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Full Length Research Paper

Brain research and reading: How emerging concepts in neuroscience support a meaning construction view of the reading process

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Emerging concepts from the neuroscientific study of brain function both support and are supported by psycholinguistic research on the reading process. These concepts challenge the claim that brain imaging studies have demonstrated the primacy of phonological processing in reading. While such studies do indeed show that brain imaging technology is sensitive enough to detect sites of increased neural activity during phonological processing, this finding is consistent with both phonics and meaning based models. This is because both models recognize that phonological processing is part of the reading process. Unfortunately, subjects in the various brain imaging studies have not been given phonological processing tasks embedded in a context that requires meaning construction. So while this kind of study could, in principle, distinguish between the two models, it remains to be carried out. In order to better understand how contemporary neuroscience bears on models of the reading process, we therefore turned from neuroimaging studies to current research on how the cortical, "thinking" areas of the brain interact with the brain's deeper, sensory processing structures. The emerging concepts from this research clearly indicate that the higher cortical structures control the transmission of information from the deeper structures. This interpretation is contrary to the classical teaching, in which deeper sensory relay stations determine what will eventually reach the cortex. The emerging view has profound implications for psychological models of mental life. Whereas the classical neuroanatomic view is most consistent with a bottom-up, information processing model, the emerging view supports an interactive, constructivist model. The cortex either promotes or inhibits the very input being transmitted to it from the eyes, ears, and other sensory receptors. The psychological interpretation of this neuroanatomic arrangement is that the cortex selects evidence to confirm or disconfirm its predictions. It anticipates what will be seen and heard using knowledge stored in memory. Both this new neuroanatomical view and its psychological reflection are consistent with a transactional socio-psycholinguistic model of reading. Drawing on extensive comparisons of expected and observed responses from oral reading miscue studies, this model of reading emphasizes the fundamental importance of effective and efficient prediction and confirmation in the construction of meaning. Eye movement analysis, a widely used reading research tool for over a century, simultaneously supports the emerging neuroscientific view of cortical control and the meaning construction model of reading. Since the most conspicuous motor behavior in silent reading is eye movement, studying it allows us to "see" the silent reading process. When combined with miscue analysis from oral reading, it is clear that cortical instructions tell the eyes where to look for cues from the signal, lexico-grammatical, and semantic levels of language. We conclude that emerging neuroscience provides evidence for the meaning-construction view of reading, and that the transactional socio-psycholinguistic character of reading is an instantiation of the memory-prediction model of brain function.

Key words: Reading, neuroimaging, phonological processing, miscue analysis, eye movement, whole language.

INTRODUCTION

Reading and biology

Over the past two decades, the neuroanatomical study of reading has been a prominent and widely popularized area of scientific research. Using computer enhanced, multi-colored pictures of the living brain in action, created from highly sophisticated neuroimaging machines, some scientists have concluded that this research has revolutionized our understanding of what the brain does during reading and, by implication, how to help children learn to read.

One of the leading figures in this area of research is Yale pediatrician Sally Shaywitz. Commenting on her own neuroimaging investigations of reading, Shaywitz stated: "The field of neuroscience is exploding. Recent advances in our understanding of the brain mechanisms underlying reading are nothing short of revolutionary" (Shaywitz, 2004). And with her colleagues, she commented on the implications of this work: "Society is on the cusp of a true revolution in its ability to use science to inform public policy– a revolution in which biological discoveries serve the health and education of our children" (Shaywitz et al., 1996).

According to this line of research, neuroimaging studies, by focusing on the conversion of letters to sounds, have elucidated the fundamental role played by "phonological processing" in reading and reading instruction. The mainstream media have trumpeted this point of view. "The brain reads sound by sound" declared a front page headline of the Baltimore Sun (November 3, 1997).

The Sun continued: "Scientists can now watch what goes on in children's brains as they read. When the lights go on, it confirms an old theory: We learn to read by linking letters with sounds."

This is, infact, an erroneous conclusion by the Sun. Even Shaywitz herself has pointed out that her neuro-imaging research on reading presupposes the correct-ness of the phonological processing model: "This discovery, isolating phonological processing as the core cognitive deficit in dyslexia, was an essential prerequisite to the study of the neural basis of the disorder. Once phonological processing had been identified, scientists knew just *what* to study; they knew on which particular cognitive system (linguistic) and on which component of that system (phonological processing) to focus in their search for the neural locus of dyslexia" (Shaywitz et al., 1996).

In other words, the correctness of the phonological processing hypothesis is built into the neuroimaging research as a premise. Neuroimaging research on reading has assumed the correctness of the phonological processing model, and has in no way confirmed it. But the Sun is indeed correct in noting how expensive it has been to support a very old theory with modern technology. The "high-tech porthole" to the brain "builds upon millions of dollars of research, conducted over the past 20 years under the aegis of the National Institutes of Health in Bethesda, that has documented similar conclusions: Children need to understand the sounds of the English language and sound-letter relationships known as 'phonics', before they can learn to read. For some, this comes naturally; others must be taught" (emphasis added).

"By contrast," stated the Sun, "whole language approaches reading instruction from the opposite direction," that is to say, opposite from what has been confirmed to be correct.

Along the same lines, Shaywitz criticizes whole language for its supposed anti-biological stance. She declared that "self-appointed opinion makers ascribe children's reading problems entirely to sociological or educational factors and totally deny the biology" (Shaywitz, 2004). But Shaywitz's biology of reading is repleted with inconsistent claims and with principles that have no precedent. Her very definition of reading and dyslexia exposes one of the more serious flaws in her biological model. For example, Shaywitz defines dyslexia as a disorder of reading not explained by other disorders of cognitive functioning. It is "unexpected for a person's age, intelligence, level of education, or profession" (Shaywitz, 2004). And, approvingly quoting Reid Lyon and the International Dyslexia Association, she adds that dyslexia "typically result[s] from a deficit in the phonological component of language that is often unexpected in relation to other cognitive abilities and the provision of effective classroom instruction".

This approach to conceptualizing the phenomenon of reading and reading disorders is grounded in the associated position that written language is artificial, and that the brain is hard-wired to process oral language, not written language. This means, according to Shaywitz, that written language must first be converted to oral language. "The reader must somehow convert the print on a page into a linguistic code—the phonetic code, the only code recognized and accepted by the language system" of the brain. Having been "translated into the phonetic code, printed words are now accepted by the neural circuitry already in place for processing spoken language. Decoded into phonemes, words are processed automatically by the language system".

