The neural correlates of strategic reading comprehension: Cognitive control and discourse comprehension

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ABSTRACT

Neuroimaging studies of text comprehension conducted thus far have shed little light on the brain mechanisms underlying strategic learning from text. Thus, the present study was designed to answer the question of what brain areas are active during performance of complex reading strategies. Reading comprehension strategies are designed to improve a reader's comprehension of a text. For example, self-explanation is a complex reading strategy that enhances existing comprehension processes. It was hypothesized that reading strategies would involve areas of the brain that are normally involved in reading comprehension along with areas that are involved in strategic control processes because the readers are intentionally using a complex reading strategy. Subjects were asked to reread, paraphrase, and self-explain three different texts in a block design fMRI study. Activation was found in both executive control and comprehension areas, and furthermore, learning from text was associated with activation in the anterior prefrontal cortex (aPFC). The authors speculate that the aPFC may play a role in coordinating the internal and external modes of thought that are necessary for integrating new knowledge from texts with prior knowledge.

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Introduction

The importance and difficulty of comprehending expository text is evident to anyone who has attempted to learn about a new field of science by reading a textbook. Comprehension is not a simple process of accessing word meanings and then combining them. The process of comprehension involves the construction of a mental representation of a text, which is referred to as a situation model (e.g., Kintsch, 1998; Zwaan and Radvansky, 1998). The construction of a situation model requires lexical processes to access word meanings, memory retrieval to elaborate on the text and form connections to prior knowledge, and inference processes to help integrate the current sentence with prior sentences and knowledge.

The complexity of text comprehension processes results in large individual differences in the strategies that students utilize to understand texts as well as what students learn from texts (e.g., Chi et al., 1989; Just and Carpenter, 1992; McNamara, 2004). Although there have been neuroimaging studies of text comprehension (e.g., Ferstl and von Cramon, 2001; Xu et al., 2005; Yarkoni et al., 2008a, 2008b), these studies have not examined the differences in brain activity associated with different reading strategies. Understanding the neural correlates of different types of strategic reading comprehension processes should help us to better understand the brain mechanisms underlying comprehension.

Strategic reading comprehension

There are a number of theoretical frameworks that describe the cognitive processes underlying text comprehension (Kintsch, 1988, 1998; McNamara and Magliano, 2009; Zwaan et al., 1995). Many of these theories propose that the reader constructs a situation model that is a representation of text content that abstracts away from the written form of the sentences composing the text and includes knowledge not contained directly in the text. Constructing a coherent situation model requires that the reader form a textbase on the basis of the propositions contained directly in the text itself, and elaborate on this information by using prior knowledge through inference processes (Kintsch, 1988, 1998; Zwaan, 1999; Zwaan and Radvansky, 1998).

The quality of the situation model depends on how successful the reader is at representing the propositions of the text, providing information missing from the text from prior domain-general and domain-specific knowledge, and forming coherent representations by drawing inferences across phrases in the text (Kintsch, 1998;

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McNamara et al., 1996). Characteristics of both the reader and the text influence success at forming a good situation model. For some readers, construction of a situation model is more difficult because they have little or no prior knowledge about the content of the text (Voss and Silfies, 1996). For example, low domain knowledge readers learn more from highly cohesive texts while high domain knowledge readers learn more from low cohesion text (McNamara and Kintsch, 1996; McNamara et al., 1996). Low domain knowledge readers are presumably unable to make the necessary inferences from low cohesion texts, whereas the low cohesion text forces the high domain knowledge readers to engage in inferencing processes resulting in a good situation model.

Reading comprehension strategies improve readers' comprehension of text, and while some readers use strategies naturally, others benefit from being provided with strategy instruction (McNamara, 2007). Self-explanation is one reading strategy that has been shown to be highly effective (Bielaczyc et al., 1995; Chi, 2000; Chi et al., 1989, 1994; McNamara, 2004). The self-explanation strategy was developed by observing what good students do naturally when studying worked examples in physics texts (Chi et al., 1989). Later studies on self-explanation found that training poor students to self-explain improved their comprehension and problem solving (e.g., Bielaczyc et al., 1995; Chi et al., 1994; McNamara, 2004).

Because instructing readers to self-explain most often benefits readers who are skilled self-explainers more than less skilled self-explainers (Chi et al., 1994), McNamara (2004) developed Self-Explanation Reading Training (SERT) in which students are provided with instruction and practice on using reading strategies while self-explaining texts. This approach combined the technique of self-explanation with five reading strategies with demonstrated effectiveness: comprehension monitoring, paraphrasing, elaboration, bridging, and prediction. Comprehension monitoring is being aware of whether the text is being successfully understood while reading. Paraphrasing is putting the text into one's own words in order to help activate relevant semantic knowledge in long-term memory and prepare the reader to make further inferences. Inferences are necessary in text comprehension situations because texts do not state all relevant pieces of information explicitly (Kintsch, 1998). Elaboration involves making inferences that aid in understanding the text by using knowledge from memory. Bridging involves making inferences across sentence boundaries to aid in understanding the text. Prediction is making predictions at the end of a sentence or paragraph about what information will be contained in the next section of the text.

