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Organizational Structure Reduces Processing Load in the Prefrontal Cortex During Discourse Processing of Written Text: Implications for High-Level Reading Issues After TBI

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Abstract

Adults with traumatic brain injury (TBI) can demonstrate marked difficulty producing discourse during story retell and story generation tasks. Changes in discourse production have been detailed in terms of fewer content units and infrequent use of story grammar elements essential for organization. One implication is that poor use of story grammar elements during discourse production may signal reduced ability to utilize these elements in other communication realms (e.g., reading comprehension). The neural architecture that supports discourse organization, primarily the medial prefrontal cortex, is particularly susceptible to damage secondary to acquired brain injury. In this event related functional magnetic resonance imaging (fMRI) study, we describe cortical activation patterns of unimpaired readers as they are presented with discourse that is varied in terms of structural organization. The results suggest reading discourse with less structure is associated with increased cortical activity (e.g., higher processing demands) as compared to reading discourse with more traditional structural cues (e.g., story grammar). We discuss cortical areas implicated and potential implications for supporting discourse communication in persons following TBI.

The connection between discourse structure and comprehension is an important avenue for exploring reading ability (McNamara, Louwerse, McCarthy, & Graesser, 2010). The clinical examination of discourse is used for the assessment of other cognitive-communication skills in healthy children and adults, as well as in persons with neurological impairments subsequent to traumatic brain injury (TBI), cerebral vascular accident, and dementia (Arkin & Mahendra, 2001; Ash et al., 2006; Brookshire, Chapman, Song, & Levin, 2000; Coelho, 2007; Lehman Blake, 2006; Mar, 2004; McCabe and Bliss, 2006; Stemmer, 1999). Given that other discourse skills such as story retell and story generation are susceptible to impairment following brain injury, further consideration of factors that influence discourse

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abilities is warranted. Many of these impaired abilities are thought to be the result of damage to the prefrontal cortex (Coelho, 2002, 2007; Ylvisaker, Feeney, & Capo, 2007) that disrupted cognitive processes and lead to disorganized information processing. Current neuroimaging data support the activation of a bilateral network (i.e., anterior prefrontal cortex, medial prefrontal cortex, and the precuneus) involved in discourse processing; however, it is not known how this network is influenced by the organizational structure inherent in different forms of discourse. Understanding how the prefrontal cortex is influenced by discourse structure has particular relevance for understanding high-level reading comprehension issues in impaired populations.

Discourse processing represents complex communication behavior that requires the integration of information across successive utterances or sentences, linguistic knowledge, the use of organizational frameworks, and pragmatic rules to create or interpret a meaningful message (Coelho, Ylvisaker, & Turkstra, 2005; Fayol, 1993). Comprehension of written text involves updating contextual information with new information, monitoring for message coherence (e.g., personal knowledge, situational pragmatics, relationship between message components), and the ability to interpret the parts of the discourse message as a unified whole (Ferstl, Neumann, Bogler, & von Cramon, 2008; Ferstl & von Cramon, 2002). As successive information is compiled and takes shape, an organizational structure or framework delineates the boundaries and influences the meaning of the message.

Story grammar is one type of organizational structure that provides a recognizable and identifiable pattern of formational regularities (Mandler, 1977; Stein & Glenn, 1979), which serves to “guide an individual’s comprehension and production of the logical relationships, both temporal and causal, between people and events” in a narrative (Coelho, 2002, p. 1233). The framework created by the discourse structure influences cognitive ability (e.g., reading speed, reaction time, memory, and recall; Bartlett, 1932; Mandler, 1977; Rumelhart, 1975; Stein & Glenn, 1979), as well as the neural substrates that support discourse comprehension (Ferstl et al., 2008; Robertson et al., 2000; Xu, Kemeny, Park, Frattali, & Braun, 2005). The observed effects on cognitive ability and neural activity is intriguing given increasing evidence suggesting a benefit of teaching other populations of struggling readers about text structure (Meyer & Ray, 2011).