Now consider Shaywitz's claim that "[r]ecent studies have shown that not only does dyslexia run in families but it is carried as a genetic trait". The gene (or genes) allegedly places a child carrier at higher risk for dyslexia. In a typical study, co-authored by Shaywitz, dyslexic subjects are identified on the basis of screening for a disorder of phonological processing and neuroim-aging studies "are consistent with the latest clinical im-aging data" (Meng et al., 2005).

But if the brain is not hard-wired for written language, why should there be a gene for a disorder of written language processing? If the gene is therefore not specific to

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written language, but can manifest itself in other areas of cognitive processing, then the subjects presumably have affiliated cognitive disorders and thus do not satisfy Shaywitz's definition of dyslexia.

Perhaps worse than an incomprehensible definition of reading and dyslexia is the fantastic claim about the power of intensive phonics instruction to fix a dysfunctional brain. She maintains, for example, that this has been demonstrated by reading research using neuroimaging technology: "We used fMRI (functional magnetic resonance imaging, SGP) to study boys and girls who were struggling to learn to read and who then received a yearlong experimental reading program. The final set of images obtained one year after the intervention had ended was startling. Not only were the right-side auxiliary pathways much less prominent but, more important, there was further development of the primary neural systems on the left side of the brain....[T]hese activation patterns were comparable to those obtained from children who had always been good readers. We had observed brain repair" (Shaywitz, 2004).

This, of course, should be a scientific achievement of such monumental theoretical and educational import as to demand attention from the entire society of neuroscientists and neurologists. But in response to an article by Simos et al. (2002), in which intensive phonics instructtion was similarly claimed to be responsible for improvements in functional brain imaging, commentators for the internationally respected journal *Neurology* observed that "reservations may be in order" that "a 'deficit in functional brain organization' has been 'reversed' by remedial training." Since remedial instruction leads dyslexic children to do "what normal readers do naturally," the study merely demonstrates "that the subject is doing something different (or differently)" (Rosenberger and Rottenberg, 2002). Explaining the neuroimaging findings in no way necessitates the thoroughly unprecedented hypothesis that the brain has been repaired.

These profound problems in the phonological processsing model of reading and the brain are serious enough to raise concerns about its claims, if not reject the model altogether. Infact, we maintain that a meaning-centered, whole language model of reading is scientifically superior to the phonological processing model from the standpoint of neurobiology.

Neuroscience has for quite some time been aware of many examples of brain functioning that demonstrate the importance of "top-down" cerebral processing. Such examples continue to multiply, as researchers are clearly not letting narrow, "bottom-up" psychological paradigms get in the way of scientific progress.

Visual processing and attention in visual space is the most firmly established area of brain research in which "top-down" influences clearly play a significant, if not dominant role. For example, it is well known that a natural, physiologic "blind spot" occupies the near center of the visual field in normal vision, a consequence of the neural structure of the retina. Yet the brain's higher centers fill in this blind spot through mechanisms that create the illusion of a continuous, uninterrupted visual display (Pessoa and De Weerd, 2003).

Similarly, quick glancing eye movements, known as saccades, and generated in the course of ordinary observation of a visual scene, are only able to project those images to the brain's integrative visual centers that correspond to points of eye fixation. During actual eye movements from one fixation point to another, no image is created. Yet the brain interprets the scanning as a visual image continuous in space and time, not interrupted by the actual blank periods. Again, visual image appears without corresponding sensory input.

The role of attention in providing top-down cortical control on lower level visual processing has also been well-investigated. In a representative study, Doherty et al. (2005) tested the reaction times of subjects asked to follow a moving image and predict the location and timing of its reappearance after occlusion behind a visual barrier. They found that reaction times shortened significantly and synergistically when the subject could predict both when and where the object would reappear.

More importantly, they found that the first positive deflection (P1) on electroencephalographic recordings of the test sessions showed significant enhancement when the target could be spatially predicted, but not when it could be temporally predicted. However, even though temporal expectation alone did not enhance the P1 response, it potentiated the response in the setting of spatial predictability. The authors concluded that "this demonstrates that temporal information can access perceptual analysis through top-down pathways when spatial information is also present".

In a review of recent neuroscience research on how the brain processes sensory information, Gilbert and Sigman (2007) point out that response of neurons in the visual cortex are dependent upon the context in which an object appears. For example, "a single oriented line segment will elicit a brisk response from a neuron when the appropriately oriented line is placed within a small part of visual space, that neuron's receptive field".

However, "when the line is embedded within a complex background of randomly oriented and positioned line elements, the neuron's response is substantially inhibited. If one shifts the elements from the background into alignment with the line within the receptive field, the neuron's response becomes greatly facilitated".

Based on these and a number of other examples, Gilbert and Sigman (2007) conclude that "both anatomic and physiologic evidence shows that even at the earliest stages of cortical processing neurons can integrate information over large areas and that they can be endowed with selectivity for complex shapes". More gene-rally, they conclude that "any cortical area is an adaptive processor. Rather than performing a fixed and stereotyped operation on input coming from the retina, it makes different calculations according to the immediate sensory and behavioral context. The construction of a subjective percept involves making the best sense of sensory inputs based on a set of hypotheses or constraints derived by prior knowledge and contextual influences". Therefore, top-down and bottom-up neural mechanisms are of equal importance, allowing Gilbert and Sigman to draw the profound conclusion that "there is no starting point for information flow".

These emerging concepts in neuroscience are clearly both relevant and crucial to deliberations on the most important questions in the theory and instructional practice of reading. They demand that a strictly bottom-up view of reading be challenged, since what is true of the general organization and functioning of the brain must hold true for its various activities, including reading.

In the discussion below, we take up this challenge in a two-pronged manner. We argue that the alleged superiority of the phonics model of reading has in no way been confirmed, supported, or justified by neuroimaging research, certainly its strongest and most widely touted card. This research is, infact, quite neutral with respect to the phonics and whole language models, and can be invoked to support either one.

