other hand can read irregular words, yet cannot pronounce pseudo-words. The dual route hypothesis proposes that there is a direct route from the orthographic representation of words to their semantic interpretation and an indirect route which requires phonological analysis prior to semantic interpretation (Fiez, Balota, Raichle, & Petersen, 1999). A second hypothesis proposes that word processing is handled by a single route in which differences between types of processing can be explained by learning the characteristics of words according to frequency of exposure (Plaut, McClelland, Seidenberg, & Patterson, 1996).

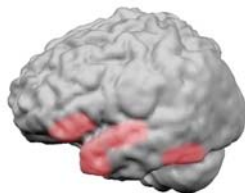
If the processing of reading progresses from the occipital lobe into the lower temporal lobe it is still not clear, even given current research, exactly where phonological processing would take place in the posterior regions of the brain. Phonological judgments related to pronunciation activate areas in the upper temporal lobe including the primary auditory cortex and orthographic decisions activated an area close to the visual word form area (Rumsey, et al., 1997). A comparison of speech versus tone discrimination also has been found to activate areas in the upper temporal lobe including the primary auditory cortex (Burton, Small, & Blumstein, 2000; Price, 2000). However, it is not clear if these types of phonological judgments would normally be required during reading. In a study directly comparing dyslexic subtypes, surface dyslexics show reduced levels of activation in an area between the temporal, occipital, and parietal lobes; and phonological dyslexic show decrease activation in temporal areas (Arnoldussen, Bookheimer, Manis, & Seidenberg, 2002). What the exact implications of these findings are will require additional research.



**Figure 7: Phonological Processing** The areas highlighted above have been found to be associated with phonological processing.

What is clear about phonological processing during reading is that it involves activation in the left frontal lobe (Figure 7; Burton, 2001; Burton, Small, & Blumstein, 2000; Fiez, 1998; Poldrack, et al., 1999; Rumsey, et al., 1997). These regions are basically the same locations implicated in syntactic processing, but some authors suggest that the basic areas reported to be active can be subdivided by specific types of phonological tasks. More specifically, Fiebach and colleagues have suggested that the more posterior region in Figure 7, is related to grapheme-to-phoneme conversion and the more anterior region supports mechanisms relating to a mental lexicon (Fiebach, Friederici, Muller, & von Cramon, 2002).

**Semantics** Semantic processing includes tasks as simple as word recognition and extends to tasks such as classification, categorization, and contextual judgements. While the exact locations and dynamics of phonological processing during reading are not clear, those related to the semantics of reading are more definitive. A number of years ago semantic processing was thought to occur in the same frontal location associated with syntactic and phonological processing, but recent research has been able to identify regions specific to semantic processing that are located more anteriorly (Poldrack, et al., 1999; Fiez, 1998) and some researchers report more activation in the right hemisphere (Kang, et al., 1999). Activation for semantic tasks was also observed in left posterior areas of the temporal lobe associated with word processing (Bokde, Tagamets, Friedman, & Horwitz, 2001) and in the anterior areas of the frontal lobe (Price, Moore, Humphreys, & Wise, 1997).

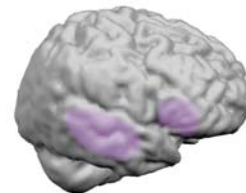


**Figure 8: Semantic Processing** The areas highlighted above have been found to be associated with semantic processing. The area in the lower temporal lobe may be associated with the semantic interpretation of words and the areas in the upper and anterior portions of the temporal lobe may be associated with the integration of meaning within a sentence.

Previously we had mentioned that general theories of neurocognitive functioning have proposed that the prefrontal lobes direct and control processing in the more posterior lobes. Fiez (1997) has proposed that this specific functional relationship applies directly to the processing of phonology and semantics. Recent

research (Bokde, et al., 2001) contrasting the functional interactions between regions has found different correlational patterns between words with high semantic valence compared to pseudowords, letter strings, and false fonts. Words activate frontal areas associated with semantics and posterior areas associated with word identification. Pseudowords, letter strings, and false fronts activate frontal areas and posterior areas associated with phonological processing. Additional involvement of the upper regions of the temporal lobe have been found (Helenius, et al., 1998). Studies of general semantic memory have identified the anterior portion of the temporal lobe as being involved in semantic processing (Martin & Chao, 2001).