The Extended Language Network

Discourse is uniquely positioned to highlight how context or structure influences neural activity and evolves over the time course of the stimuli (Ferstl et al., 2008; Xu et al., 2005). As language is understood in context, increasing neural activity or spreading activation is considered to be typically observed beyond the left hemisphere perisylvian areas as part of a larger “extended language network (ELN)” (Ferstl et al., 2008, p. 581). In a meta-analysis of 10 neuroimaging studies investigating the neural substrates of the ELN involved in processing coherence during discourse comprehension, Ferstl et al. (2008) found a number of brain regions consistently activated. These regions included bilateral activation of the anterior temporal lobes and the posterior superior temporal sulci; right-sided activation of the venteromedial prefrontal cortex; and left hemisphere activation of the medial middle temporal gyrus, inferior frontal gyrus (opercular portion), dorsal medial prefrontal cortex, and the inferior precuneus (Ferstl et al., 2008). These areas are thought to more generally support basic-level text processing (e.g., sentence-level comprehension or syntactic computation) and are commonly activated in studies of language comprehension (Hickok & Poeppel, 2007; Poeppel & Hickok, 2004). Ferstl et al. (2008) also identified a number of regions thought to be unique to the coherence-building process, including activation in the posterior cingulate cortex, inferior precuneus (BA23/31), and aspects of the dorso-medial prefrontal cortex (BA 9/10; Ferstl et al., 2008). Xu et al. (2005) observed activation in medial and lateral pre-motor areas and the expected language centers of the perisylvian areas within the left hemisphere during story narrative processing. These areas became increasingly active in intensity and greater in volume as language tasks required higher levels of integration (i.e., words < sentences < narratives). Additionally, beyond the perisylvian regions were unique bilateral activations of the dorsal and ventral medial prefrontal regions (BA 8, 9, & 10) and the dorsal precuneus (BA 7/31) observed in the contrasts between reading unrelated sentences as opposed to coherent narratives. These findings, in conjunction with previous work, suggest a distinct bilateral processing network comprised of medial prefrontal cortical areas as well as the precuneus, implicated in binding subcomponents of discourse into a cohesive whole (Bottini et al., 1994; Ferstl & von Cramon, 2001, 2002; Xu et al., 2005).

However, ascribing task-specific functions to any cortical region or network is problematic in that it describes a particular set of circumstances in which a region is activated, but not necessarily the “the information processing that is performed by that region” (Ramnani & Owen, 2004, p. 190). A number of the aforementioned medial prefrontal cortical regions active during discourse processing have also been attributed to other task-specific complex cognitive functions (e.g., processing of internal states, memory retrieval, and the branching and reallocation of attentional processes). From an informational processing standpoint, Ramnani and Owen (2004) have described the supramodal cortex of the anterior prefrontal region as being involved in cognitive processes of relational integration. That is, this area is engaged when more than one cognitive process is necessary to solve a problem and the results of two or more cognitive processes must be integrated to solve such a problem. This view is consistent with the functional anatomy of these regions and is generally in agreement with task-specific functions, including those related to discourse. A coherent discourse message necessarily relies on decoding smaller units of information with unique meaning (e.g., words, phrases, sentences) and integrating them into discourse text via the combinatorial properties that create higher-level meaning gleaned only through integration.

The prefrontal cortex accomplishes this large-scale information integration through the activation of unique stores of knowledge called *structured event complexes* (SEC), which are goal oriented, sequentially structured, thematic, and rule governed (Grafman, 1995; Grafman & Litvan, 1999; Partiot, Grafman, Sadato, Flitman, & Wild, 1996; Sirigu et al., 1998; Sirigu et al., 1995; Wood & Grafman, 2003; Wood, Knutson, & Grafman, 2005). SEC information is thought to be stored as cognitive frameworks that are used to guide information processing and are encoded and retrieved as complete episodes (Wood & Grafman, 2003). Narrative schema and organizational principles in the form of a story grammar rule system represent a type of SEC that would be employed during the comprehension or production of a story (Grafman, 1995; Sirigu et al., 1998).