We also discuss those emerging neural concepts from top-down processing studies that are contributing to the construction of an empirically-based model of how the brain predicts and then confirms or disconfirms its predictions. These are the central psychological processes of a meaning-construction model of reading. It will become clear that, far from denying biology, whole language instead contributes to freeing the field of neuroscience from its bottom-up psychological shackles. In turn, it is supported by recent thinking among neuroscientists. The way this has occurred is itself a lesson in how distinct areas of science can fertilize and enrich each other.

In the end, therefore, and contrary to the claims of the phonological processing model, whole language, alone of the two, is supported by linguistics, sociology, education, and biology.

Brief overview of emerging concepts in neuroscience and their implications for reading

As a scientific paradigm, whole language is based on a psycholinguistic model of the reading process, along with corresponding methods of classroom teaching and assessment. The model characterizes reading as an active process of meaning-construction brought about via the reader's selective testing of meaning-based predictions against confirmatory or disconfirmatory textual and non-textual material. Confirmed predictions are incorporated into the reader's expanding mental representation of meaning. Disconfirmed predictions are modified or discarded. Inconclusive predictions are tentative and await further confirmatory or disconfirmatory evidence (Goodman, 1996).

To the extent that mental processes like predicting and confirming/disconfirming are supported by the facts of reading, it must then follow that they therefore represent the psychological reflection of specific brain processes. This principle applies to each and every psychological mechanism of reading, and is precisely what supporters of phonological processing maintain when they search for brain sites that correspond to letter-sound conversion.

But until the field of neuroscience discovers how the brain predicts, confirms, and disconfirms, it can be said that this branch of psychology anticipates the neurology. The neuroscientific research agenda must include a search for those aspects of brain anatomy and physiology that can perform these psychological acts. In general, and in so far as it is the study of brain function, psychology is therefore one of the driving forces of neuroscience.

Infact, over the past few years, a number of brain scientists have reached new conclusions about the physical organization of the brain. In order to explain a range of puzzling facts, they are beginning to recognize that the higher structures of the brain, those involved with thought and reasoning, actually control the lower structures, those involved in collecting sensory input from the environment. This is contrary to traditional teaching in neurology, which instead sees sensory input as triggering the activation of higher, cortical structures. The emerging view is that the brain can first activate the higher structures, and only afterwards use the psychological entities generated by these structures to guide the selection of sensory input collected and made available by the deeper structures (Hawkins, 2004).

This is the true revolution taking place in neuroscience, though still admittedly young and merely inchoate, and likely to generate considerable debate. This is the area of neuroscience that reading researchers and practitioners should be paying close attention to.

A neuroscientist compelled by the anatomic and physio-logic facts to conclude that higher structures control the lower ones will be at a distinct scientific disadvantage if there is no extant psychological model of some aspect of human mental life whose processes correspond to this new anatomical and physiological perspective. This is not to say that the new biological perspective is for that rea-son incorrect, only that the possibility of drawing on existing psychological principles, like predicting and confirming/disconfirming, provides it with legitimate and independent plausibility.

Neuroscientists who are now proposing a reformulation of the relationship between higher cortical structures and deeper regions of the brain are moving their field of study forward, since the traditional view, in which the brain works by having deeper regions feed information about the environment to the cortex, is simply unable to explain a number of stubborn and well-known facts. Such facts are efficiently accounted for by the new perspective.

Meaning-centered models of reading function as a scaffold for this scientific progress by providing independent confirmation from psychology to the emerging understanding of anatomic and physiological organization of the brain. In this sense, whole language is wholly consistent with biology.

Neuroimaging research on reading: nearly cueless

If neuroimaging studies of reading begin with the premise that reading is matching letters to sounds, then the fundamental research question is not to find out whether reading is the matching of letters to sounds, but rather whether brain sites exist where this matching occurs. The answer to this question has been affirmative.

But since any psychological phenomenon, such as phonological processing, is rooted in cerebral anatomy and physiology, neuroimaging studies of reading simultaneously pose another fundamental question, namely, whether the technology is sensitive enough to detect this special anatomy and physiology. It may or may not be. If the special brain sites lie outside the temporal and spatial resolution capacity of the technology, as it would, say, with an ordinary pocket camera, then the psychological process can still be considered real even though the technology is physically unable to detect it. In this case, we would simply conclude that the technology, despite being very expensive, is still relatively primitive.

Indeed, it should be clear that the phonological processing model is a psychological model. Letters are not really turned into sounds. This could only occur by magic. If the model is correct at all, it is only because mental representations of letters transform into mental representations of sounds. Neuroimaging research of this psychological model fully expects to find neuroanatomic correlates. It is simply a matter of finding the right technology to do it.

But suppose it was not the case that reading is simply matching letters to sounds. Subjects could still be given tasks of phonological processing, and neuroimaging machines would still show us where the mental letters were turning into mental sounds. How would we now interpret this?

The answer to this question depends on how we understand the role of letter-sound conversion in reading. In a hypothetically extreme position, letter-sound conversion might play no role whatsoever in reading, nor in any other functionally significant psychological process. In this case, the neuroimaging studies would be about whether the technology was sensitive enough to find out which regions of the brain were recruited to carry out this otherwise useless task.

In a typical imaging experiment, subjects are presented, while in a magnetic resonance imaging (MRI) machine, with pronounceable non-words, like *lete* and *jeat*, or *moab* and *haib* (Shaywitz, 2004), and asked to press 'Yes' or 'No' on a console indicating whether or not the words rhyme. The MRI machine now detects those parts of the brain that undergo a detectable depletion of oxygen, which implies a heightened level of metabolic activity, which in turn implies a spike in electrical activation of neuronal cells.

In this indirect way, the researchers claim to have found those parts of the brain that are specifically recruited to "sound out" letters. Without disputing this particular finding, we are still no closer to an understanding of where reading occurs in the brain. We only know where sounding-out occurs, and the only truly significant result of such experiments is the finding that magnetic resonance imaging is a piece of technology powerful enough to identify regions of the brain used for letter-sound processing.

Such experiments are completely neutral with respect to the various competing models of reading. This is because meaning-centered models do not deny that letter-sound connections play a role in proficient reading of alphabetic languages (Goodman, 1996). Therefore, when proficient readers are shown isolated letter strings like *jeat*, advocates of meaning construction views have no theoretical problem in expecting that they will recruit their knowledge of graphophonic relationships in order to sound out the word. They have not been asked to make sense of *jeat,* nor have they been given enough information to construct meaning. In the absence of any authentic linguistic context, neither semantic nor syntactic information is available to the research subject.

