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Neurobiology Research Findings: How the Brain Works During Reading

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Abstract

In the past, neurobiology for reading was identical with neuropathology. Today, however, the advancement of modern neuroimaging techniques has contributed to the understanding of the reading processes of normal individuals. Neurobiology findings today have uncovered and illuminated the fundamental neural mechanism of reading. The findings have helped researchers and educators in the field of reading expand their understanding of the different levels of the reading process for evidence-based reading instruction. The aims of this paper are to provide a review of the results of neuroscience laboratory research for understanding the reading process. First, the sub-processes of reading and the activated areas of the brain at every stage of reading are discussed. Second, the paper indicates how reading involves both linguistic and non-linguistic processing, and the interconnectivity of the cognitive and emotional networks, which takes place, from the visual recognition of letters to comprehension at the discourse level, and to articulation. An overview of research on the neurobiology of reading such as this will contribute to the understanding of the overall neural basis of reading and has the potential to be integrated into a model of automatic reading and reading comprehension.

Keywords: reading comprehension, neurobiology, brain, reading process

Introduction

Reading is a fundamental academic skill in the 21st century. However, many students lose their interest in schooling because of their low performance in reading. One way to solve this problem is to understand how the brain works while reading, and to apply this knowledge in the real world of classroom reading instruction. Most reading models today, however, have not integrated the neurological perspective. Most of them illustrate that reading is a straight forward graph-to-sound decoding mechanism, which implies that the reading activity only takes place in a single region of the brain. An ideal model needs to include the relevant neurological findings of the reading process at different stages. A more precise model will show how students develop their comprehension from word recognition to the high-order thinking sub-process, and to sounding out. The purpose of this paper is to outline the neurological research findings that inform reading researchers and educators.

The findings of neuroscience open the door to evidence-based reading instruction and reveal the neural mechanism that underpins reading—how the brain functions and changes during the skill development of reading, the mapping of the comprehension sub-processes of reading comprehension, and the process that makes comprehension evolve into an automatic skill (Buchweitz et al., 2009). Each sub-process, such as the sensory visual processing of letters and visual word forms, speech motor processing, comprehension, working memory and long-term memory, takes place in different areas of the brain. More regions will be activated for more complicated reading tasks. For example, one-word reading takes place in the Broca's area, the inferior frontal gyrus and the insular cortex (Perfetti et al., 2004), while sentence reading requires the activation of more areas.

So far the studies that have explored the interactions of neurological processes and education have been categorized into five frames of laboratory studies: word-processing, syntactic processing, syntactic-semantic processing, sentence and discourse processing, and comprehension-related processing.

In short, neuroscience is concerned with the relation between word identification and the sub-processes of reading. It also examines how reading, cognition, emotion, learning, and memory work together to promote better education, and how the components of the reading skill, such as the skillful use of vocabulary, influences reading instruction.

Reading and the Cognitive Functioning of the Brain

As a complex skill, reading involves all of the regions of the brain, because it involves all cognitive functioning of humans -- verbal and non-verbal -- such as attention, planning, abstract reasoning, predicting, inhibition, use of strategies, problem solving, working memory, and long-term storage memory and retrieval of vocabulary and concepts, the procedural skill of retrieval, the use of grammatical knowledge, and the motor mechanism for visual processing, and production. It begins with the visual recognition of letters and continues from phonological processing and higher-level processing from content comprehension to critical and interpretive reading. Even for the simplest language production, the PET technique can show the parts of the brain responsible for attention, audition, and eye movement.

Due to the involvement of multiple brain regions, brain activation not only independently takes place in those brain structures, but also in the neural pathways which connect and coordinate those regions. Information obtained from the linguistic system is projected and distributed to higher-order association. This diverse neural involvement of multiple processes in the numerous cortical systems enables the processing of working- and long-term memory in semantic, gestural, emotional, and intellectual dimensions. All of these processes make it possible to derive meaning from individual letters, words, sentences of increasing structural complexity, and discourse. Reading is also processed in areas which were once thought to be unlikely for language processing, such as the neocerebellum, which plays an important role in making inferences and predictions, and other higher cognitive and, potentially, linguistic functions (Robbins, 1992).