Collectively, these strategies help the reader to process challenging, unfamiliar material by scaffolding the comprehension process. The process of self-explaining externalizes the comprehension process by helping the reader to understand the text (i.e., using paraphrasing and comprehension monitoring) and go beyond the text by generating inferences (i.e., using elaboration, bridging, and prediction). The study presented in this paper uses an intelligent tutoring system, iSTART (McNamara et al., 2004), to teach the five SERT strategies so that the neural correlates of reading comprehension strategies can be examined during comprehension of expository texts.

Neuroimaging studies of reading comprehension

There have been a number of neuroimaging studies that have investigated text comprehension (Ferstl and von Cramon, 2001, 2002; Ferstl et al., 2005; Friese et al., 2008; Hasson et al., 2007; Maguire et al., 1999; Mar, 2004; Siebörger et al., 2007; Xu et al., 2005; Yarkoni et al., 2008b). In a recent meta-analysis of neuroimaging studies of text processing, Ferstl et al. (2008) identified a set of areas common to many studies of text processing including the anterior temporal lobe (aTL), areas along the superior temporal sulcus, inferior temporal

gyrus (ITG), inferior frontal gyrus (IFG), inferior frontal sulcus, pre-supplementary motor area (pSMA), and the cerebellum. In addition, they also identified a set of regions that are associated with coherence building processes including aTL, posterior superior temporal sulcus, middle temporal gyrus (MTG), IFG, dorsal and ventral medial prefrontal cortex (dmPFC and vmPFC), and precuneus. These latter set of areas as well as the angular gyrus and posterior cingulate cortex (PCC) are active in studies examining coherence building processes such as inferencing and linking text content with global themes and other information in memory (Ferstl and von Cramon, 2001, 2002; Kuperberg et al., 2006; Maguire et al., 1999; Mellet et al., 2002).

Other discourse comprehension studies have attempted to map processes such as situation model construction and updating on to brain regions (e.g., Yarkoni et al., 2008b). In particular, Yarkoni et al. examined areas that showed a linear increase in activation during reading that might be associated with maintaining and integrating information into a situation model as the reader proceeds through the text. These areas include bilateral aTL, bilateral IFG, bilateral ITG, left precentral gyrus, bilateral posterior parietal cortex (PPC), left fusiform gyrus, and right precuneus. In addition, they also found that bilateral dmPFC was activated exclusively in the story condition. Yarkoni et al. argue that this dmPFC activation may reflect processes of integrating information into a coherent situation model or that activity in this area may reflect perspective-taking or theory-of-mind processes associated with the narrative rather than more general comprehension processes. Situation model construction and updating are exactly the kind of processes that a reading strategy such as self-explanation is thought to enhance. Thus, it is likely many of these areas would also be active when self-explaining.

Areas such as dmPFC, the angular gyrus, and the precuneus that are involved in discourse comprehension are also considered part of the brain's default network that is active when people are not engaged in an external task (Buckner et al., 2008; Gusnard et al., 2001; Raichle et al., 2001). Some studies of discourse processing have noted this partial overlap between the default network and areas active during comprehension (Xu et al., 2005; Yarkoni et al., 2008b). The default network has been associated with self-referential processing and the mental generation of a coherent scene through the retrieval and integration of information (Hassabis and Maguire, 2007). These cognitive processes should be involved in both comprehension and reading strategies as the goal is to form a coherent representation of the text being studied, and therefore one hypothesis is that areas such as dmPFC, the angular gyrus, and the precuneus will be active during the use of self-explanation.

Expository texts are designed to communicate knowledge often including technical ideas and terms with which the reader is unfamiliar embedded in low coherence text (Graesser et al., 2003). Due to these properties of expository text, implicit and explicit inference processes are likely to be needed more when processing expository text than when processing narrative text. The effectiveness of reading strategies has mostly been examined using expository texts. However, most neuroimaging studies of discourse processing have used narrative texts. The comprehension of narrative texts is thought to be similar to but also different from expository texts (Graesser et al., 2003; Kintsch, 1998). In particular, it could be expected that theory-of-mind processes play less of a role in expository text comprehension while casual and elaborative inferences play a larger role. Examining the brain areas associated with using reading strategies should provide more information about the role these areas play in the coherence building processes that are essential for expository text comprehension.