The chronology of semantic processing appears to occur in two phases. Hahne and Friederici (1999) have proposed that early syntactic processing (~140 ms) is automatic and late semantic processing (~600 ms) is controlled by attentional processes. Helenius and colleagues (1998) have proposed that initial semantic processing for word meaning occurs between 250 to 350 ms and that semantic integration into sentence context occurs from 350 to 600 ms. Regardless of the exact onset of semantic processing it seems clear that a number of syntactic, phonological, and semantic processes involved in the parsing of sentences is occurring in parallel as words are being recognized and later integrated into some form of comprehensive representation. What is not clear is if the intermediate syntactic structures hypothesized in linguistic theories are constructed in the brain during reading.



**Figure 9: Comprehension** The areas highlighted above have been found to be associated with comprehension in the right hemisphere.

### Comprehension

Within the last few years researchers have begun to investigate processes related to comprehension beyond the sentence level. Although, imaging research in this area is new, Mark Beeman has hypothesized a difference in the processing of comprehension between right and left hemispheres for a number of years (1993; 1998; 2000). Beeman has proposed that the left hemisphere is involved in the comprehension (course coding) of closely related semantic relations and the right hemisphere processes more abstractly and distantly related concepts. In support of Beeman's hypothesis, an imaging study by Robertson and

colleagues (2000) found that coherent sets of sentences generate more activity in the frontal regions of the right hemisphere, than less coherent sets of sentences. A study by St George, et al. (1999) found that when paragraphs were made unambiguous by providing titles a reader showed greater activation in the right middle temporal regions (See Figure 9). In a study that attempts to project the discourse processing model on neuroanatomy, Long and Baynes (2002) found that prepositional relation appear to be represented in the left hemisphere, while both hemispheres seem to represent contextually appropriate semantic information. Contrary to the assumption of a special role for the right hemisphere in comprehension, Ferstl and von Cramon (2001) found greater activation in the left temporal lobe in relation to coherent versus incoherent sentence pairs. However, left hemisphere dominance may be due to a close semantic relationship between sentence pairs that did not require engagement of the coarse coding properties of the right hemisphere.

Neurocognitive research into aspects of comprehension is just beginning to give us insights into the processes involved in reading. With a national emphasis on research into the neurocognitive foundations of reading it is likely that we will be learning much more in the near future.

## **Mathematics**

The research into the neuroscience of reading is extensive, although not exhaustive. Regrettably, the research into the neurocognitive foundations of mathematics is not currently as complete, still there are many studies that can help provide us with a framework for understanding how the processing of numbers and calculation occurs in the brain. Another difficulty is that while linguistics literature has provided a general structure for neuroscience research in reading, research in the neurocognition of mathematics has been guided more by individual theorists than by comprehensive progress within a discipline.

Perhaps the most dominant theorist in the neurocognition of mathematics has been Stanislas Dehaene (1997). Dehaene and his colleagues have proposed that thought processes related to numbers are supported by at least two types of disassociatable systems: a language-independent system used to judge the magnitude of numbers and a language related system used to store language related number facts (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). However, these assumptions have been questioned by other researchers (Pesenti, Thioux, Seron, & De Volder, 2000).

Regardless of differences in the theories of mathematical cognition, we can analyze the literature in much the same manner as with reading, that is chronologically as processing occurs in the brain. And, since mathematics is itself a language possessing its

own syntax and semantics, we can also analyze it from this perspective as well. However, the task is complicated because mathematics has several cognitive components not shared by reading: counting, magnitude estimation, and algorithmic calculation.

## **Visual Processing**

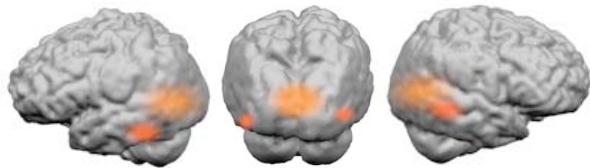
Once again processing in the primary visual area begins approximately 80 ms after the presentation of a stimulus, but in the case of numbers we now have two types of notations. Numbers can be represented as words, "thirty-two," or using Arabic numerals, "32." Are these representations processed in the same brain regions? A study by Pinel and colleagues (2001) has shown that both representations activate bilateral regions in the occipital lobe. However, number words activate the left posterior region more strongly than Arabic numerals and Arabic numerals activate the right posterior region more strongly. When these stimuli were analyzed in relation to their ERP, signals a difference in wave forms generated by words and numerals was observed in between 120 ms and 144 ms. At approximately 184 ms, activation progresses bilaterally into the regions between the occipital and temporal lobes. Although, these findings are based on a single study, we can speculate that these activation patterns are similar to those seen in the early stages of reading, but with activation occurring in both hemispheres in locations approximating that of the visual word form area in the left hemisphere observed during reading (Figure 10).