Reading is part of general language processing, which involves more than the two related classic regions of the Broca's area (the posterior part of the left inferior frontal gyrus) and the Wernicke's area (the posterior part of the superior temporal gyrus). They are related because they are not activated in isolation; they modulate and are associated with each other. The Broca's area is associated with the prefrontal cortex and the anterior cingulate. The Wernicke's area, at the end of the Sylvian fissure, is associated with the temporo-occipital area. Today it has been discovered that it is not only the inferior frontal gyrus or frontal operculum which is involved in language processing, but also the superior and the middle frontal gyri. Further, it is not only the superior temporal gyrus, but also the middle temporal gyrus, and the basal temporal language area, including the inferior temporal gyrus, and parahippocampal gyrus. The supramarginal gyrus in the parietal lobe is also involved in language perception and processing. The motor cortex includes the premotor cortex for naming, articulation, semantic planning, semantic processes and categorization (Fadiga *et al*, 2000; Martin & Chao, 2001) and the somato-sensory areas for comprehension. The dorsolateral prefrontal cortex is also involved in non-verbal language processing.

To summarize, basically besides the Broca's and Wernicke's areas involved in language functions, six more areas are involved and are active at the same time: the anterior cingulate gyrus, the prefrontal cortex, the basal temporal language area or fusiform gyrus, the cerebellum, the right hemisphere, and the elements of the limbic system. Earlier it was thought that reading was mainly a serial activity. According to this thinking, beginning with the visual cortex, the information from the sighted printed materials is transferred to the angular gyrus and then to the adjacent Wernicke's area. At this point the visual information becomes a phonetic representation. This representation is sent through the Anterior Fusiform Gyrus, arcuate fasciculus to Broca's area. When this information is conveyed to the motor cortex, articulation is initiated (Lem, 1992; Tucker et al, 2008). Today, however, it has been discovered that the reading process is also a parallel, interconnected activity.

Reading and the Limbic System: Emotion and Memory

Reading, like other learning activities, depends on the interconnectivity among cognition, emotion, memory, and physiology. Affection or emotion is a cerebral process centralized in the limbic system, especially for attention, problem solving and support relationships. It is our emotion that re-sculpts the neural tissue. This is the reason why the holistic approach to reading cannot separate the interplay between emotion and cognition. Cognitive performance will certainly suffer when there is excessive stress and intensive fear in learning.

Some stress is essential for meeting challenges and can lead to better cognition and learning, but beyond a certain level, stress can be counter-productive. This is because, besides regulating emotion, the limbic system also regulates memory. The limbic system--together with the paralimbic regions--is closely related to the hypothalamus and brainstem nuclei. Here lies the crucial link among emotion, cognition, and memory. This is key evidence thats show the importance of emotional development for literary achievement, especially for children and adolescents (Beaucousin et al., 2007; Kuhl & Rivera-Gaxiola, 2008; Hruby & Goswami, 2011; Tucker et al., 2008).

Next, the limbic system also modulates the right hemisphere. During reading, emotions are not only processed in the limbic system, but also in the right hemisphere. The emotional states of the left limbic networks facilitate the processing of close (or focal) semantic relationships, whereas the right hemisphere may support a broader range of meaning associations (Frishkoff, 2007).

Still other evidence comes from studies on words that convey emotions while reading. Emotion prolongs attention in reading, especially there is emotion-specific lexical mechanisms that operate neurologically. A word's emotional qualities, such as *asylum, erotic, rude* were discovered to influence the time spent for viewing that word in the context of normal reading. Fixation times on emotion words (positive or negative) were consistently faster than those on neutral words with one exception. This suggests that stories which stimulate emotion can be useful for motivation and attention (Scott et al., 2012).