Current study

The current study examines the brain areas active during performance of reading comprehension strategies that vary in complexity and

effectiveness. Participants were taught self-explanation using iSTART, an intelligent tutoring system previously found to teach self-explanation effectively using the SERT strategies (McNamara et al., 2007). Paraphrasing a text to put it into one's own words is another reading strategy that could be used to aid comprehension, and it is one of the five SERT included in iSTART self-explanation training (McNamara et al., 2009). Finally, a commonly used reading strategy is to simply reread the material. Rereading is known to be less useful than self-explanation and is often used as a control condition to evaluate the effectiveness of self-explanation training (e.g., Chi et al., 1994). Participants were asked to reread, paraphrase, and self-explain three different expository texts on biology topics in a block design fMRI study. The comparisons of interest were between the relative activation of brain areas during performance of these three reading strategies. Learning was also assessed via improvement from pretest to posttest. Pre–post data allowed for verification of the expected effectiveness of the reading strategies as well as an analysis of the brain areas that correlated with measurable learning.

Because self-explanation is an intentional strategy that enhances a reader's existing comprehension processes, then it can be expected to involve areas of the brain that are normally involved in reading comprehension along with areas that are involved in strategic control processes. A network of brain areas including dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex/pre-supplementary motor area (ACC/pSMA), dorsal pre-motor cortex (dPMC), anterior insular cortex (AIC), inferior frontal junction (IFJ), and PPC have been shown to be active in a variety of tasks involving executive control (Brass et al., 2005; Chein and Schneider, 2005; Cole and Schneider, 2007; Dosenbach et al., 2006; Schneider and Chein, 2003; Wager et al., 2004). These areas also show high functional connectivity (Cole and Schneider, 2007), and the amount of controlled processing necessary for a task is related to the degree of activation in these areas (Chein and Schneider, 2005). To aid in localizing the executive control network, a variant of the line orientation search task used by Cole and Schneider (2007) was used as a functional localizer to define regions of interest (ROIs) for each subject.

Because reading strategies such as self-explanation are effortful and complex, we hypothesize that this executive control network will be active during self-explanation. We also expect lower levels of activation in this network for less complex reading strategies that do not involve as much effort and management of complex information, such as paraphrasing or rereading. It was also predicted that more complex strategies would show more activation of areas that previous studies have associated with discourse comprehension. It is an open question whether strategy effectiveness is primarily a function of more engagement (as measured by activation of the executive control network) or primarily a function of specific text comprehension processes beyond the executive control components.

Method

Participants

Twenty-two right-handed, native English speakers were recruited from the University of Pittsburgh and Carnegie Mellon University communities (14 female, M age = 20.7; SD = 2.4; range = 18–28). None of the participants were biology majors. One participant was excluded from analysis due to excessive head motion (more than 9 mm) during the scanning session.

Materials

Three biology texts that were matched on length (approximately 580 words) were selected along with a set of short-answer questions. Text and question difficulty were equated using data from a pilot study in which another group of participants answered the questions before and after reading and self-explaining the texts. The three texts discussed the following topics: the process of cell mitosis, the structure and function of DNA, and the circulatory system's role in heat transportation. The texts were from different topic areas to minimize transfer between them. Approximately half of the questions for each text were text-based, meaning that they could be answered given information from one sentence in the text. The answers for the other half of the questions required bridging information across multiple sentences in the text. Each text was separated into 12 paragraphs, with each paragraph containing 2–4 sentences, so that they could be presented one paragraph at a time during the study.

Design

Each participant performed all three reading strategies: rereading, paraphrasing, and self-explaining. Each participant was instructed to use a given reading strategy to read all of a given text. The assignment of reading strategies to texts was counterbalanced across participants. The order in which participants performed the reading strategies was randomized.

Each text was broken up into three sections consisting of four paragraphs each. Each of these four-paragraph sections was presented in a single data acquisition run. Because strategies were assigned to texts, participants were always performing a single strategy during each acquisition run. One four-paragraph section of each of the three texts was presented before the next four-paragraph section of each text. For example, this organization implies that the first (second) and second (third) blocks of paragraphs from a particular text were separated by a block of each of the other two texts (e.g., Text1–Block1, Text2–Block1, Text3–Block1, Text1–Block2, …). The blocks were presented in this fashion so that each reading strategy would be performed once in each third of the acquisition session in order to help control for potential confounding effects (e.g., fatigue).

Procedure

This study took place over two sessions, separated by 2–5 days, with fMRI data collected only during the second session.

Session 1

During the first session, participants were given up to 30 min to complete a pretest including all of the questions for each of the three texts. Participants then completed an iSTART session, which provided instruction on how to self-explain using reading strategies.

iSTART, described in greater detail by McNamara et al. (2004, 2006, 2007), provides students with instruction and practice on how to self-explain texts using the five SERT reading strategies: comprehension monitoring, paraphrasing, elaboration, bridging, and prediction. iSTART uses animated agents to introduce each of the five strategies by having a student agent receive instruction on the strategy by a teacher agent, and then the student agent uses the strategy. Following this introduction, for each strategy, the system asks the participant a set of questions about each strategy and has the participant identify each strategy in a set of example self-explanations. The participant then reads one expository text and practices each of the five strategies by typing in self-explanations and receiving feedback from the iSTART system on the content and quality of the self-explanations. iSTART training took approximately 90 min.