In other words, an advocate of reading as meaning construction could devise precisely the same experiment in order to test the hypothesis that magnetic resonance imaging is a powerful enough piece of technology to detect those sites in the brain that are recruited for graphophonic processing. Neuroimaging findings are entirely consistent with the whole language model, and in no way distinguish the whole language model from the phonological processing model.

The neuroimaging experiment that needs to be done in order to justify the phonics position has simply not been done. This would involve presenting subjects with a word already embedded in an authentic linguistic context. The context could be piped into headphones, for example. The target word could then follow, flashed on the MRI screen in typical fashion.

In this manner, a proficient reader would demonstrate the validity of the phonics model if he or she typically excited neurons in the sounding-out regions of the brain prior to activation of the more syntactic and meaning-based areas. This is because phonics advocates claim that words must first be sounded out before they can be identified, and therefore before their syntactic and semantic properties can be retrieved from the brain's mental lexicon. In other words, the phonics position would be confirmed if, despite the availability of other cuing systems, proficient readers still reached first for the letter-sound rules. But the phonics position would be refuted if proficient readers typically shunned sites of letter-sound processing and opted instead for sites more directly concerned with meaning. Since whole language claims that authentic text provides the proficient reader with a variety of cuing systems, and that the relatively inefficient graphophonic cuing system is not fully utilized, such a finding would directly support the whole language model.

Principles of whole language

A brief review of some whole language principles of reading will make this obvious. Over the last half century, and with roots that go back much farther than that, reading miscue research has revealed that reading is a far more complex process than matching letters to sounds. It is a socio-psycholinguistic process of making sense of written language, parallel to and using much the same resources as oral language (Goodman, 1996).

This research on real readers reading real, authentic written texts has shown that readers simultaneously use three cuing systems. These are the graphophonic cuing system (the system of written symbols and their relationships to the phonology in alphabetically written languages), the syntactic, and the semantic or meaning system. These three systems correspond roughly to what functional-systemic linguist Michael Halliday calls the strata of language: the signal system, the lexico-grammatical, and the semantic. Halliday places the wording of language in the same middle level with the syntactic since wording depends on syntax and syntax depends on wording (Halliday, 1985).

In 1967 Goodman characterized reading as a psycholinguistic guessing game- a process whereby the reader generates predictions and inferences, forming hypotheses and then disconfirming or confirming, and correcting as necessary, to construct meaning while transacting with the written text. The research methodology used in building this view he called miscue analysis. He found that in oral reading all readers produce miscues, points where what they are observed to say (the observed response, OR) does not match the expected response (ER) to the written text. His assumption was that miscues result from the same processes that produce expected responses, and that by carefully comparing ER with OR the process by which readers construct meaning would be revealed (Goodman, 1967).

Effective reading is making sense of print. Efficient reading is doing so using the least amount of time, energy, and visual input to be effective. So readers are selective, sampling from the visual input to construct perceptions based on their tentative predictions and using subsequent input to confirm or disconfirm as they construct meaning.

If reading were merely the conversion of letters to sounds, and if comprehending proceeded only after this conversion on the basis of ordinary principles of oral language comprehension, as Shaywitz has claimed (2004), then reading, technically speaking, is not really language. It is a low-level decoding process that gets the reader from written language into the supposedly more natural world of oral language.

Whole language rejects this view. Low-level decoding is an extremely inefficient cuing system, yielding far less in return for each psychological effort than high-level intelligent guessing, that is, than predicting based on syntax and semantics. And making sense is not unique to reading, it is the nuts and bolts of oral language use as well. Fundamentally, reading is as much a language process as speaking and listening.

Infact, making sense is not unique to language. We make sense of visual scenes, the sounds of nature, even the sensations from internal organs of the body. Therefore, the way the brain makes sense of print must be representative of how the brain makes sense of everything else. It hypothesizes, then seeks evidence to confirm or disconfirm.

Clearly, general processes like predicting and testing the predictions apply to all meaning-making events. They will differ in their particulars, more specifically, in their cuing systems. The cuing systems of oral language include semantics, syntax, and sound patterns. The cuing systems of alphabetic written language include semantics, syntax, and letter patterns. The cuing systems of visual interpretation include shapes, orientation, movement, and so on (Hoffman, 1998). The next step for a neuroscience based on higher structures controlling lower ones is to elaborate the various cuing systems of psychological life and how these fit into the general, overarching capacity of the brain to manipulate cuing systems in the service of making sense of the world. A successful effort in this endeavor will hark back to the psychologist and reading researcher Edmund Huey, who said, more than a century ago, that if we understood reading we would understand the basic functioning of the human mind (Huey, 1908, 1968).

In written language comprehension, therefore, graphophonic relationships constitute one of a number of cuing systems, and far from the most efficient. A proficient reader hardly needs to sound out the first word of the page when the last line of the preceding page ends with “January is the first month of the...” Syntax and semantics fill in the blank immediately. A reader who requires more confirmatory evidence, to make sure, for example, that the next word is not ‘new’, as in “January is the first month of the new millennium,” may need to identify only the first letter of the next word to make this distinction. Matching letters to sounds, one-to-one, is very inefficient because of the unnecessary time and energy it takes away from meaning making.

Still, it is one of the cuing systems available to a proficient reader, and that is precisely why the neuroimaging studies of phonological processing do not decide between phonics and whole language.

Eye movement research

Studying oral reading miscues requires reading aloud. Therefore, any inferences about silent reading from re-

research done on oral reading would require the additional demonstration that the reading process for oral reading is essentially the same as for silent reading.