It is the emotional factor that influences the deployment and operation of attention, especially in the dorsolateral prefrontal cortex and the dorsal anterior cingulate cortex (Compton et al., 2003). These two areas are activated while reading, because reading requires attention, planning, making associations, and monitoring. Attention itself is the ability to select or focus on a small fraction of the incoming sensory information (Corbetta et al., 1991). It involves both sensory data and stored memory, especially for detection. The prefrontal cortex is the integrator of sensory information for attention, because of its connectivity, while the anterior cingulate keeps the reader focused on what he or she is reading (Posner & Petersen, 1990). Without attention, a reader cannot translate print into speech, and it is crucial for achieving fluent and automatic reading (Reynolds & Besner, 2006).

The Single Word Processing and Beyond during Text Comprehension

Reading begins with the activation of the left posterior brain regions for orthographic-phonological recoding at the presentation of a printed word. It only takes place within 400 milliseconds. Then, it is immediately followed by the word identification process in terms of the syntactic or semantic function before it can be definitely identified or sounded out correctly as a noun or a verb, or a present tense or a past tense. Syntactic and semantic processing takes place in two different areas of the brain, but they overlap. Syntactic processing is the identification of the grammatical function and the grammatical interrelationship of words in a clause or sentence. Semantic processing is the identification of the indicative intention of words, phrases, and idioms, and their intentional relationship at a clausal, sentential, or passage level (Hruby & Goswami, 2011). The syntactic processing of the word class identification takes place in the Broca'a area, while semantic processing takes place at the temporal lobes and left frontal areas for semantic reference. During the word identification process morphological analysis also takes place. It is a distinct sub-process that involves the left frontal areas of the brain.

Comprehension takes place beyond the level of single-word processing; it takes place on the sentence level of the neural mechanism. Meaning is not directly extracted from every word on the printed image, but from the combined meaning of individual words, and the context to produce a coherent meaning.

It was long speculated by psychologists whether the syntactic parser was an autonomous module, and what the integration and interplay between syntax and semantics was. Today imaging studies show that at the early stage of processing, semantic (thematic) and morpho-syntactic processing mostly take place separately and in parallel. Then, the two are integrated at the anterior inferior frontal gyrus. The integration of syntactic and semantic processes occurs at approximately 400-600 milliseconds (Friederici & Weissenborn, 2007).

In order to understand the differences of the following three sentences, for example:

(1) The secretary helps the principal,

(2) The principal helps the secretary, and

(3) The principal is helped by Paul,

the neural processing does not only recognize the words *secretary, help* and *principal*, and semantically retrieve their meaning, but also analyses its semantic and syntactic relations. For example, the secretary is the agent or the benefactor, word order, subject-word agreement, tenses, and the verbal sequences, as the morpho-syntactic pattern (Steinhauer & Connolly, 2008).

Segalowitz and Zheng's and Marinkovic et al.'s study (as cited by Hruby & Goswami, 2011) discovered that syntactic processing begins in the left frontal and anterior temporal lobes with phrase-structure monitoring; then, it is expanded to the verb-subject or syntactic/thematic processing in the left inferior gyrus for the assessment of the semantic intention within the sentence. A syntactic recheck for more complex syntactic structures or for an incongruity/novelty effect also takes place at this stage. Kiehl et al. (2002), for example, discovered that at the sentence level, bilateral inferior frontal cortices, most significantly in the left dorsolateral prefrontal cortex, are more activated during the reading of incongruent sentences (4) than during the reading of congruent sentences (5):

(4) They called the police to stop the soup.

(5) The dog caught the ball in his mouth.

Sentence level semantic processing takes place in the left inferior frontal areas proximal to Broca's area, while at the text level semantic processing is more distributed in the frontal and parietal areas depending on the task complexity or the degree of abstraction (Binder et al., 2009; Hruby & Goswami, 2011). Comprehension also involves memory, and it takes place in the left polar and inferolateral temporal cortex; for example, some temporal lobe regions specialize in retrieving information related to persons and tools, while other regions specialize in other categories (Marinkovic, 2004).