After iSTART training, the participants were provided with task practice in an MRI simulator. The MRI simulator was designed to closely simulate the physical conditions of the MRI scanner and included a magnetic tracking system to track and present feedback to the participant regarding head movement. The simulator practice was done to screen for claustrophobia, to train participants to perform the experiment (especially talking) without excessive head motion, and to provide them with practice on the experimental task using the

same button response system they would use during the scanning session. In the simulator, participants were presented with 14 paragraphs from two practice texts that were of a similar expository nature but contained different content than the texts in the experiment. Before each block of paragraphs, participants read instructions on the screen indicating the reading strategy they were to use for that block.

The title of the text was centered on the top of the screen with the paragraph appearing on the center of the screen. Along the bottom of the screen was a prompt reminding the participant of the current strategy. Participants were instructed to read the paragraph aloud once, and then to press a button on a response glove. Once they did so, the color of the paragraph's text changed from black to blue which served as a cue that they were to perform the given reading strategy aloud. The participants then reread, paraphrased, or self-explained the text and pressed a button to move to reading the next paragraph.

The paraphrasing and self-explanation strategies had been introduced within iSTART, and thus, participants were provided only brief instructions on how to either paraphrase or self-explain out loud each sentence in the text. In the paraphrase condition, participants were told to put each sentence in the paragraph into their own words without using any of the other SERT strategies. In the self-explanation condition, participants were instructed to self-explain each paragraph using the reading strategies covered in iSTART. For the rereading condition, they were told to read and then reread each paragraph out loud until the computer indicated it was time to move to the next paragraph of text. A prompt, which flashed at the bottom of the screen, instructed the participant to stop rereading and move on to the next paragraph. The rereading condition was designed this way in order to roughly equate the amount of time spent rereading with the amount of time spent paraphrasing and self-explaining. The amount of time allotted for rereading was 45 s, which was determined from a pilot study in which participants applied the three strategies to the same texts. Paraphrasing and self-explanation were self-paced with the constraint that the participant could take no longer than 60 s. Participants were prompted to move on using the same flashing prompt if they reached 60 s.

Session 2

The second session occurred 2–5 days after the first session in order to reduce the chance that participants would read the passages with the pretest questions in mind. This session began with an iSTART practice session lasting at most 30 min, which gave the participants additional practice self-explaining. This practice session was similar to the final part of the initial iSTART training in which participants read and self-explained an expository text while receiving feedback on the self-explanations from iSTART. fMRI data was collected for the remainder of the session. All tasks were presented using E-Prime (Schneider et al., 2002) on a Windows PC for task presentation and response collection. To verify strategy use within each condition, verbal responses were collected using an active noise canceling microphone system (Psychology Software Tools, Inc., Pittsburgh, PA), which almost entirely removed the scanner background noise.

Participants were reminded of the instructions for the experiment before and after being placed in the scanner. The only difference from the MRI simulator procedure was that a 30-second rest period was placed before and after each block of four paragraphs. A fixation cross was presented in the middle of a white screen for the rest period. Participants were told to relax and to try not to think about anything during this time. The participants completed a total of 9 fMRI runs with each run consisting of 4 paragraphs (3 runs while performing each of the 3 strategies). Following these 9 learning runs, participants were presented with a posttest for each text. Although the posttest was collected in the scanner, we do not examine the posttest imaging data in this paper.

After the posttest runs, participants were presented with a line search task that served as a functional localizer to localize activity in control areas (Saxe et al., 2006). A version of this task has been used in prior research on executive control (Cole and Schneider, 2007). Participants received instructions on how to complete this task just before the start of fMRI data acquisition. The task involved detecting a target line orientation of 65° by monitoring lines of differing orientation in four locations on the screen (see Fig. 1). There were three angles of distractor lines: 85°, 45°, and 155°. The line in each of the four locations changed orientation every 2 s. Only one location changed at a time, and the orientation changes proceeded in a clockwise fashion every 500 ms. Targets appeared at least 2 s apart. The participants' task was to press a button when the target was present. A control task was also presented with almost identical visual stimuli except that the participants' task was to press a button every time the central fixation cross blinked. The central fixation cross blinked the same number of times as there were targets in the line search task while all other stimuli were static. Each participant completed one to two runs of this task depending on time constraints, and each run consisted of 4 blocks of each task with blocks alternating between the line and control tasks. Each block of the tasks began with 6 s of encoding, followed by 30 s of the task (control or line search), followed by a 6 s delay before the next block began.

In order to increase statistical power in the pretest/posttest comparison across reading strategy conditions while constraining the number of fMRI participants, a second group of 14 behavioral participants was run using the same reading strategy paradigm. The only differences between the groups were that the behavioral group was run in front of a computer instead of in the scanner and did not complete the line search functional localizer task.