Story grammars are based on an episode, similar to the situation model concept described in previous articles of this issue, that constitutes the core elements of a story narrative. The basic episode structure contains background information (i.e., a setting), typically followed by an initiating event in which the characters are faced with a problem. Subsequently, the characters are set into action to solve the problem (i.e., action or goal-oriented centering point) and the action continues until a resolution (i.e., direct consequence) of that action is reached (see Table 1). This schema or SEC conceivably includes the constituent parts of the story (e.g., type of content to be included) as well as the logical and relational arrangement of the information in a generic manner that could be employed regardless of the story content (e.g., “the wolf in sheep’s clothing” versus “the hare and the tortoise”; Wood & Grafman, 2003).

Purpose

Current neuroimaging data support the activation of a bilateral network (i.e., anterior prefrontal cortex, medial prefrontal cortex, and the precuneus) involved in discourse and narrative processing. However, how discourse processing is influenced by the organizing structure of the story is unknown. Our intent in the present study was to explore the influence of structure in the comprehension of story narrative discourse by utilizing story narrative stimuli created to directly conform to the theoretical story grammar framework (Hickmann & Schneider, 1999; Schneider & Winship, 2002). We reverse-engineered the narratives in the present study to precisely conform to story grammar episode structure and they are completely novel in content (see Appendix A. Story Narrative Condition). The purpose of creating these novel story narratives was to limit factors that could potentially influence discourse processing but were not related to story structure or coherence building (e.g., familiarity with the stories/fables, inferred messages of morality, memories associated with particular fables, emotional associations with fables, etc.; e.g., Xu et al., 2005). We hypothesized that well-structured story narratives, based on story grammar episode structure, would differentially activate regions in the prefrontal cortex required to combine related verbal information for story coherence (i.e., global relationship to a single storyline influenced by structural regularity). More specifically, when the story narrative condition is compared to non-cohesive sentences, processing resources would be greater for information that was not organized in schematic frameworks, indicating a potential role for the influence of SEC knowledge related to stories.

Methods

Participants

Twelve right-handed native English-speaking subjects (4 females), over the age of 18 years (mean[SD] age = 25.67[2.5], range 23–32), participated in this study. Handedness was assessed through participant self-report. Participants denied any prior history of neurological or psychiatric disorders or language-learning disabilities and verified they had never received special education or speech-language therapy service. All participants gave informed written consent in accordance with the study protocol approved by the Committee on Human Research for Medical Sciences at the University of Vermont.

Procedure

Participants came to the University of Vermont Functional Brain Imaging Facility for an appointment that lasted approximately 2 hours. Subjects were paid $30 for their participation.

Language Tasks—We developed nine narratives, each 60 words in length, for this study. Narratives were based on the original work of Hickmann, Schnieder, and Winship (Hickmann & Schneider, 1999; Schneider & Winship, 2002), designed to conform strictly to story grammar conventions by creating a simple story narrative, each with a single complete episode (see Appendix A). To model children’s narratives, the stories included concrete high-frequency words and simple syntactic structures. Each narrative included introductory and setting information, followed by an initiating event (problem introduced), an attempt (to solve the problem), a direct consequence (success or failure at attempt), and an internal response of the character (reflective thought following episode conclusion; see Table 1). Narratives were randomly assigned to one of three text-manipulation conditions: (a) random words, (b) random sentences, and (c) story narratives. Narratives assigned to the random words condition were reorganized into 60-word sets, using the list randomizer function provided by Random.org (2012). Narratives assigned to the random sentences condition were also reorganized by sentence, using the list randomizer function provided by Random.org (2012). The three remaining story narratives were left in their original and complete story narrative form. In addition to the three narrative forms, we created three additional texts containing 60 pseudo-word constructions to serve as a comparative baseline or resting condition. Randomly generated letter strings (Random.org, 2012) served as pseudo-words (i.e., without vowels). Overall, we created 12 equivalent sets of 60-word or pseudo-word constructions that each had an identical number of letters, words (or pseudo-words), and sentence (or pseudo-sentence) length (see Appendix A).

