The Contribution of Neuroimaging to the Study of Reading Comprehension

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Abstract

In this position paper, we advocate that advancements made in other disciplinary areas such as neurolinguistics should be included into contemporary reading comprehension courses and programs. We present findings from neurobiology of reading that suggest explanation of certain reading behaviors: (1) the differences between reading disability and typically developing readers; (2) an inverted U-shaped function that reflects the fact that learning to read is associated with increased activation (the rising part of the inverted U) and activation decreases are associated with familiarity, experience, and expertise (the falling part of the inverted U); (3) and, the identification of reading networks. As potential pedagogical implications of neuroimaging studies to reading, a list of sentence structures is proposed as an example to further relate reading comprehension to cognitive capacity limits. (133 words, 200 words as required).

Key words: inverted U, reading networks, functional magnetic resonance imaging (fMRI), neurolinguistics.

Interdisciplinary studies typically involve a combination of two or more academic disciplines in order to achieve a common task that is related to various disciplines (Ausburg, 2006). In this position paper, we argue for the inclusion of interdisciplinary studies of neuroimaging and neurolinguistics in contemporary reading comprehension courses and programs, because the neurobiology of reading can provide a deeper understanding, in our opinion, of reading mechanisms and processes.

We present three sets of findings from the neuroimaging, cognitive science, and the neural basis of reading research literature that suggest explanations of certain reading behaviors: (1) the differences between reading disability and typically developing readers; (2) an inverted U-shaped function that reflects the fact that learning to read is associated with increased activation in the reading network (the rising part of the inverted U) and that activation in the reading network decreases with familiarity, experience, and expertise (the falling part of the inverted U; (3) and, the identification of reading networks. We are unaware of any direct pedagogical implications of neuroimaging studies for reading comprehension, but we do include an array of sentence structures that might impact comprehension because of cognitive capacity constraints-- a major focus in neurobiology and cognitive science.

The neuroimaging studies cited in this paper used functional magnetic resonance imaging (fMRI) which is a measure of brain activity that detects changes associated with blood flow. Cerebral blood flow and neuronal activity are related because there is an increase in blood flow to an area of the brain that is activated by some event. One use of fMRI is to identify which region(s) is(are) active during a specific function like reading.

Reading Disability and Typically Developing Readers

Pugh et al. (2013) conducted a study to identify the cortical and subcortical networks that best discriminate children with better or worse reading readiness skills assessed with measures of phonological awareness, decoding, and rapid auditory processing abilities (p. 175). Their results indicated that (1) the skilled-correlated circuitry in beginning readers is broadly distributed, with neural activation and responses in left hemisphere temporoparietal, occipitotemporal, interior frontal gyrus, visual cortex (cuneus), precuneus, posterior thalamus (centered in pulvinar), prefrontal cortex, and right hemisphere parietal and temporal networks (p. 179); (2) several right hemisphere regions were positively correlated with reading skill, including inferior temporal gyrus/middle temporal gyrus and parietal loci (p. 180); (3) and, a distributed, multimodal, attentionally-controlled, learning circuit for reading was proposed.

In their review of the literature, Pugh et al. (2013) listed the following differences between reading disability (RD) and typically developing (TD) readers: (1) RD readers tend to under-activate left hemisphere temporoparietal and occipitotemporal networks (Meyler et al., 2007); (2) RD readers often compensate left hemisphere posterior dysfunction by increasing activation in right hemisphere posterior regions (Sakari et al., 2002); (3) RD readers can increase their bi-hemispheric frontal activation (Shaywitz et al., 2002); (4) right hemisphere contributions are strong but attenuate with age, experience, and expertise in TD readers but not in RD readers (Shaywitz et al., 2002; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003); (5) in adolescent readers who participated in a repeated exposures study, Pugh et al. (2008) found that changes in brain activation in left hemisphere thalamus discriminated TD readers from RD readers; (6) older RD children readers, relative to TD readers, showed reduced activation in the pulvinar area on a variant of the temporal order judgment task (Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007); (7) and, RD children readers showed increased activation in the pulvinar area on the temporal order judgment task after intervention (Temple et al., 2000).