Data acquisition and analysis

Structural and functional images were collected on a whole body Siemens Trio 3 T scanner at the Magnetic Resonance Research Center of the University of Pittsburgh Medical Center during a 2-hour scanning session. The scanning session began with the acquisition of structural images, which included scanner-specific localizers and volume anatomical series. The volume anatomical scan was acquired in a sagittal plane (1 mm^3) using the Siemens MP-RAGE sequence and the functional data were co-registered to these images. The functional runs were acquired as 39 oblique-axial slices parallel to the AC–PC plane using a T2*-weighted echo-planar imaging (EPI) pulse sequence (TE = 25 ms, TR = 2000 ms, FOV = 21, slice thickness = 3.5 mm with no gap, flip angle = 76, in-plane resolution = 3.28 mm^2).

The raw neuroimaging data were preprocessed and analyzed using the AFNI software package (Cox, 1996). Preprocessing included slice scan time correction, three-dimensional motion correction, and spatial smoothing. All functional images were realigned to the first image of each run, which were aligned to the first run of each subject. The signal for each voxel was spatially smoothed (7 mm FWHM). Each subject's MP-RAGE anatomical images were co-registered to their functional images by applying a transformation to the anatomical images. The structural and functional images were then transformed into a canonical Talairach space (Talairach and Tournoux, 1988).

Analyses of the fMRI data used voxel-based statistical techniques. Unless otherwise specified, all results were corrected for multiple comparisons using family-wise error (FWE) cluster size thresholding to an FWE corrected p-value of less than .05 (Forman et al., 1995). Cluster sizes were determined using AFNI's Alphasim, which allows for determination of cluster size using Monte Carlo simulations. At the individual subject level, general linear models were fit to the data using a set of boxcar functions convolved with a standard hemodynamic response function (Boynton et al., 1996). Separate regressors for reading, rereading, paraphrasing, and self-explaining were included in
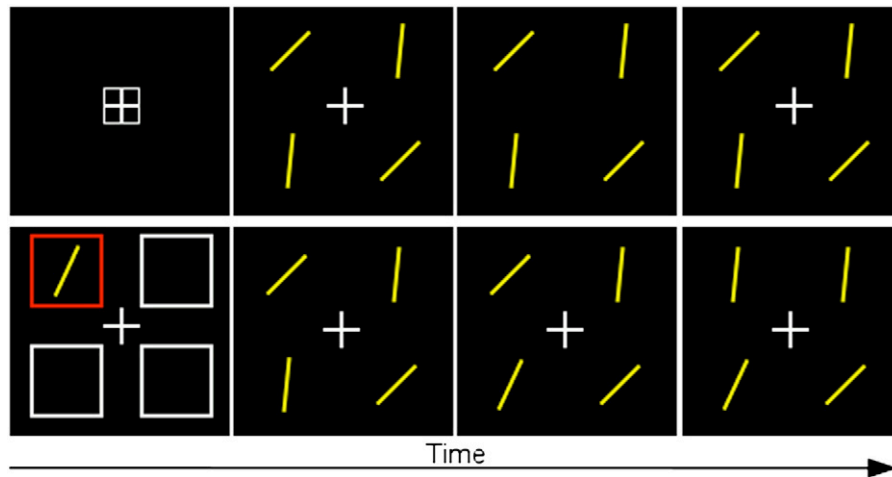
Fig. 1. Line search task. The top row is the control condition, and the bottom row is the search condition.

the model. Each group-level analysis used a mixed effects model with subjects as a random factor.

The line search task was used as a functional localizer to define subject-specific ROIs corresponding to the six bilateral areas of the executive control network (DLPFC, ACC/pSMA, dPMC, AIC, IFJ, PPC). The line search fMRI data were not spatially smoothed for this analysis. ROIs corresponding to the control net regions were defined on the basis of each subject's FWE-corrected statistical map for the contrast of the line search and control conditions. A corrected p-value of .05 was obtained by using the combination of a voxel-based p-value of .01 with a cluster threshold of 6 contiguous voxels. Local peaks of activation corresponding to the anatomical location of the control net areas were used to identify each ROI for each subject, and then all statistically significant voxels within a sphere of radius 15 mm from the peak were included in the ROI.

Results

Behavioral results

The proportions correct on the pretest and posttest were used to calculate a learning gain score, where gain = (posttest − pretest)/(1 − pretest). This gain score adjusts for the fact that questions already answered correctly on the pretest cannot be improved upon on the posttest (Cohen et al., 1999). Due to technical difficulties, the recordings from a portion of two participants' posttests were not available to be scored. These missing scores corresponded to the paraphrase strategy for one participant and the self-explanation strategy for another.