Participants were presented with three blocks of stimuli that included all 12 conditions. Stimuli within blocks and the blocks themselves were presented in a pseudo-randomized order, so that each block contained each story type and the pseudo-word conditions. Each block lasted 30 seconds, followed by 16 seconds of rest (i.e., visual fixation of + on the screen). Participants were instructed to pay attention to each item that appeared on the computer screen and to try to read each item silently and attentively without moving their mouth. Participants were not required to respond in any way.

Hypotheses

We hypothesized that well-structured story narratives, based on story grammar episode structure, would differentially activate networks in the prefrontal cortex compared to unstructured narratives and control texts. Differential activation in the prefrontal cortex could be attributed to differences in processing demands based on the organizational structure of texts. We hypothesized that structured narratives would provide more support for readers and require less activation. In contrast, unstructured narratives not organized by predictable story grammar elements would require more processing by the reader to generate a cohesive representation and hence would require increased activation.

Results

All areas of significant difference between the sentence and narrative conditions were indicative of greater activation in the sentences condition, suggesting reduced processing demands in this contrast for the narrative condition (i.e., random sentence activation subtracted from story narratives activation). Significantly less activation was noted in bilateral portions of the medial frontal gyrus (i.e., left BA 10 and right BA 8), bilateral portions of the middle frontal gyrus (i.e., left BA 46 & 9, right BA 8 & 9), bilateral portions of the superior temporal gyrus (i.e., left BA 39, right BA 39), and in the precuneus of the left hemisphere (i.e., BA 7). All areas representing significant differences between conditions are organized in the table below (Table 2; Figures 1 and 2).

Discussion

The findings generally supported our hypothesis: Well-structured story narratives, based on story grammar episode structure, differentially activated networks in the prefrontal cortex compared to unstructured texts. These differences suggest that schematic mental models of narrative organization (i.e., story episode structure delineated by story grammar analysis) significantly influenced processing of medially situated cortical areas (i.e., medial and lateral aspects of the prefrontal cortex, and the precuneus). These brain areas are more activated when readers must generate understanding without the benefit of structural organization of the text. Conversely, these brain areas are relieved of their processing demands when the texts provide more structural support (i.e., structured narratives). These findings are most remarkable in the fact that, across the entire brain, without exception, significantly less activation was observable in the story narrative condition than in the unlinked sentences condition. This was true in early language processing areas as well, suggesting a top-down effect of structure reducing basic linguistic processing loads on areas such as BA 39 (see Figure 2).

The most parsimonious explanation for the present results is derived from a representational understanding of the type of knowledge stored in the prefrontal cortex. That is, SEC knowledge, stored in the form of neural networks that are used to encode and retrieve hierarchical sequences related to everyday life activities, are activated during SEC processing (Grafman, 2006a, 2006b; Krueger, Moll, Zahn, Heinecke, & Grafman, 2007; Wood & Grafman, 2003; Wood et al., 2005). Story narratives, and their goal-directed episode core comprised of story grammar components, are thought to be one type of SEC that facilitates performance of narrative activities (Grafman & Krueger, 2008; Krueger et al., 2007; Rumelhart, 1975; Stein & Glenn, 1979; Wood et al., 2005). The data from the current study suggest that discourse information, presented in a simplistic and archetypical organizational pattern, reduces processing load to the point where comprehension becomes predictable and automatic. This type of neural priming has been empirically demonstrated in the lateral prefrontal cortex, where reduced demand for processing resources is seen when prior knowledge is in place (Race, Shanker, & Wagner, 2009). As SEC knowledge is a type of pattern abstraction of prior experience (e.g., exposure to stories leads to a mental model or story schema), it is reasonable to assume that this prior experience with simplistic story patterns provides a base of experience that actually deactivates or reduces the load during story narrative comprehension (Maguire, Frith, & Morris, 1999).