Comprehension requires the integration of semantic and syntactic processing. Semantic integration in sentences is partly guided by syntactic structure; conversely, semantic information also influences syntactic parsing decisions. In order for semantic information to influence syntactic parsing decisions, for example, it must be available much earlier in the sentence, or in a discourse. In order to fully understand the syntactic-semantic parsing of (6), for example, we need to know who 'he' is in the previous context of (6). A discourse provides either one or two potential referents, which lead to further specification (Steinhauer & Connolly, 2008).

(6) He is one of the few good generals we have.

At some point, syntactic and semantic processing might overlap, but for anomalous sentences, such as (7), they are processed in a different area; that is, the central parietal region. The anomalous syntactic structure is also charged in the left anterior region, instead of the left inferior frontal gyrus (Hruby & Goswami, 2011).

(7) When peanuts fall in love ….

Almost similar to the results of mentalistic linguistic investigations, neurobiological studies discovered that syntactic processing and semantic processing are not as separate as they were understood to be, but they can also be interconnected in their operations. Chomsky (1957, 1965, 1970) was once very firm in holding that the nature of language was basically abstract syntax, but recently he has also incorporated the syntax-semantics interface (Chomsky, 1981, 1995). Recent investigations on the syntactic-semantic processing have refuted traditionally-localized processing mainly to the Broca's area for syntax and Wernicke's area for semantic processing. Nevertheless, a debate is still undergoing in neuroscience, particularly regarding the autonomy of syntactic processing in sentence comprehension from lexical and semantic processing, and how syntactic analysis interacts with a word's semantic information (Embick et al., 2000; Keller, 2001; Cooke et al., 2006).

Although syntactic processing and semantic processing are difficult to separate, syntactic priming or word class identification is important in syntactic processing, while semantic priming is important for semantic processing. On a word-by-word basis, syntactic identification takes place before semantic identification. ERP studies have shown that the subject's brain activates differently when it encounters content and function words, and concrete and abstract nouns (Hruby 2009, p. 204). Initially, comprehension is syntactic. It takes place around 400-500 milliseconds; then, it is swiftly followed by syntactic-semantic interaction. For instance, that parsing begins with syntax is shown by the syntactic priming effect that does not require any semantic stimuli. When a reader reads 'the' he/she expects a noun phrase, without any lexical information. However, when he/she reads 'school', he/she interprets it as teacher or students, rather than 'market' or 'garbage.'

Discourse Comprehension

Concerning discourse comprehension, such as narratives, Hruby (2009, pp. 204-8) emphasizes that the activated areas are highly distributed in several areas across the right hemisphere, and the bilateral activation of the anteriortemporal poles. This is because of more memory retrieval, concept integration, abstract or thematic relationship, story structure construction, and emotional valuation. Robertson et al. (2000) discovered that the right cortical areas are more active when stories were presented without titles. Imaging studies on discourse comprehension also have investigated the processing of figures of speech, the function of prior knowledge, making inferences, tracking, and emotional associations in language comprehension (Perfetti & Frishkoff, 2008; Friese et al., 2008; Mason & Just, 2010; Sesma et al., 2009, and Mashal et al., 2008).

Neurologically, discourse is extended, multisentence texts, with all of the micro- and macro-structural elements (Lillywhite et al., 2010). Discourse contains more than a sentence, and its meaning is more than the sum of its component propositions. In order to understand a discourse a reader needs to understand the cues that link one sentence to another, such as the use of the pronoun *he* in (8):

(8) The bank officer talked to the bank teller. *He* asked her to empty all the cash drawers.

This process of discourse comprehension operates in close concert with cognitive-attention and memory-and socio-emotional processes. A network of brain areas in the frontal and parietal cortex is essential to discourse comprehension. A number of imaging studies have shown that the anterior temporal lobes are involved in greater activation when one is involved in discourse-level semantic processing compared to the understanding of word lists (Mazoyer *et al.*, 1993). In an experiment, Hagoort *et al* (2004) presented sentences, such as (9) to (11):

(9) The Dutch trains are *yellow* and very crowded.
(10) The Dutch trains are *white* and very crowded.
(11) The Dutch trains are *sour* and very crowded.