The gain scores for the behavioral and imaging participants did not differ on any of the three conditions (for all comparisons, $p > .3$), so the data for these two groups were combined for the analysis of the effect of strategy on learning. Planned comparisons showed that rereading gain ($M = .41$, $SD = .26$) did not differ from paraphrasing ($M = .42$, $SD = .22$), $t < 1$. As expected, self-explanation led to greater learning ($M = .51$, $SD = .19$) than paraphrasing, $t(32) = 2.41$, $p = .02$, Cohen's $d = 0.4$, and rereading, $t(33) = 2.03$, $p = .05$, Cohen's $d = 0.4$.

All participants in the imaging portion of the study performed the line search task well; d' was greater than 2 for all participants.

Imaging results

Analysis of areas that were more active in the line search task than in the control condition confirmed that the task served well as a functional localizer. As can be seen in Fig. 2, this task activated the expected set of six bilateral ROIs consistent with prior work on a domain-general control network (e.g., Chein and Schneider, 2005).

Average percent signal change in the control network ROIs for each of the three reading strategies relative to the rest condition is presented in Fig. 3. For each ROI, an ANOVA was run to test for differences between the three strategies. Bonferroni corrections were used because 12 separate ANOVAs were conducted. For ANOVAs indicating a significant difference, a series of planned comparisons was used to determine whether certain strategies activated the control regions more than other strategies in a particular ROI. The 12 ROIs fell into two groups. One group did not show any differential activation for the three strategies. This group included right AIC, right IFJ, and right DLPFC. The second group, consisting of the remaining 9 control network ROIs, all showed greater activation for the paraphrase and self-explanation strategies relative to the reread strategy but no difference in activation between the paraphrase and self-explanation strategies. Overall, the results indicate that with the exception of 3 ROIs in the right hemisphere the control network was more active during performance of paraphrasing and self-explanation, but the control network did not differentially activate for these two strategies.

In order to directly examine differences in activation between the different strategies, a voxel-wise ANOVA with strategy (reread, paraphrase, self-explain) as a within-subjects factor was conducted followed by three planned contrasts (paraphrase–reread, self-explain–reread, and self-explain–paraphrase). Contrasts were done using the strategy participants had been instructed to perform as well as using a self-explanation coding process to determine whether they had indeed self-explained each paragraph. The self-explanation strategy training consisted of five separate techniques: comprehension monitoring, paraphrasing, bridging, elaboration, and prediction. The verbal protocols from both the behavioral and imaging participants were transcribed, and the self-explanation for each paragraph was coded for whether it contained each of the five techniques comprising self-explanation using a coding scheme based on prior self-explanation research (McNamara, 2004). Inter-rater agreement between two independent coders was good (89% agreement; Cohen's kappa = .66). If the self-explanation for a paragraph did not contain any self-explanation strategy other than paraphrasing, then that self-explanation was classified as being in the paraphrase condition. This reclassification resulted in an average of 1.7 out of 12 self-explanations per participant being reclassified as paraphrases. The fMRI results were similar for both versions of this analysis with the reclassified data generally showing slightly more significant local maxima, therefore only the reclassified analysis is reported.

For the contrasts between the reading strategies, activation in the line search task was examined to identify clusters of activation that fell both inside and outside of the control net. Tables 1 and 2 show for each
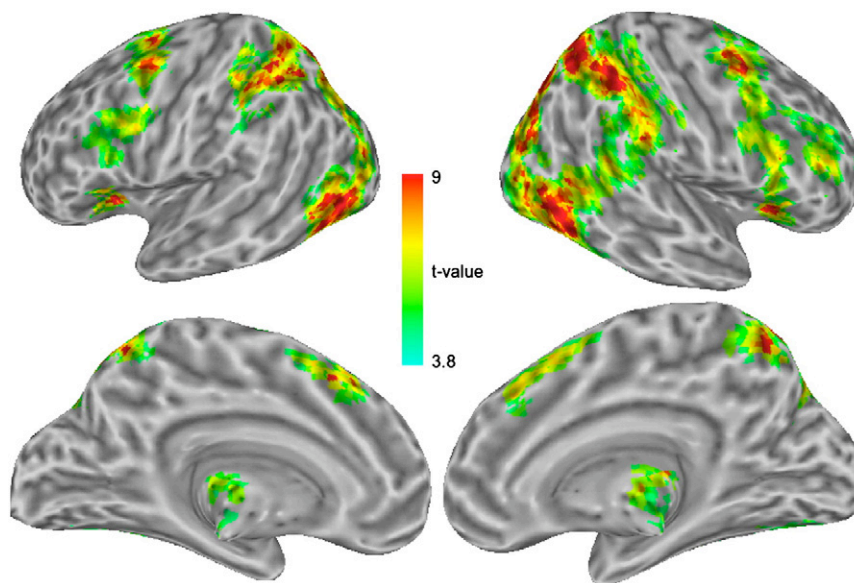
Fig. 2. Statistical map for group analysis of areas active in line search functional localizer task projected on to cortical surface ($p<.001$, minsize $= 490$ mm^3). Statistical maps projected on to cortical surface. Corresponds to table of regions in supplementary materials. For all figures, left hemisphere lateral and medial views are on the left of the figure.