## **Numeric Comparison and Approximation**

Considering the evidence above and other lesion studies (Dehaene & Cohen, 1995), it is reasonable to assume that number words are predominately processed in the left hemisphere and Arabic numerals in the right, but what about the underlying semantics of numbers, numerosity, and numerical processing? Does the cognitive processing of word numbers and Arabic numerals converge to a common location? To answer this question, we have to differentiate between different types of numerical processing. We begin by considering the comparison of numeric magnitude; is one number larger, smaller, or the same as another?

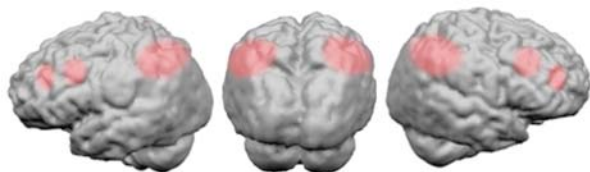
Dehaene has proposed that our brains contain the equivalent of a mental number line that is used to judge the magnitude of numbers and that this representation is shared in common by both number words and numerals (1997). Imaging studies have shown that bilateral areas of the parietal lobes are active when people are asked to compare two numbers, and that these activations are independent of the format the numbers are presented in (Le Clec'H, et al., 2000; Pinel, et al., 2001). However, other researchers have suggested that numerical comparison activates an area in the left parietal lobe more strongly and the activation in the right parietal lobe may be more closely related to general working

memory, attention, and visuospatial processing (Pesenti, et al., 2000). In terms of timing, the processing of number words appears to occur a little more slowly than for numerals and the processing of the comparison appears to occur between 200 and 400 ms.



**Figure 10: Suggested Patterns of Activation During the Recognition of Number Words and Numerals.** Areas in orange may be activated at ~144 ms and those in red at ~184 ms. Areas on the left show more activation for number words and those on the right for numerals. Activations are interior to the surface of the brain and are visible as if the brain were semi-transparent.

In addition to numerical comparison, the parietal lobe also seems to play a part in numerical approximation. That is, when people are asked to approximate the answer to an arithmetic problem, rather than giving an exact answer, activation was observed in approximately the same locations as for comparison. Differences in ERP waves between exact calculation and approximation were observed beginning at 216 ms (Stanescu-Cosson, et al., 2000). This would imply that commonalities in visual processes end at this time and it is when mental processing related to the tasks begins.



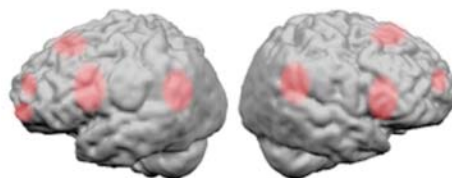
**Figure 11: Areas Activated During Numerical Comparison and Approximation.**

### Arithmetic

Dehaene's theory proposes that there are two primary representations of number: one for quantity manipulation and approximation and another language based representation used for exact arithmetic. We have discussed how comparison and approximation comprise a network of frontal and parietal regions. We now review where the processing of exact arithmetic is localized in the brain; however, this discussion will be clouded by a number of confounding factors. According to Dehaene and Cohen, "Mental arithmetic is intimately linked to language and to a verbal representation of numbers..." (1995, p. 89) Thus, teasing out the unique contribution of computation may be difficult. Also, in complex or in multiple-step calculations, the mental

processing related to computation are confounded with the need to store intermediate results, which may activate areas more closely related to working memory than to computation.