Experience, Expertise, and the Inverted U-shaped Function

Cao (2016), Price (2013), and Price and Devlin (2011) have proposed an inverted U-shaped function with the acquisition of expertise and experience. Price (2013) explained the inverted U-shaped function as follows:

> The rising part of this inverted-U is illustrated by the studies showing that learning to read increases activation in mid-regions of the left ventral occipito-temporal cortex … The falling part of the inverted-U shaped learning function is illustrated by studies showing that activation is higher for newly learnt or less familiar words than it is for familiar words that are frequently experienced (p. 132).

Price (2013) offered the following evidence to support the claim that neural activation in the left temporo-occipital region increases during initial learning and decreases with increased experience and expertise. Responses are higher after adults learn a new script (Mei et al., 2013). Young children, ages 5-8, having better performance on phonological awareness, pseudo-word decoding, and word reading ability exhibit higher activation in active reading networks (Pugh et al., 2013). As the readers' experience and expertise with a script increases, activation in the left ventral occipito-temporal cortex decreases (Twomey et al., 2013). Adult activation is less than in children (Olulade, Flowers, & Eden, 2013). And, increases in word frequency co-occur with decreases in inferior frontal area activation and for words relative to pseudo-words (Hemi, Wehnelt, Grande, Huber, & Amuts, 2013).

Keller, Carpenter, and Just (2001) investigated the effect of word frequency on comprehension, as another empirical example to show an inverted U-shaped function with the acquisition of expertise and experience. Earlier research (Carpenter & Just, 1983) noted that the gaze duration on a word during reading comprehension decreased with the logarithm of a word's normal frequency. Keller et al. (2001) reported reliably more activation for sentences with low-frequency nouns than sentences with high-frequency nouns. High-frequency words may be automatically recognized and accessed during the reading comprehension process, while low-frequency words might entail controlled processing or alternate searches for lexical access, thereby increasing the gaze duration.

Reading Networks

Based on published neuroimaging studies, researchers have proposed reading networks which are usually defined as a complex, amply interconnected network within large-scale networks having cortical and subcortical regions in both hemispheres, but predominately left hemisphere focused (Cao, 2016).

Brain Areas Related to a Reading Network

Constable et al. (2004) proposed that the following brain regions are involved in a reading network. Pars triangularis and pars opercularis are implicated in grapheme-to-phoneme conversion, working memory, and sentence parsing. Wernicke's area is believed to serve a variety of functions including ordered recall of words, phonological memory storage, phonological analysis, lexical semantic processing and sentence interpretation. The researchers state that a reading network has locations in both hemispheres, but the majority of activation occurs in the left hemisphere. "The left hemisphere reading circuit contains ventral (occipitotemporal), dorsal (temporoparietal), and anterior (inferior frontal gyrus) components" (p. 12).

More recently, Cao's (2016) network includes

> left temporo-occipital regions for visual-orthographic recognition, left inferior parietal lobule for conversion from orthography to phonology and semantics, left superior

temporal gyrus for phonological representation, left middle temporal gyrus for semantic representation, and left inferior frontal gyrus for semantic, syntactic, and phonological processing (p. 683). (A gyrus is a convolution on the cortex of a cerebral hemisphere. A sulcus is a groove on the cortex).

Similarly, Froehlich et al. (2016) propose a reading network consisting of the left posterior inferior occipital and left ventral occipital temporal for visual and orthographic activations, left temporal and left inferior frontal regions for phonological and semantic activations along with a general language processing system mainly located in the frontal and temporal areas of the left hemisphere, especially middle and temporal regions around Broca's area.