Dutch subjects know very well the famous yellow trains, so when the word *white* appears they know the sentence is false. The N400 elicited by the pragmatic anomaly 'white' is indistinguishable in latency and distribution, from the semantically anomalous 'sour'. When they presented the same materials in a fMRI task, Hagoort *et al* . (2004) found that *sour* and *white* both produced increased activation in the left inferior PFC and near the areas associated with semantic processing, including the left temporal lobe. The increased temporal lobe activity in processing the two kinds of anomaly reflects a difference in degree, rather than one-of-a-kind. Thus, the anterior temporal lobes are important in sentence- and text-level semantic integration. This indicates how the brain differentiates semantics or what is true, and pragmatics or what is sensible.

It was discovered that in order to maintain coherence, especially co-reference, the superior dorsomedial prefrontal region (BA 8–9) is activated. This region also appears to be involved when integration demands long reaches for knowledge (Schmalhofer & Perfetti, 2008). For example, Ferstl & von Cramon (2001) had their subjects read discourses (12) and (13). In each discourse the sentences lacked explicit overlap for the support of integration:

(12) *The lights* have been on since last night. *The car* doesn't start.

(13) Sometimes *a truck* drives by the house. *The car* doesn't start.

When sentences could be linked through a backward inference, as in (12), activation was greater in the superior dorsomedial prefrontal region and posterior cingulate cortex. When cohesive ties were added to the second sentence to suggest a link to the first, for example, *that' s why the car doesn't start*, increased activation was observed in the left PFC for the unrelated case (15), but not the related cases of (14):

(14) The lights have been on since last night; that is why the car doesn't start.

(15) Sometimes a truck drives by the house; that is why the car doesn't start.

Ferstl and von Cramon (2001) suggested the activation in the unrelated case with the 'why' phrase added reflects additional processing required to reconcile the linguistic information in favour of integration with the pragmatic understanding that the car's starting and the truck's passing are unrelated.

Conclusion and Suggestion

Neuroscience findings have opened the door to evidence-based reading instruction. Reading is no longer considered a straight-forward graph-to-sound decoding mechanism. It consists of subprocesses that take place in different areas and pathways of both hemispheres of the brain, including the neocerebellum, which was once considered unlikely for higher cognitive and linguistic functions. Those subprocesses are not isolated from each other. They can take place in parallel and modulate each other. Neurologically, reading is part of the general language perception and processing that begins with letter recognition in word identification processing in the visual cortex and extends to morpho-syntactic, syntactic-semantic, syntactic-thematic, and discourse processing. The process includes such components of reading skills as vocabulary skills, grammatical skills and rhetorical skills; non-verbal cognitive processing, which involves the interconnectivities of attention, learning processes, memory, and inferential procedures; and emotion. It also begins with paying attention to letters and continues with automaticity in reading and critical and interpretive reading. Comprehension begins at the sentential level. More areas across the right hemisphere are involved in discourse processing because it involves more memory retrieval, concept integration, abstract or thematic relationships, and story structure construction and emotional valuation. The brain does not differentiate semantic from pragmatic meaning; the two are processed in the same temporal lobes, and the two differ only in terms of degrees.

The neural process of reading is varied and complex. Therefore, a complete model of reading, both for the first and second language, is crucial for reading instruction, especially in terms of what to teach, how to teach and when to teach. Today we have equipped ourselves with at least minimum knowledge about the anatomy of the brain and its gradient activities during reading, regarding both serial and parallel processing, and under automatic and conscious control at different stages of reading. The recent neurobiological findings can help reading researchers and educators develop an overall model of the reading process within an individual when he/she reads silently and reads aloud. This would cover at least the three main interrelated components of reading, i.e. the cognitive component, and the emotional and linguistic components. Especially regarding the cognitive component, the model would cover the processing systems of attention, memory, learning, and inferential procedures. Further, the model would explain the major stages of the reading process, from visual input, word identification, and comprehension processes, and the use of world knowledge and linguistic knowledge. Finally, the complete model would demonstrate how an individual gradually shifts from learning to read to reading to learn.

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