peak whether or not the peak fell within a control net region or not. The areas more active for the paraphrase condition compared to rereading are shown in Table 1. Areas outside of the control net included left pSMA, left IFG, right lingual gyrus, right cerebellum, and bilateral areas of the basal ganglia. The self-explanation–reread contrast yielded many of the same regions as the paraphrase–reread contrast as can be seen in Table 1 and Fig. 4 (see supplementary materials for an image of the paraphrase–reread contrast). In addition to the areas outside of the control net seen in the paraphrase–reread contrast, regions of activation included left dmPFC, left superior frontal gyrus, left precuneus, left MTG, and the thalamus. Given that many of the peaks overlapped with the control network, these results are consistent with the hypothesis that there is engagement of a domain-general control network with the use of complex reading strategies.

However, the contrast between the self-explanation and paraphrase conditions shows a different pattern of results as seen in Table 2 and Fig. 5. None of the regions are part of the control network, and they include bilateral activations in prefrontal cortex, PCC, precuneus, and the angular gyrus.

An additional analysis was conducted to examine whether the contrasts between the learning strategies may be explained in part by production processes that differ across the three reading strategies rather than comprehension processes. Coh-Metrix (Graesser et al., 2004) was used to examine the transcribed utterances produced by participants. Coh-Metrix analyzes text and provides a number of variables related to the content of the texts being analyzed including syntactic variables. The variables that Coh-Metrix reported were examined to see if they differed across the reading strategies.
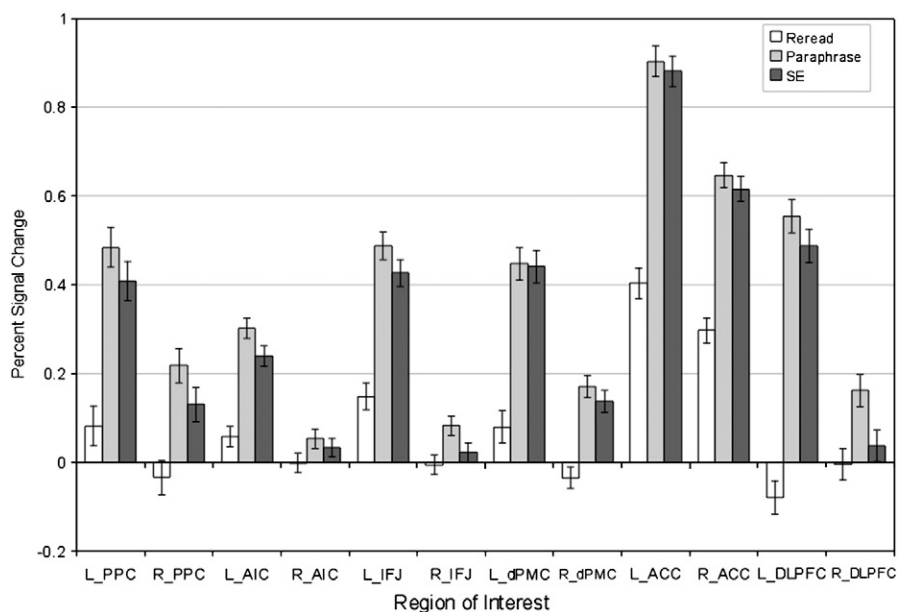
Fig. 3. Mean signal change and standard error in each executive control network ROI for each reading strategy.

Table 1
Local maxima of regions showing positive activation in paraphrase–reread and self-explanation–reread contrasts ($p<.001$, minsize $= 490$ mm^3).