**Simple Computation** There are a number of locations in the brain that are commonly associated with simple computation, such as two operand addition, subtraction, multiplication, and division (Burbaud, et al., 1995; Cowell, Egan, Code, Harasty, & Watson, 2000; Dehaene, et al., 1999; Gruber, Indefrey, Steinmetz, & Kleinschmidt, 2001; Hayashi, Ishii, Kitagaki, & Kazui, 2000; Rueckert, et al., 1996; Zago, et al., 2001). In support of Dehaene's hypothesis that memorized tables are stored in areas that are commonly associated with language, there are areas in these locations active during simple arithmetic operations. These areas include a region between the temporal and parietal lobes, and an area in the lateral frontal lobes associated with syntactic and phonological processing. However, contrary to Dehaene's contention, activations in arithmetic operations appear to be distributed more bilaterally than would be expected during language processing and other researchers have found greater involvement of the parietal lobes than would be expected (Gruber, et al., 2001; Zago, et al., 2001). Zago and colleagues have suggested that these left parietal activations may reflect a finger counting representation (2001). Developmentally, almost all humans use a finger counting strategy for learning how to count. This left parietal activation which is also correlated with activation in an area of the frontal lobes associated with movement (the premotor area) may be the residual trace of initial learning during development (see Figure 12).



**Figure 12: Areas Activated During Numerical Comparison and Approximation.**

**Complex Computation** When problems involve a series of computations or multiple digit operands, Dehaene predicts that the additional cognitive demands will involve the coordination of visuo-spatial and language representations. Although there does seem to be an interaction between areas in the frontal lobes and areas in the lower portions of the parietal lobes in both simple and complex computation, it has not been shown that there are consistent activations across studies in other parietal regions. However, research in relational reasoning provides an indication that while simple two-operand problems may be solved using language areas, more complex three-operand problems may require a

visual strategy and involve activation in areas of parietal lobes related to problem visualization (Goel & Dolan, 2001). And, the study by Zago, et al., (2001) has also indicated the existence of a left parietal/frontal network maintaining multidigit numbers in visuospatial memory and a bilateral processing in the lower temporal lobes related to a visual resolution strategy. A better understanding of the dynamics and localization of complex computation will require additional research. However, we can estimate that the onset of computation occurs at approximately 230 ms and is well underway at 350 to 400 ms (Dehaene, et al. 1999; Niedeggen, Rosler, & Jost, 1999; Pinel, et al., 2001).

Although the exact interplay between frontal and parietal regions remains to be determined, it does seem clear that increasing complexity of computation tends to increase the amount of activation in the lower portion of the left frontal lobe known to support linguistic functions and working memory (Menon, Rivera, White, Glover, & Reiss 2000; Gruber, et al., 2001). Frontal areas may also be involved maintaining the goals and sub-goals involved in problem solving (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999). We hope and expect that future research will help to clarify the dynamics of mathematical neurocognition and its relation to reasoning and other thought processes.

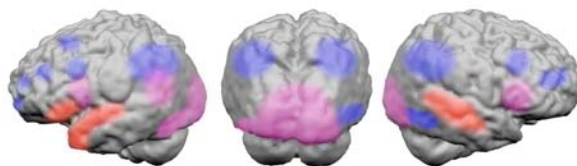
### Reading and Arithmetic: Similarities and Differences

If we use the same chronological approach in analyzing the progression of cognition in reading and mathematics, we can see that in the initial stages of visual processing activations are much the same. Visual processing of numerals and letters both activate the primary visual cortex and progresses to adjacent areas in the first 150 ms of processing

Because language processing structures much of human cognition, it has been proposed that many aspects of arithmetic processing is language related, and indeed we see many of the same areas active during reading and simple computation. Computation thought processes seem to occur at approximately the time as the initial processing of syntax, phonics, and semantics during reading, around 250 ms.

The unique activations observed in mathematical cognition appear related to spatial conceptualizations of quantities and mathematical relations; the activation of areas related to movement of fingers; and areas of the frontal lobes related to the maintenance of goals, sub-goals and intermediate results. The unique activations observed in the cognition of reading appear to be those related to semantics and comprehension. Initially it appears that reading and computation follow a ventral path from the occipital lobe into the temporal lobe. Numerical comparisons then appear to be routed into the parietal lobe, while processes related in the parsing

process during reading begin an interplay between left frontal regions and posterior regions related in syntactic, phonological, and semantic analysis. Perhaps the greatest difference in activation occurs for comprehension, but this may simply be because of the complexity of mathematical problems used in previous research; however there is an area in the right frontal lobe that is activated by both reading and mathematics, although its significance is not immediately obvious. We believe that it is likely that analogous activations will be observed in the right hemisphere for more complicated forms of mathematical cognition.