The results of reduced processing load related to coherent story organization are further supported by participant report following the text-reading tasks in this study. One participant noted that it was enjoyable and relaxing when the stories made sense. One interpretation is that skilled readers expect that letters form words, words form sentences, and sentences combine in meaningful ways to create discourse, and absence of these structural aspects is taxing (Carpenter, Miyake, & Just, 1995; Vogeley et al., 2001). The orderly and coherent nature of the story narratives may also be responsible for a top-down facilitation and deactivation in more posterior aspects of the cortex, namely in bilateral aspects of BA 39, as the integration of text and reading are supported and primed by the context provided by the discourse text (e.g., Hagoort, 2005).

Overall, this investigation provides additional evidence of differential activation of the prefrontal cortex that varies as a function of the presence or absence of organizational elements. However, this investigation is limited in that only one type of well-structured narrative was used. Future investigations comparing the neural architecture of different organizational structures in discourse (e.g., personal narratives versus story narratives versus procedural narratives) or a range of organizational patterns (e.g., chain narratives versus heap narratives versus classic narratives) will better elucidate varying influences of structure on processing demands.

These results nonetheless may signify a number of implications for clinical and educational practice. As this issue of *Perspectives on Neurophysiology and Neurogenic Speech and Language Disorders* describes, it is well known that persons who have suffered TBI often demonstrate changes in discourse ability measurable via story grammar analysis; little is known regarding effectiveness of treatment of these communication deficits (Cannizzaro & Coelho, 2002; Coelho, 2002, 2007; Coelho et al., 2005; Ylvisaker, Szekeres, & Feeney, 2001). Disrupted discourse and communication abilities following TBI are often characterized as being more debilitating than the physical consequences of the injury, reducing the quality of interpersonal relationships for sufferers of TBI, and acting as a barrier to independent and productive employment in this population (Coelho, 2007; Coelho et al., 2005; McCabe & Bliss, 2006; Snow, Douglas, & Ponsford, 1998; Ylvisaker et al., 2007; Ylvisaker et al., 2001). Understanding how discourse structure influences discourse processing abilities and the role of the prefrontal cortex in that process can inform assessment and intervention practices. For example, making structural discourse elements more salient or altering discourse frameworks to increase their predictability may lead to improvements in communication abilities. Awareness of discourse elements may also guide strategy development that can then be used by both persons with TBI and their communication partners (McCabe, Bliss, Barra, & Bennett, 2008; Togher, McDonald, Code, & Grant, 2004).

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Biographies

Michael Cannizzaro is an associate professor in the Department of Communication Sciences and Disorders at the University of Vermont. He conducts research investigating the relationships between language structure and cognitive abilities (e.g., executive functions) in typical and brain-injured adults. His current research incorporates the study of discourse processing using behavioral, linguistic, functional magnetic resonance imaging (fMRI), and functional near-infrared (fNIR) imaging methodologies.

Julie Dumas is a research assistant professor in the Department of Psychiatry and the Clinical Neuroscience Research Unit at the University of Vermont. She completed her PhD in cognitive psychology from the University of North Carolina at Chapel Hill in 2002 and her BA from the University of Virginia in 1996. Dumas' research program examines the neurobiology underlying age-related cognitive dysfunction.

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Patricia Prelock is the dean of the College of Nursing and Health Sciences at the University of Vermont. She also coordinates the parent training programs and resource modules designed for caregivers and providers serving children with autism spectrum disorders through the Vermont Interdisciplinary Leadership Education for Health Professionals (VT-ILEHP) Program, a Maternal & Child Health Bureau (MCHB) federally funded interdisciplinary training grant.