Eye movement research is ideally situated to help demonstrate whether the conclusions of oral reading miscue studies can be validly generalized to silent reading, or, more specifically, whether the transactional socio-psycholinguistic model of reading, based on oral reading miscue analysis, also explains the properties of strictly silent reading. This is because the most conspicuous motor activity of silent reading is eye movement, which implies that a detailed analysis of eye movement patterns allows us to “see” the process of silent reading in action. Indeed, research over more than a decade, in which subjects silently read authentic text, but where the reading process can still be inferred via a careful analysis of the reader’s eye movements, has confirmed the fundamental principles of the socio-psycholinguistic model (Paulson and Goodman, 2008). For example, instead of reading proceeding on a letter-by-letter or word-by-word identification process, more than a century of eye-movement research has demonstrated that readers never look at every word in a text, infact, "at least 20 to 30% of the words in text are skipped altogether" (Rayner, 1997). This word skipping is not a haphazard, random activity, however. Content words, for example, are fixated to a greater degree than are function words (Just and Carpenter, 1987). And the words that are skipped will vary greatly between readers because it is individual readers' own context-driven predictions that allow them to skip words while reading, as discussed in several research reports (Balota et al., 1985; McClelland and O'Regan, 1981; Rayner and Well, 1996).

Of the three regions of viewing information the eye provides during a fixation—foveal, parafoveal, and peripheral—only the first provides the brain with in-focus information; visual acuity in the latter two fields drops off rapidly. The foveal region is the area of vision that is in focus, and subsumes 1 - 2 degrees of visual angle, or about 3 - 6 letter spaces around the point of fixation. The parafoveal region extends about 24 - 30 letters around the point of fixation, and the peripheral region includes everything in the visual field beyond the parafoveal region (Just and Carpenter, 1987). Thus, the farther away from the fovea an object is viewed, the more difficult it is to identify it. What this means for reading is that when letters are viewed within the fovea, they are physiologically able to be accurately discerned by the reader, and when letters are viewed outside the fovea the reader can see shapes but not distinguishable, in-focus letters. These physiological limitations are important in under-standing what the location, duration, and direction of eye fixations reveal about reading processes.

Predictions of semantic and syntactic context allow the brain to use the out-of-focus information outside the fovea to perceive the words they skip (Ehrlich and Rayner, 1981; Rayner and Well, 1996) and still feel as though they have clearly seen and read every word in the text. In addition, those words that are fixated are not necessarily looked at in the order they are presented in the text, since about 10 - 20% of fixations are regressions (Rayner and Pollatsek, 1989), meaning that readers' eyes proceed from right to left through a previously viewed section of text.

Eye movement research has also demonstrated that readers do not proceed through text on a predetermined, regular time schedule: the variability in fixation duration can be significant, and there is considerable between-reader and within-reader variability in the amount of time a reader spends looking at a word (Paulson, 2005; Rayner, 1998).

In short, eye movement research provides powerful evidence that readers utilize prediction and hypotheses consistently and constantly as core parts of reading processes.

The brain is not dependent on the eyes to provide all the possible textual information to the brain. Rather, the eyes are in the service of the brain while the reader is constructing meaning. If the brain has no need for textual information in a specific area—for example, if there is a strong hypothesis that the next word will be a determiner that carries only grammatical information in the text—then the brain can direct the eyes to skip that word and go to the next area in which textual information is needed.

All this clearly supports a view of the brain as predicting visual input before it is actually encountered. As Krauzlis (2005) has pointed out, recent work in the neurobiology of eye movement has shown that contrary to the “traditional” understanding, in which “eye movements have been viewed as distinct systems that are driven automatically by low-level visual inputs,” they actually “are not automatic responses to retinal inputs but are regulated by a process of target selection that involves a basic form of decision making. The selection process itself is guided by a variety of complex processes, including attention, perception, memory, and expectation” (Krauzlis, 2005). Patterns of eye movements are selective and purposeful, organized around the construction of meaning, not letter identification (Paulson, 2005; Paulson and Freeman, 2003).

Brain research and the whole language model of reading

Neuroimaging studies of reading have been proclaimed as providing phonics-based models, and no others, with suportive evidence from hard core science. We are supposed to believe that research from biology and neuroimaging trumps arguments based on linguistics, psycholinguistics, and the use of their principles to study how readers read real, authentic, meaningful texts.

Conversely, important new work in neuroanatomy and neurophysiology provides striking evidence that vindicates the fundamental prediction-based principles of

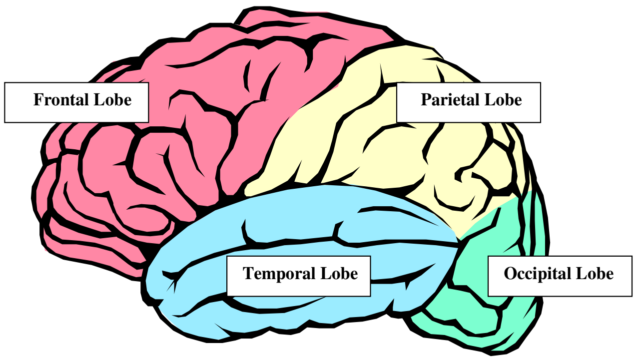

Figure 1. The outer cortical surface of the human brain (left hemisphere).

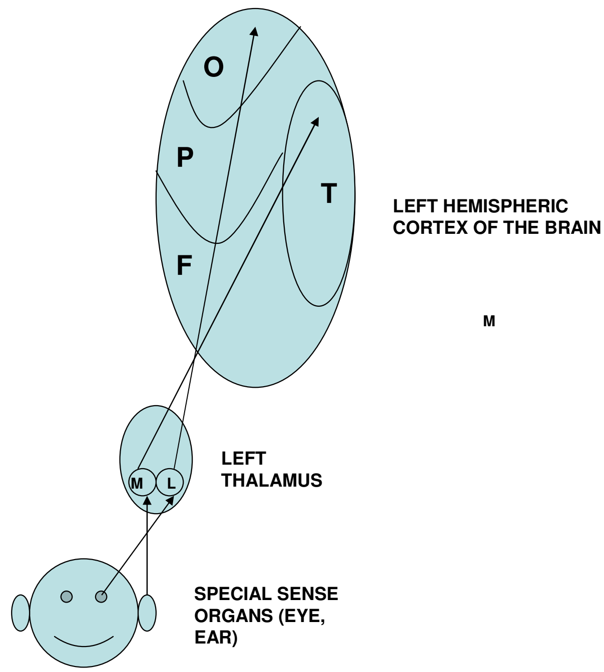

Figure 2. Sensory transmission from special sens organ to thalamus to cortex. M = medial geniculate nucleus, L = lateral geniculate nucleus, F = frontal lobe, P = parental lobe, O = occipital lobe, T = temporal lobe.

meaning-centered models of reading. Neuroscientists are beginning to unravel how the active brain formulates predicttions and then searches for sensory information that confirms or disconfirms its predictions. This research supports the conclusion that the view of reading as meaning construction is consistent with the basic way the brain constructs meaning in all contexts.