**Figure 13: Hypothesized Areas Activated by Reading and Math Cognition** Blue areas are predominately activated by mathematics cognition. Red areas are predominately activated reading cognition. Violet areas share activations common to both mathematics and reading.

### Implications for Educational Research

Although you may have found our description of the neurocognition of reading and mathematics interesting, you may still be asking yourself what value such information has for education. The answer lays in the directions and clues it provides for educational researchers, not in its direct applications. For instance, it appears that rote memory skills in mathematics are language based and more complex tasks may involve visual or spatial processing. If so, are there specific types of problems that benefit from visual/spatial orientations in instructional methods? Given that many simple math skills are language based how can they best be taught? These are questions for educational researchers that can be investigated using conventional research designs or research designs augmented with neuroscience methodologies (Atherton & Bart, 2001).

Neuroscience research also provides us with directions for research in reading instruction and theory. The research clearly shows that reading is a combination of top-down attentional processes and automated bottom-up processes. It may also indicate that there are multiple levels of comprehension, one operating at the sentence level and another operating at the story or paragraph level. The research may also call into question the representation of parsing proposed by traditional models in linguistics, which may have implications for instructional methods. And, although we have not directly covered dyslexia, neuroscience

research offer some visibility into what has been a black box. Research has shown that dyslexics show higher activation in the frontal lobes, implying an overcompensation for lower levels of activation in the posterior regions related to word recognition and processing (Pugh, et al., 2000).

Our prognosis for the application of neuroscience research to educational practice is then both optimistic and cautious. There is clearly room for misapplication and the vagaries of popular fashion (Bruer, 1999); on the other hand, if educational psychology strives to develop effective instructional methodologies, we should go directly to the source of cognition rather than remain on the outside looking in.