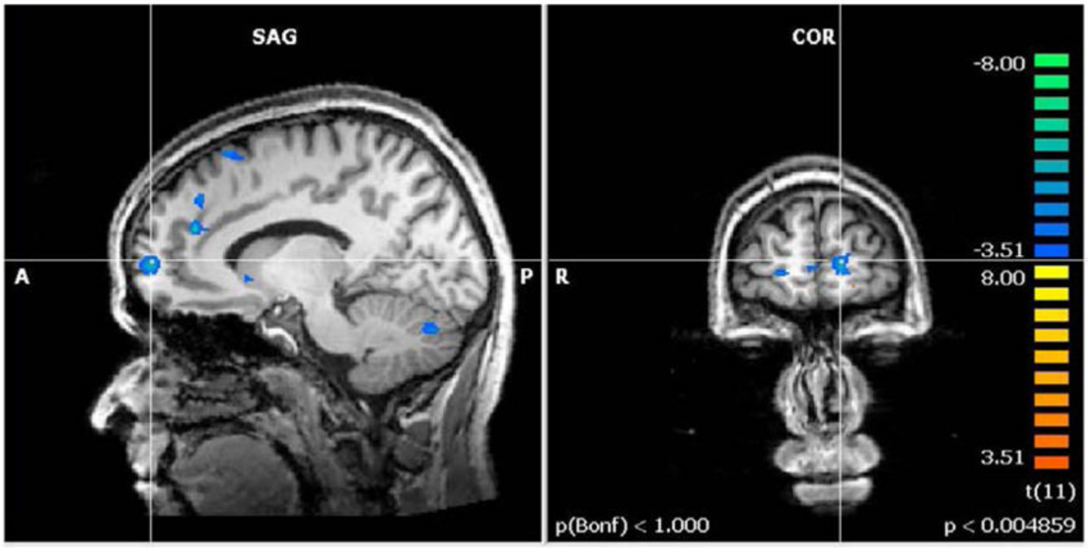

Figure 1.
Story Narratives–Random Sentences: Significantly Less Activation of the Left Medial Frontal Gyrus, BA 10

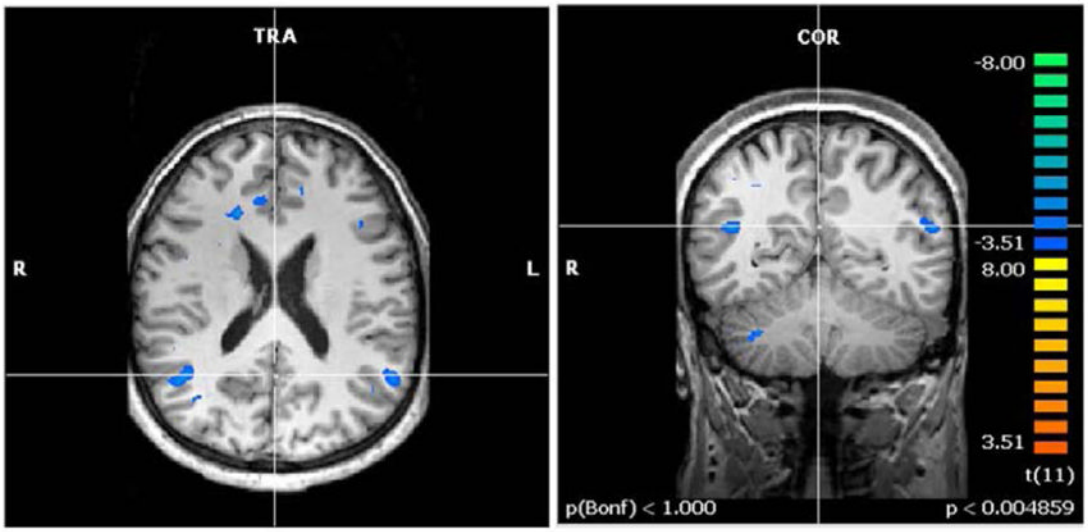

Figure 2.
Story Narratives–Random Sentences: Significantly Less Activation of the Bilateral Superior Temporalis, BA 39