Neuroscience can now be added to the researcher's and practitioner's toolkit to justify viewing reading as a psycholinguistic guessing game, as Goodman demonstrated forty years ago and supported through his analysis of oral reading miscues (Goodman, 1967). Moving through the text, the proficient reader constructs tentative meanings. The tentativeness of these meanings indicates that they are, at the same time hypotheses about meaning. As hypotheses, they need to be tested against perceptions being formed mentally. These perceptions may or may not cohere with the whole, so the proficient reader is continually accepting, discarding, or correcting tentative meaning hypotheses. In reading, as in every other mental process, the brain is not the prisoner of the senses. Rather, it controls and uses the sensory organs to provide the inputs it is seeking.

Until recently, cognitive notions such as prediction and confirmation lay wholly in the world of psychology. Even among those whose psychology requires a material basis, the areas of the brain that could be pointed to as playing a role in predicting and confirming had to await further research.

But emerging concepts in neuroscience are leading to a new understanding of the relationship between the cerebral cortex and deeper brain structures in such a way that the cerebral basis of prediction and confirmation is becoming increasingly clear. In particular, predictions and confirmations have been shown to be psychological phenomena rooted in a special relationship between the cortex and deeper brain structures.

The cortex of the brain lies mainly on its outer surface. Under the microscope, the cortex can be seen to consist of numerous cell bodies arranged in six layers. The cell bodies are actually the heads of neurons, or nerve cells, each of which continues as a narrow, long wire, or axon, as it descends into the substance of the brain that lies below the surface.

Traditionally, the human cortex is divided into distinct lobes (Figure 1). The right and left occipital lobes, in the rear of the brain, receive visual information from the eyes. The right and left parietal lobes receive sensory information, such as pain, touch, and temperature, from the body. The right and left temporal lobes, or at least their posterior portions, receive auditory information from the ears.

The right and left frontal lobes exhibit at least two distinct functions. The portion of the frontal lobes that lie just anterior to the parietal lobes exert direct control over the various muscles of the body. But the portion of the frontal lobes even more anterior exhibit what is traditionally called an "executive function."

The executive function refers to mental activities such as planning and decision-making. These can remain in the domain of thought, or they can manifest themselves through motor activity, such as walking, talking, and moving one's eyes.

Deep in the brain, just above the brain stem, lies the thalamus. Joined at its inferior midline, the thalamus branches into a right and left portion. With the exception of olfactory sensation, every sensory modality travels through the thalamus on its way to the cortex (Figure 2).

For example, auditory input travels from the ear along the auditory nerve to the medial geniculate nucleus of the thalamus. From there, "relay" neurons transmit the auditory signal to the posterior temporal lobes.

Similarly, visual input travels from the eye along the optic nerve to the lateral geniculate nucleus. From there, "relay" neurons transmit the visual signal to the occipital lobes.

For many years, the thalamus has been thought of as a gating mechanism that selects sensory inputs for passage to the higher cortical regions. Once in the cortex, the sensory information is processed into more and more abstract entities, so that scenes are perceived out of raw shapes and colors, melodies out of raw sounds and sound durations, and so on.

The psychology that corresponds to this conception of neuroanatomy is fundamentally an information processing one. Information, in the form of sensory input, travels from the special sense organs to the thalamic relay station, where gated controls allow some of the signals to pass further along, while others fade away.

A number of leading neuroscientists are now questioning this traditional view of the relationship between the thalamus and the cortex. For example, Sherman and Guillery (2006) describe the "classical" view of the thalamus as "the major relay to the cerebral cortex" or "the gateway to the cortex." According to the classical view, "[a]lmost everything we can know about the outside world or about ourselves is based on messages that have had to pass through the thalamus". These cortex-bound messages are the visual, auditory, and tactile inputs transmitted from special sense organs (eye, ear, skin) to distinct thalamic "nuclei."

However, on the basis of detailed investigations of the intricate connectivity between the thalamus and the cortex, Sherman and Guillery conclude that the classical view is "beginning to be less useful than it was in the past". They point to studies that demonstrate that "thalamic circuitry allows transmission to be modified in relation to current behavioral needs or constraints". For this to happen, a thalamic nucleus receives inputs not only from a special sense organ, "but from cerebral cortex" as well. The thalamic nucleus functions not only to relay primary sensory information to the cortex. It is also "concerned with sending messages from one cortical area to another. The importance of this pathway, which allows one cortical area to receive inputs from another cortical area through a thalamic relay that can be modulated in accordance with behavioral constraints, is not widely appreciated and has been but poorly explored".

Sherman and Guillery also observe that "the pathways that are relayed in the thalamus ... carry not just the sensory messages represented by the classical model but also copies of motor commands that have already been sent out to the motor periphery before any messages can reach the cortex". This "close link between action and perception" has "long puzzled philosophers, psychologists, and psychophysicists". But its biological basis can be appreciated when it is recognized that the "thalamic inputs to higher cortical areas represent copies of outputs from lower cortical areas. That is, they represent the actions that the lower levels are currently initiating, so that the higher levels can be informed about the actions likely to occur at lower levels, rather than merely receiving reports about lower levels from intermediaries".

A similar discussion is found in Destexhe (2000). Like Sherman and Guillery, Destexhe points to a number of well-known facts about corticothalamic connections that are not easily explained by the classical, bottom-up view. He notes, first of all, that just as there are neurons that transmit information from the thalamus to the cortex, so too are there neurons that begin in the cortex and travel to the thalamus. Infact, there are ten times as many corticothalamic neurons as there are thalamocortical neurons (Figure 3).

Second, whereas primary sensory neurons as well as cortical neurons both connect to the thalamic cell bodies, they do so over different regions of the nerves. In this, they appear to complement each other in determining the ultimate behavior of a thalamic relay neuron. Furthermore, the effect of the corticothalamic neuron on the relay cell in the thalamus, while usually excitatory, may also be inhibitory.