Price (2013) and Friederici and Gierhan (2013) include the role of pathways in a reading network. Price notes that

> at least three different white matter pathways pass near the peak fMRI reading activation and may carry reading signals: (i) the inferior longitudinal fasciculus that links occipital cortex to the anterior and medial temporal lobes; (ii) the inferior fronto-occipital fasciculus that links occipital cortex to the ventrolateral prefrontal cortex; and (iii) the vertical occipital fasciculus that project dorsally to the lateral occipital parietal junction including the posterior angular gyrus and lateral superior occipital lobe (p. 132).

Friederici and Gierhan (2013) discuss the importance of information transfer between different language processing areas of the brain. The roles of the dorsal and ventral pathways follow. A dorsal pathway connects the temporal cortex and Broca's area for supporting syntactic processes. The arcuate fasciculus connects Broca's and Wernicke's regions.

Feng, Chen, Zhu, He, and Wang (2015) advocate a fronto-temporal-parietal network that supports reading across languages that manifest surface structure differences between linguistic systems. There is a reading-related network (RN) and a default-mode network (DMN).

> The RN consists of several regions consistently implicated during reading, including the inferior frontal gyrus, most of the temporal lobe regions, and part of the parietal lobe in both hemispheres. Some regions that were consistently involved in a wide range of reading tasks fall under the fronto-parietal control network and the dorsal-attention network. In contrast, the DMN is consistently deactivated during reading and other cognitive tasks, and is comprised of the posterior cingulate cortex, medial prefrontal cortex, inferior parietal lobe, and lateral temporal cortex, suggesting an association with internal mental processing and semantic cognition (Feng et al., 2015, p. 104).

Zhu, Fan, Feng, Huang, and Wang (2013) studied the integration of widespread functionally separate brain regions into a functional network for sentence processing. They studied responses to sentence violation which was an implicit task and high and low cloze procedure which was an explicit task. From these data analyses, they posited various hubs. There were ten common hubs in the networks corresponding to the implicit and explicit tasks which included bilateral supplementary motor area, bilateral median cingulate, bilateral middle temporal gyrus, and left middle occipital gyrus. The left superior temporal gyrus and the right inferior temporal gyrus were included in the hubs related to the implicit language task. Hubs specifically implicated in the explicit language tasks included the left precentral gyrus, right medial orbitofrontal cortex, and the right parahippocampal gyrus.

Variability in a Reading Network

Shifts can occur in a reading network as readers mature. Pollack, Luk, and Christodoulou (2015) note that during early reading development, children produce bilateral activation in the temporo-parietal, temporo-occipital, and inferior frontal regions. Early elementary school readers shift to left lateralization, which is relatively stable into adulthood.

There may be a difference in reading networks for typical and struggling readers. According to Pollack, Luk, and Christodoulou (2015), typical readers are lateralized in frontal and temporal areas, while struggling readers manifest more diffuse activation in bilateral frontal, occipital, and temporal regions.

Nakamura et al. (2012) added a "culture-specific tuning" component to their proposed reading network. They employed fMRI in a semantic task with words written in cursive font and proposed two universal circuits, a reading-by-eye shape recognition system and a reading-by-hand gesture recognition system. Their discussion includes a posterior left-hemisphere network (the lateral occipito-temporal visual word-form area for perceptual analysis of written words, the inferior parietal and superior temporal cortices for print-to-sound conversion, and lateral temporal cortices for access to word meaning).

> Our results point to an extended reading network that invariably comprises the occipito-temporal visual word-form system, which is sensitive to well-formed static letter strings and a distinct left promotion region, Exner's area which is sensitive to the forward or backward direction with which cursive letters are dynamically presented (Nakamura et al., 2012, p. 20762).

Buchweitz, Mason, Tomitch, and Just (2009) produced evidence that differences in the readers' working memory capacity can result in different configurations of a reading network. Their research indicated that readers with lower working memory capacity evidence a spillover of activation in the prefrontal cortex, while readers with higher working memory produce more activation in the left angular and precentral gyri, and right inferior frontal gyrus. Buchweitz et al. (2009) reported that phonological rehearsal which entails verbal working memory elicits additional activation in a reading network in inferior frontal gyrus, medial frontal gyrus, and angular gyrus.