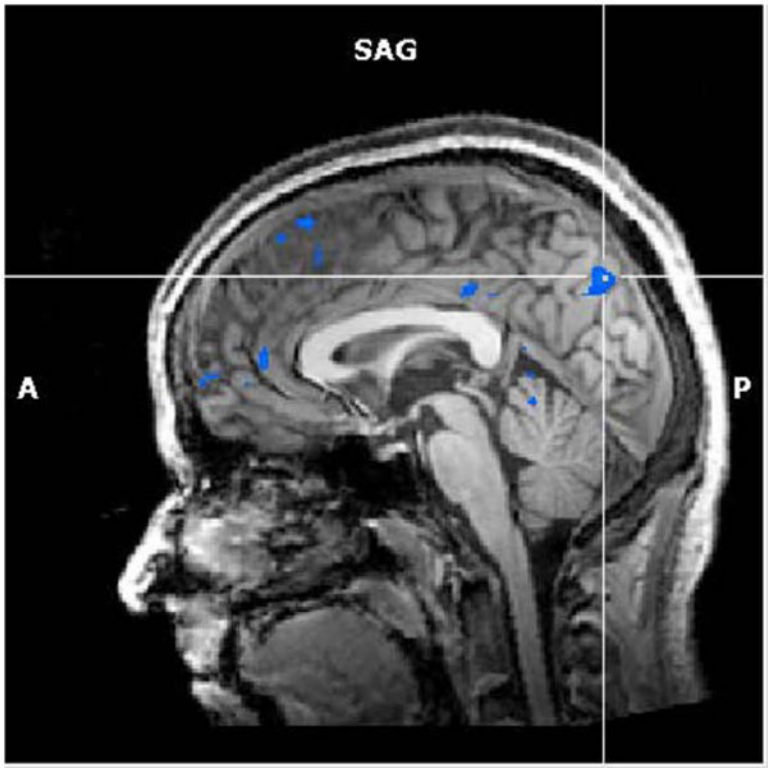

Figure 3.
Story Narratives–Random Sentences: Reduced Activation of the Left Precuneus

Table 1

"Bird Story" Subjected to Story Grammar Analysis

Story Proposition		Story Grammar Component	
1	Once there was a bird who was very playful.	**1**	Setting
2	He was in his tree and saw a kite caught on a higher branch.	**2**	Initiating Event
3	He decided to try and free the kite, so he flew up and pulled on the branch with his beak.	**3**	Internal Response & *Attempt*
4	The branch broke and he fell to the ground.	**4**	Direct Consequence
5	He was unhappy because he felt very silly.	**5**	Reaction

Adapted with permission from Schneider, P., & Winship, S. (2002). Adults' judgments of fictional story quality. *Journal of Speech, Language, and Hearing Research*, *45*(2), 372–383. Italicized components comprise the three elemental story episode components.

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Table 2

Significantly Different Activation in the Contrast Between Story Narratives and Sentences

Contrast	Coordinates			Cluster Extent	Region Description	*t* value	*p* value
	x	y	z				
Narratives > Sentences	−12	59	7	511	Left medial frontal gyrus (BA 10)	−6.157	0.000071
	9	32	22	200	Right anterior cingulate (BA 32)	−5.638	0.000151
	9	29	40	143	Right medial frontal gyrus (BA 8)	−7.299	0.000015
	33	17	37	424	Right middle frontal gyrus (BA 8)	−5.436	0.000205
	−39	20	22	141	Left middle frontal gyrus (BA 46)	−5.340	0.000237
	−9	20	58	210	Left superior frontal gyrus (BA 6)	−6.382	0.000052
	−42	20	34	257	Left precentral gyrus (BA 9)	−4.488	0.000919
	39	−61	43	598	Right inferior parietal lobule (BA 7)	−7.513	0.000012
	45	−55	19	304	Right superior temporal gyrus (BA 39)	−5.399	0.000217
	−54	−55	22	427	Left superior temporal gyrus (BA 39)	−5.078	0.000356
	−3	−76	37	376	Left precuneus	−4.377	0.001102
	39	20	1	341	Right insula	−7.186	0.000018