Third, individual thalamic nuclei, studied in isolation, exhibit their own patterns of rhythmic electrical activity. Such "pacemaker" activity, however, is modified in an interesting manner when the thalamic neurons are left with their intact connections to the cortex. In such situations, it can be clearly seen that the individual electrical rhythms are synchronized together under the influence of the cortex.

Based on these facts, Destexhe draws a number of conclusions. Because "corticothalamic synapses largely outnumber afferent synapses, … the notion of the thalamus as a relay station, linking the periphery to the cerebral cortex, should clearly be revised".

And even though "early studies have most often considered the cortex as passively driven by a 'thalamic pacemaker', the synchronizing effect of corticothalamic feedback suggests that "rather than providing an autonomous, independent drive, the thalamic pacemakers are controlled and co-ordinated by the cortex".

Finally, he notes that the existence of cortical connections to the thalamus via mostly excitatory, but also inhibitory synapses, shows that "the cortical influence can either promote or antagonize the relay of information" from the thalamus. Despite distinct sites where cortical neurons connect to thalamic relay cells, compared to where primary sensory neurons connect to thalamic relay cells, the "kinetics and timing' of the corticothalamic and primary sensory neurons are similar, suggesting that cortical connections "complement" the primary sensory connections. Or, as Destexhe alternatively puts it, the cortical connections may "predict" the sensory information: "...corticothalamic inputs seem capable of comple-

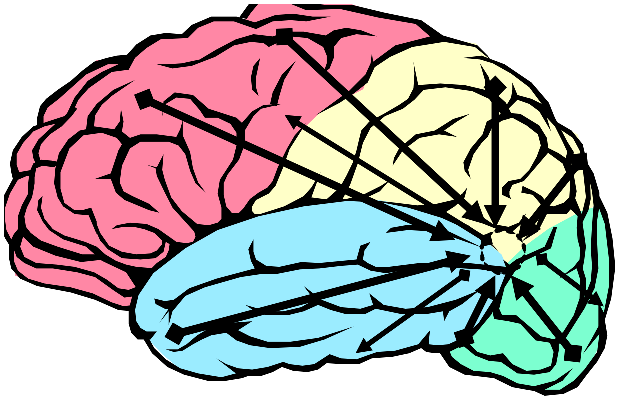

Figure 3. There are ten times as many neurons carrying information from the cerebral cortex to the thalamus (central dot) as there are carrying information from the thalamus to the cerebral cortex.

menting the sensory information at the level of relay cells. The descending corticothalamic information could therefore be a 'prediction' of the sensory input. This is consistent with the previously proposed idea that a very significant part of thalamocortical processing occurs within corticothalamic loops while sensory information provides a modulation of this intrinsic activity" (Destexhe, 2000).

Since the cortex generates the functional molecules of mental life - ideas, plans, beliefs, questions - Destexhe's "prediction" is no less a psychological construct than it is a biological one. Infact, it is a psychological construct whose biological basis is becoming increasingly well understood.

The neural basis of prediction is taken up in a popularized form by Jeff Hawkins (2004) in his book On Intelligence. Synthesizing a wide range of neuroanatomical and neurophysiological facts, Hawkins concludes that "[T]he brain uses vast amounts of memory to create a model of the world. Everything you know and have learned is stored in this model. The brain uses this memory-based model to make continuous predictions of future events. It is the ability to make predictions about the future that is the crux of intelligence".

And the crux of prediction itself is that "the neurons involved in sensing … become active in advance of them actually receiving sensory input. When the sensory input does arrive, it is compared with what was expected".

Such neural activity must be operating in reading much as it does in the most ordinary of experiences. "As you start to push the door open, your cortex predicts how much resistance the door will offer and how it will sound. When your predictions are all met, you'll walk through the door without consciously knowing these predictions were verified. But if your expectations about the door are violated, the error will cause you to take notice. Correct predictions result in understanding. The door is normal. Incorrect predictions result in confusion and prompt you to pay attention. The door latch is not where it's supposed to be".

In this way, according to Hawkins, "[w]e are making continuous low-level predictions in parallel across all our senses". He concludes that "[t]he cortex is an organ of prediction".

But if the cortex is the organ of prediction, then the thalamocortical connection is the organ of confirmation and disconfirmation. Yet it is not only "low-level" sensory information that figures into cortical predictions. "The human brain is more intelligent than that of other animals because it can make predictions about more abstract kinds of patterns and longer temporal pattern sequences".

So, for example, "[w]hen you listen to a familiar melody, you hear the next note in your head before it occurs". Or, "[w]hen listening to people speak, you often know what they are going to say before they've finished speaking….Sometimes we don't even listen to what the speaker actually says and instead hear what we expect to hear". So there are listening miscues as well as reading miscues. These are examples of abstract predictions, involving not merely sound and sight through the medial and lateral geniculate bodies, but musical and linguistic structures as well.

According to Hawkins, the neural basis of prediction and confirmation has been known for a long time, though it was only recently understood as such. The neural basis for prediction and confirmation lies in the vast amount of feedback connections from the cortex to deeper structures in the brain. Thus, not only are there ten times as many neurons feeding back from the cortex to the thalamus as there are feeding forward from the thalamus to the cortex, but "[f]eedback dominates most connections" between the cortex and subcortical structures. "No one understood the precise role of this feedback, but it was clear from published research that it existed everywhere".

In viewing feedback connections from the cortex as the basis of prediction and confirmation, it is clear that the term itself has been misleading. "Feedback" implies that the information running from the cortex to the deeper structures follows and depends on, or is subordinate and secondary to, the primary feed-forward connections running from the deeper structures to the cortex. The transmission of sensory information from the thalamus to the cortex is primary. The reverse process is secondary.

But, for the reasons cited above, including the sheer volume of corticothalamic neurons, the synchronizing control by the cortex over thalamic electrical activity, and the pattern of inhibition and excitation of thalamic relay cells exerted by the cortex, it is now becoming clear that neither direction is inherently primary. The thalamus can transmit unexpected sensory information - a cold breeze, a sudden noise - which can be interpreted by the cortex. But the cortex can itself initiate cerebral events by formulating an interpretation or a meaning or an expectation or an idea and then control the thalamic gates in its physiologic drive to find confirmatory or disconfirmatory evidence. And since the phenomenon is not restricted to low-level sensory inputs, but can operate entirely at abstract levels, the cortex can search regions outside the thalamus itself for confirmatory or disconfirmatory evidence. In the strictly linguistic predictions involved in ordinary thinking, listening, and reading, cortically-generated meanings and their morphosyntactic realizations will search and selectively use both thalamic auditory and visual inputs as well as left-hemispheric language areas to confirm or disconfirm the predictions. Mental behavior adjusts accordingly, just as motor behavior adjusts when a door does not open as expected.