## References

- Abdullaev, Y. G., & Posner, M. I. (1997). Time course of activating brain areas in generating verbal associations. *Psychological Science, 8*, 56-59.
- Arnoldussen, A., Bookheimer, S., Manis, F., & Seidenberg, M., (2002, April). *Dyslexic subtypes: An fMRI study of reading pathways*. Poster session presented at the annual meeting of the Cognitive Neuroscience Society.
- Atherton, M. & Bart, W. M. (2001, April). *Education and fMRI: Promise and Cautions*. Paper presented at the annual meeting of the American Educational Research Association, Seattle, WA.
- Beeman, M. (1993). Semantic processing in the right hemisphere may contribute to drawing inferences from discourse. *Brain and Language, 44*, 80-120.
- Beeman, M. (1998). Coarse semantic coding and discourse comprehension. In M. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 255-284). Mahwah, NJ: Erlbaum.
- Beeman, M. J., Bowden, E. M., & Gernsbacher, M. A. (2000). Right and left hemisphere cooperation for drawing predictive and coherence inferences during normal story comprehension. *Brain & Language, 71*, 310-336.
- Bokde, A. L. W., Tagamets, M. A., Friedman, R. B., & Horwitz, B. (2001). Functional interactions of the inferior frontal cortex during the processing of words and word-like stimuli. *Neuron, 30*, 609-617.
- Bruer, J. T. (1999). In search of...brain-based education. *Phi Delta Kappan, 80*, 648-654.
- Burbaud, P., Degreze, P., Lafon, P., Franconi, J-M., Bouligand, B., Bioulac, B., Caille, J-M., & Allard, M. (1995). Lateralization of prefrontal activation during internal mental calculation: A functional magnetic resonance imaging study. *Journal of Neurophysiology, 74*, 2194-2200.
- Burton, M. W. (2001). The role of inferior frontal cortex in phonological processing. *Cognitive Science, 25*, 695-709.
- Burton, M. W., Small, S. L., & Blumstein, S. E. (2000). The role of segmentation in phonological processing: an fMRI investigation. *Journal of Cognitive Neuroscience, 12*, 679-690.
- Clark, V. P., Fan, S., & Hillyard, S. A. (1995). Identification of early visual evoked potential generators by retinotopic and topographic analyses. *Human Brain Mapping, 2*, 170-187.
- Cohen, L., Dehaene, S., Naccache, L., Lehericy, S., Dehaene-Lambertz, G., Henaff, M., & Michel, F. (2000). The visual word form area: Spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain, 123*, 291-307.
- Cohen, J. D., & Tong, F. (2001). Neuroscience - The face of controversy. *Science, 293*, 2405-2407.
- Coles, M. G. H., & Rugg, M. D. (1995). Event-related brain potentials: An introduction. In M. D. Rugg & M. G. H. Coles (Eds.), *Electrophysiology of mind: Event-related brain potentials and cognition* (pp. 1-26). New York: Oxford University Press.
- Cowell, S. F., Egan, G. F., Code, C., Harasty, J., & Watson, J. D. G. (2000). The functional neuroanatomy of simple calculation and number repetition: A parametric PET activation study. *NeuroImage, 12*, 565-573.
- Crozier, S., Sirigu, A., Lehericy, S., van de Moortele, P. F., Pillon, B., Grafman, J., Agid, Y., Dubois, B., & LeBihan, D. (1999). Distinct prefrontal activations in processing sequence at the sentence and script level: An fMRI study. *Neuropsychologia, 37*, 1469-1476.
- Dale, A. M., Liu, A. K., Fischl, B. R., Buckner, R. L., Belliveau, J. W., Lewine, J. D., Halgren, E. (2000). Dynamic statistical parametric mapping: Combining fMRI and MEG for high-resolution imaging of cortical activity. *Neuron, 26*, 55-67.
- Dapretto, M. & Bookheimer, S. Y. (1999). Form and content: dissociating syntax and semantics in sentence comprehension. *Neuron, 24*, 427-432.
- Dehaene, S. (1997). *The number sense*. New York: Oxford University Press.
- Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1*, 83-120.
- Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science, 284*, 970-974.
- Ferstl, E. C. & von Cramon, D. (2001). The role of coherence and cohesion in text comprehension: An event-related fMRI study. *Cognitive Brain Research, 11*, 325-340.
- Fiebach, C. J., Friederici, A. D., Muller, K., & von Cramon, D. Y. (2002). fMRI evidence for dual routes to the mental lexicon in visual word recognition. *Journal of Cognitive Neuroscience, 14*, 11-23.