Cognitive Capacity and Linguistic Complexity

We are not aware of any direct pedagogical implications from neurolinguistics research; however, we think that there is an indirect pedagogical implication based on the research that has been conducted on cognitive capacity and linguistic complexity.

Learners can only attend to a finite amount of information at a given time due to the limited capacity of the working (short-term) memory system (Sweller, 1988). Originally, Miller (1956) advanced the notion that a person could hold from five to nine pieces of unrelated information (i.e. numbers) in short-term memory for processing, but more recent research now indicates that that estimate should be lowered to as few as four, when it comes to words instead of numbers (Cowan, 2001; Feldon, 2010; Janssen, Kirshner, Erkens, Kircher, & Pass, 2010).

According to Feldon (2010, p. 18), cognitive load is "conceptualized as the number of separate chunks" or schemas "processed concurrently in working memory" while performing a task, plus "the resources necessary to process the interaction between them". Cognitive load is experienced as mental effort. When cognitive load, that is the information to be processed, exceeds working memory's capacity to process it, students will have difficulties learning the material.

Cognitive load is very similar to Just and Carpenter's (1992) capacity theory of comprehension, that is, "cognitive capacity constrains comprehension" (p.122). Language comprehension is defined as a task that "demands extensive storage of partial and final products in the service of complex information processing" (p. 122). Cognitive capacity refers to "the maximum amount of activation available in working memory to support either storage or processing functions" (p.123). When language comprehension has high demand "(either because of storage or computational needs)", the speed of processing will decrease, and "some partial results may be forgotten" (p. 123).

Grammatical Features and Structures Impacting Reading Comprehension

At the conclusion of this section of the paper, we provide a list of grammatical features that may cause sentences to be more (or less complex). We offer these grammatical features because we think classroom reading teachers should be aware of phenomena that can impact sentence and text comprehension.

Thompson and Shapiro (2007) list grammatical features that may cause sentences to be more (or less) complex:

> (1) the number of propositions (which translates in most cases to the number of clauses in the sentence); (2) the number of embeddings (defined as the extent to which clauses are hierarchically embedded within other clauses); (3) the order in which major grammatical elements appear in the sentence, whether canonical (i.e., elements follow the English-favored subject-verb-object [SVO] word order) or not, as in passive voice and cleft sentences; and (4) the distance between related grammatical elements (e.g., between a relative pronoun and the "trace" left by the noun it replaces in the embedded relative clause; as cited in Scott & Koonce, 2014, p. 284).

Following Thompson and Shapiro's (2007) features, Scott and Koonce (2014) listed the following grammatical constructions and sentence patterns that could impact sentence and text comprehension: concealed negatives, literary negatives, "long subject noun phrases", "ellipsis in coordinated sentences", wh-clauses as subjects, "nonfinite clauses used as subjects", " optimally deleted function words", "words that belong to more than one grammatical class", structural ambiguity, "structures that interrupt main subjects and verbs", and "ellipsis with long distances between the ellipsis and its referent" (p. 285).

Caplan and Waters (1999) and Evans and Orasan (2019) note that the number of propositions in the sentences of a text affects the text comprehension of readers with different levels of verbal working memory. Evans and Orason point out that "propositionally dense sentences are relatively difficult to understand" (p. 80) and that "compound and nominally bound relative clauses contribute to sentence complexity" (p. 81). These linguistic phenomena are probably related to capacity constrained comprehension.

Conclusion

We have presented three sets of neuroimaging findings which we think provide additional insight and explanation for certain observed reading behaviors. We have also presented information from cognitive science about phenomena which may impact sentence and text comprehension. Neuroimaging is a relatively new field but has shown strong application to various fields. Perhaps, in the years to come, further developments in neuroimaging and its related disciplines will provide insights and guidance for the improvement of teaching and learning.

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