Eye movements during reading are tangible instanttiations of brain activity

The entire phenomenon of cortical prediction and confirmation must operate at multiple levels simultaneously. And this is consistent with meaning construction views of reading. During reading, tentative meanings are formulated. The input to the cortex that is then tested against these meaning hypotheses is quite heterogeneous- visual elements from the page, abstract perceptual categorization of the visual elements into letters and words, meanings associated with the words and phrases, syntactic patterns that organize the input into meaningful language. But the search for these elements is itself a prediction and confirmation phenomenon.

Eye movement studies show that readers do not look at every word, do not necessarily look at the words in order, and do not look at the words for an equal amount of time (Paulson, 2005). If we were to approach this as an isolated phenomenon, much the same way phonological processing has been studied in isolation; we would have to conclude that reading is some kind of arbitrary, haphazard act. After all, a typical eye movement record shows regressions, multiple fixations, skipped words, varying durations, and other "irregular" aspects of reading.

But such a conclusion would be erroneous. Far from being anomalies, eye movement phenomena like regressions, skipping words, differing durations, and nonsequential viewing of text make up a substantial portion of "normal" eye movement patterns found in reading (Hogaboam, 1983). While reading may feel like a sequential process of looking at each word once, one after another from left to right, it is not.

Brain activity during reading has direct physiological manifestations, such as eye movements. The largely invisible activity of the brain during the process of making sense of written text is linked to the readily observable data source of readers' eye movements. Interpreting the patterns of eye movements during reading is, in reality, the study of the psychology of eye movement.

The heterogeneity of movements of the eyes during reading receives a unifying, and theoretically quite satisfying psychological explanation with the notion that they reflect neural decisions about where crucial information is likely to be found. In the course of constructing meaning, the eyes are sent to text sites where the cortex expects to find the information it needs—syntactic, semantic, graphophonic, and other types of information the text can supply. Depending on what is found, the brain can confirm a hypothesis, disconfirm a hypothesis, continue looking for more disambiguating information, construct a new hypothesis to be tested, and so on.

Summary

From time to time, very different research agendas and paradigms reach a point of convergence in which the significance of each is amplified, providing a basis for forward leaps in their respective programs.

In this article we have shown how an emerging conception of brain structure and function, one that includes Hawkins' "memory prediction" view of human intelligence, is consistent with the previously developed socio-psycholinguistic transactional view of the reading process as developed by Goodman and others. In particular, we have shown how studies of eye movements during reading provide strong evidence that the cortex directs these movements as it seeks to make sense of print. This conclusion is achieved when miscue analysis, which studies unexpected responses to print in oral reading, is combined with eye tracking research. Combining these two methodologies yields an exceptionally powerful research tool. Examining the eye-voice span tells us what the brain has already processed at the same time that it is dealing with new input from the eye.

For more than a century, eye movement studies have demonstrated that about a third of the words in a text are not fixated at all by a reader. The process is clearly selective. Miscue analysis lets us compare what the reader produces orally with the selective eye fixation patterns. When eye movement analysis and miscue analysis are combined, we get a sense of how the reader's mental perceptions are constructed from input the eye is providing. But we also get a sense of how predictions guide the eye movements themselves (Paulson, 2002; Paulson, 2005; Paulson and Freeman, 2003). And that is precisely what new brain research is telling us should be happening.

The brain builds a model of the world and stores this in memory. In reading, as in other aspects of mental life, it selectively searches its memory stores for information it uses to formulate instructions that will be sent from the cortex to subcortical structures. At the molecular level, these instructions excite and inhibit neurons that, in turn, direct motor behavior. In reading, the fundamental motor behavior is eye movement, and the cortical instructions tell the eyes where to look for cues from three levels of language: signal, lexico-grammatical, and semantic. At the same time the brain turns the selected input into perceptions. So what we think we see is in fact more important than what we actually see, and that explains why proficient reading is such an efficient and effective process of writers and readers transacting to exchange meaning.

The process of convergence of the two research fields also brings to light the inadequacies of alternative views in each area. The new insights on brain function replace information processing with a constructivist view of psychological processing. Whereas information processing psychology is supported by the notion that input from the senses arrives at a thalamic gatekeeper, it has been known for a long time that many more neurons travel from the cortex to the thalamus than the other way around. So the new view is that the brain is not a prisoner of the senses– rather, on the basis of stored knowledge, it predicts experience before it happens. It uses the senses selectively as it makes sense of the experiences it is having with the world.

The functional MRI studies which claimed to show that the brain uses letter-sound relationships as it reads, and that reading is essentially matching letters with sounds, were based on an inadequate understanding of human brain function. The studies indeed demonstrated that a sufficiently advanced machine can reveal brain sites where letter-sound processes occur. But they were misinterpreted to imply that nothing else of significance to reading is going on when the reader transacts with a whole, meaningful text.

Similarly, a century of eye movement research has been misrepresented to support a letter by letter, word by word view of reading, when it fact it was always much more consistent with a dynamic, meaning construction view of reading. At times, the eye movement findings were forced to fit uncomfortably into a view of reading as sequential word identification, a view that the eye movement patterns did not in fact support.

The prediction-confirmation view of brain structure and function is being developed on the basis of research quite distinct from psycholinguistic research on reading. Therefore, miscue analysis and eye movement studies (Duckett, 2002; Paulson, 2005; Paulson and Freeman, 2003) serve as important confirmatory instantiations of the theory that brain function fundamentally involves cortically-based predictions tested against selectively screened subcortical inputs. At the same time, biological studies of brain function strongly support a constructivist view of reading. It follows then that the pedagogy most commonly called whole language, which is based on treating learning to read as learning to make sense of print, is strongly supported by the prediction-memory model of human intelligence. Eventually, as this convergence becomes more widely understood it should lead to major progress in furthering our understanding of human intelligence and to better understandings of how reading develops and how teachers can support children in learning to read.

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