- Fiez, J. A. (1998). Phonology, semantics, and the role of the left inferior prefrontal cortex. *Human Brain Mapping, 5*, 79-83.
- Fiez, J. A., Balota, D. A., Raichle, M. E., & Petersen, S. E. (1999). Effects of lexicality, frequency and spelling-to-sound consistency on the functional anatomy of reading. *Neuron, 24*, 205-218.
- Friederici, A. D., Wang, Y., Herrmann, C. S., Maess, B., & Oertel, U. (2000). Localization of early syntactic processes in frontal and temporal cortical areas: A magnetoencephalographic study. *Human Brain Mapping, 11*, 1-11.
- Fulbright, R. K., Jenner, A. R., Mencl, W. E., Pugh, K. R., Shaywitz, B. A., Shaywitz, S. E., Frost, S. J., Skudlarski, P., Constable, R. T., Lacadie, C. M., Marchione, K. E., & Gore, J. C. (1999). The cerebellum's role in reading: A functional MR imaging study. *American Journal of Neuroradiology, 20*, 1925-1930.
- Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R. (1998). *Cognitive neuroscience: The biology of the mind*. New York: W. W. Norton & Company.
- Goel, V. & Dolan, R. (2000). Anatomical segregation of component processes in an inductive inference task. *Journal of Cognitive Neuroscience, 12*, 110-119.
- Graesser, A. C., Millis, K. K., & Zwaan, R. A. (1997). Discourse comprehension. *Annual Review of Psychology, 48*, 163-189.
- Gruber, O., Indefrey, P., Steinmetz, H., & Kleinschmidt, A. (2001). Dissociating neural correlates of cognitive components in mental calculation. *Cerebral Cortex, 11*, 350-359.
- Hagoort, P., Brown, C. M., & Osterhout, L. (1999). The neurocognition of syntactic processing. In C. M. Brown & P. Hagoort (Eds.), *The neurocognition of language* (pp. 273-316). New York: Oxford University Press.
- Hahne, A. & Friederici, A. D. (1999). Electrophysiological evidence for two steps in syntactic analysis: Early automatic and late controlled processes. *Journal of Cognitive Neuroscience, 11*, 194-205.
- Hayashi, N., Ishii, K., Kitagaki, H., & Kazui, H. (2000). Regional differences in cerebral blood flow during recitation of the multiplication table and actual calculation: a positron emission tomography study. *Journal of the Neurological Sciences, 176*, 102-108.
- Helenius, P., Salmelin, R., Service, E., & Connolly, J. F. (1998). Distinct time courses of word and context comprehension in the left temporal cortex. *Brain, 121*, 1133-1142.
- Horwitz, B., Friston, K. J., & Taylor, J. G. (2000). Neural modeling and functional brain imaging: an overview. *Neural Networks, 13*, 829-846.
- Indefrey, P., Hagoort, P., Herzog, H., Seitz, R. J., & Brown, C. M. (2001). Syntactic processing in left prefrontal cortex is independent of lexical meaning. *NeuroImage, 14*, 546-555.
- Ivanitsky, A. M., Nikolaev, A. R., & Ivanitsky, G. A. (2001). Cortical connectivity during word association search. *International Journal of Psychophysiology, 42*, 35-53.
- Jackson, A. (1997a). The math wars: California battles it out over mathematics education reform (part I). *Notices of the AMS, 44*, 695-701.
- Jackson, A. (1997b). The math wars: California battles it out over mathematics education reform (part II). *Notices of the AMS, 44*, 817-823.
- Kang, A. M., Constable, R. T., Gore, J. C., & Avrutin, S. (1999). An event-related fMRI study of implicit phrase-level syntactic and semantic processing. *NeuroImage, 10*, 555-561.
- Khateb, A., Michel, C. M., Pegna, A. J., Thut, G., Landis, T., & Annoni, J. M. (2001). The time course of semantic category processing in the cerebral hemispheres: an electrophysiological study. *Cognitive Brain Research, 10*, 251-264.
- Koechlin, E., Basso, G., Pietrini, P., Panzer, S., & Grafman, J. (1999). The role of the anterior prefrontal cortex in human cognition. *Nature, 399*, 148-151.
- Le Clec'H. G., Dehaene, S., Cohen, L., Mehler, J., Dupoux, E., Poline, J. B., Lehericy, S., van de Moortele, P. F., & Le Bihan, D. (2000). Distinct cortical areas for names of numbers and body parts independent of language and input modality. *NeuroImage, 12*, 381-391.
- Long, D. L., & Baynes, K. (2002). Discourse representation in the two cerebral hemispheres. *Journal of Cognitive Neuroscience, 14*, 228-242.
- Martin, A. & Chao, L. L. (2001). Semantic memory and the brain: structure and processes. *Current Opinion in Neurobiology, 11*, 194-201.
- McIntosh, A. R. (1999). Mapping cognition to the brain through neural interactions. *Memory, 7*, 523-548.
- McIntosh, A. R. (2000). Towards a network theory of cognition. *Neural Networks, 13*, 861-876.
- Menon, V., Rivera, S. M., White, C. D., Glover, G. H., & Reiss, A. L. (2000). Dissociating prefrontal and parietal cortex activation during arithmetic processing. *NeuroImage, 12*, 357-365.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24*, 167-202.
- National Reading Panel. (2000). *Report of the National Reading Panel. Teaching Children to Read: An Evidence-Based Assessment of the Scientific Research Literature on Reading and Its Implications for Reading Instruction*. Washington, DC: National Institute of Child Health and Human Development Clearinghouse.
- Niedeggen, M., Rosler, F., & Jost, K. (1999). Processing of incongruous mental calculation problems: Evidence for an arithmetic N400 effect. *Psychophysiology, 36*, 307-324.

- Owen, A. M. (1997). The functional organization of working memory processes within human lateral frontal cortex: The contribution of functional neuroimaging. *European Journal of Neuroscience*, *9*, 1329-1339.
- Perfetti, C. A. (1999). Comprehending written language: A blueprint of the reader. In C. M. Brown, & P. Hagoort (Eds.), *The neurocognition of language* (pp. 167-208). New York: Oxford University Press.
- Pesenti, M., Thioux, M., Seron, X., & De Volder, A. (2000). Neuroanatomical substrates of Arabic number processing, numerical comparison, and simple addition: A PET study. *Journal of Cognitive Neuroscience*, *12*, 461-479.
- Pinel, P., Dehaene, S., Riviere, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *NeuroImage*, *14*, 1013-1026.
- Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review*, *103*, 56-115.
- Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *NeuroImage*, *10*, 15-35.
- Price, C. J. (2000). The anatomy of language: Contributions from functional neuroimaging. *Journal of Anatomy*, *197*, 335-359.
- Price, C. J., Moore, C. J., Humphreys, G. W., & Wise, R. J. S. (1997). Segregating semantic from phonological processes during reading. *Journal of Cognitive Neuroscience*, *9*, 727-733.
- Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J. R., Shaywitz, S. E., & Shaywitz, B. A. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities Research Reviews*, *6*, 207-213.
- Pulvermuller, F. (1999). Words in the brain's language. *Behavioral and Brain Sciences*, *22*, 253-279.
- Robertson, D. A., Gernsbacher, M. A., Guidotti, S. J., Robertson, R. R., Irwin, W., Mock, B. J., & Campana, M. E. (2000). Functional neuroanatomy of the cognitive process of mapping during discourse comprehension. *Psychological Science*, *11*, 255-260.
- Rueckert, L., Lange, N., Partiot, A., Appollonio, I., Litvan, I., Le Bihan, D., & Grafman, J. (1996). Visualizing cortical activation during mental calculation with functional MRI. *NeuroImage*, *3*, 97-103.
- Rumsey, J. M., Horwitz, B., Donohue, B. C., Nace, K., Maisog, J. M., & Andreason, P. (1997). Phonological and orthographic components of word recognition. A PET-rCBF study. *Brain*, *120*, 739-759.
- Sakai, K. L., Hashimoto, R., & Homae, F. (2000). Sentence processing in the cerebral cortex. *Neuroscience Research*, *39*, 1-10.
- Schendan, H. E., Ganis, G., & Kutas, M. (1998). Neurophysiological evidence for visual perceptual categorization of words and faces within 150 ms. *Psychophysiology*, *35*, 240-251.
- Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: Evidence from eye movements and event-related potentials. *Neuroreport*, *9*, 2195-2200.
- Snyder, A. Z., Abdullaev, Y. G., Posner, M. I., & Raichle, M. E. (1995). Scalp electrical potentials reflect regional cerebral blood flow responses during processing of written words. *Proceedings of the National Academy of Sciences of the United States of America*, *92*, 1689-1693.
- Shapiro, K. A., Pascual-Leone, A., Mottaghy, F. M., Gangitano, M., & Caramazza, A. (2001). Grammatical distinctions in the left frontal cortex. *Journal of Cognitive Neuroscience*, *13*, 713-720.
- St George, M., Kutas, M., Martinez, A., & Sereno, M. I. (1999). Semantic integration in reading: Engagement of the right hemisphere during discourse processing. *Brain*, *122*, 1317-1325.
- Stanescu-Cosson, R., Pinel, P., van de Moortele, P. F., Le Bihan, D., Cohen, L., & Dehaene, S. (2000). Understanding dissociations in dyscalculia - A brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation. *Brain*, *123*, 2240-2255.
- Tarkiainen, A., Helenius, P., Hansen, P. C., Cornelissen, P. L., & Salmelin, R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain*, *122*, 2119-2131.
- Tyler, L. K., Russell, R., Fadili, J., & Moss, H. E. (2001). The neural representation of nouns and verbs: PET studies. *Brain*, *124*, 1619-1634.
- Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Engle, M. A. Goodale, & R. J. Mansfield (Eds.), *Analysis of visual behavior* (pp. 549-586). Cambridge, MA: MIT Press.
- Walsh, V., & Cowey, A. (2000). Transcranial magnetic stimulation and cognitive neuroscience. *Nature Reviews Neuroscience*, *1*, 73-79.
- Zago, L., Pesenti, M., Mellet, E., Crivello, F., Mazoyer, B., & Tzourio-Mazoyer, N. (2001). Neural correlates of simple and complex mental calculation. *NeuroImage*, *13*, 314-327.