Regions	Control net	BA	Self-explanation–reread					Paraphrase–reread				
			Cluster size (mm^3)	x	y	z	Peak t	Cluster size (mm^3)	x	y	z	Peak t
Frontal cortex												
L dPMC	Partial	6	57,956	−33	6	52	11.25	47,631	−30	0	56	10.54
L ACC/pSMA	Partial	6,32	–	−10	13	52	10.61	–	−10	13	52	10.77
L ACC	Partial	32						–	−7	23	35	7.99
R ACC	Yes	32	–	3	19	38	7.06	–	3	19	38	6.6
R pSMA	Yes	6	–	3	10	56	6.43	–	3	10	56	5.97
L IFJ	Yes	6,9,44	–	−36	13	31	8.93	–	−39	6	35	8.78
L inferior frontal g	No	44,45	–	−46	13	10	6.68	–	−49	16	17	8.08
L inferior frontal g	No	13,47	–	−43	29	0	6.44	–	−39	23	−1	3.34
L superior frontal g	No	6,8	–	−10	33	52	5.5					
L superior frontal g	No	8	–	−10	49	42	4.6					
L insula	Yes	13,45	–	−26	26	3	6					
L inferior frontal g	No	10,46	–	−43	36	17	5.28	753	−33	33	13	5.04
R dPMC	Yes	6	980	20	−7	56	5.18	1394	26	0	55	5.43
Parietal cortex												
L superior parietal	Yes	7	9345	−23	−69	49	8.41	9646	−13	−69	49	10.25
L precuneus	No	7	–	−3	−66	42	7.24					
L parietal/occipital	Yes	7,19	–	−26	−66	31	6.9					
L inferior parietal	Yes	40						–	−33	−43	35	6.4
R superior parietal	Yes	7						3052	26	−69	38	7.4
Temporal cortex												
L middle temporal g	No	21,37	2788	−56	−46	−4	6.92					
Occipital cortex												
R lingual g	No	18	980	13	−82	−8	7.25	528	16	−79	−8	4.86
R middle occipital g	Yes	19						565	33	−79	10	4.51
Cerebellum/subcortical												
R cerebellum	No		12,548	23	−66	−25	9.24	10,099	23	−59	−29	7.62
R cerebellum	Yes		–	33	−49	−29	8.11	–	39	−59	−25	7.11
R cerebellum	No		–	39	−56	−46	5.23	–	39	−46	−46	4.35
R cerebellum	No							–	16	−72	−39	6.37
L caudate	No							4521	−16	10	14	6.63
L globus pallidus	No		9345	−13	−4	3	9.89	–	−13	−4	3	8.64
L midbrain	No		–	−3	−23	−11	4.71					
L thalamus	No		–	−7	−17	17	4.66					
R globus pallidus	No		3617	16	−4	3	8.55	641	13	0	3	5.35
R caudate	No		–	16	6	21	5.11					

Note. All regions within a connected cluster are presented on consecutive lines. The first row within a cluster contains the cluster size, and all regions within the same cluster contain a '–' for cluster size.

Verbalizations during rereading had fewer verbs and a lower Flesch Reading Ease score than paraphrases and self-explanations. Because rereading was just a repetition of the texts, these differences indicate that verbalizations composed by participants did differ from the original texts. Paraphrases also differed from rereadings on variables related to cohesion including noun-stem overlap, temporal cohesion, and incidence of intentional actions/participles. Self-explanations had higher frequency words, more adverbs, more connectives, and a higher proportion of causal participles to causal verbs than did rereadings.

Self-explanations differed in a number of ways from paraphrasing. Syntactic differences included more adverbs, a higher proportion of function words, higher lexical diversity, lower syntactic similarity across sentences, fewer modifiers per noun phrase, and nouns with lower hypernym value for self-explanations than paraphrases. Measures of cohesion that differed included lower noun-stem overlap and more causal verbs/participles for self-explanations than paraphrases. Also, self-explanations had a lower incidence of intentional actions/events but a higher ratio of intentional participles to intentional actions/events indicating that intentional cohesion was higher for self-explanations.

Any variable that differed significantly across the strategies was included as a covariate in a group analysis of the imaging data that replicated the contrasts reported above. Inclusion of the covariates did not alter the significance or location of any of the peaks reported for the strategy contrasts.

The previous contrasts examine areas that were more active when participants were self-explaining. However, another approach to examining self-explanation is to examine those times when it led to measurable learning. Thus, a separate analysis was conducted to examine whether there were brain regions that had activity parametrically modulated by successful learning. This analysis was conducted by using an amplitude-modulated regressor in addition to the strategy regressor for the self-explanation runs. The amplitude of this regressor was based on the gain score for a particular paragraph. The gain score for each paragraph was calculated by first determining for each question on the pre/posttests in which paragraph the information to answer the question was presented. Some paragraphs may have mapped to multiple questions. In this case, the average gain across all questions mapping to that paragraph was calculated. The regressor for the analysis was formed by convolving a boxcar function whose amplitude was determined by the gain score with a hemodynamic response function. The mean gain score for each subject was subtracted from the amplitudes to yield a regressor that was used to identify brain areas exhibiting a linear relation to gain scores (e.g., Buchel et al., 1998).

This learning analysis identified a set of bilateral prefrontal areas that were positively associated with learning gains. These areas are shown in Fig. 6 and Table 3. There were no areas negatively associated

Table 2
Local maxima of regions showing positive activation in self-explain–paraphrase contrast ($p < .001$, minsize = 490 mm^3).

Regions	Cluster size (mm^3)	Control net	BA	x	y	z	Peak t
Frontal cortex							
L orbital g	942	No	10	−3	59	7	4.77
R orbital g	–	No	10	3	49	−1	4.51
L superior frontal g	942	No	9,10	−7	59	24	5.59
R superior frontal g	–	No	9,10	3	56	28	3.98
L anterior cingulate	490	No	10,32	−7	49	3	4.91
Parietal Cortex							
L posterior cingulate	12,360	No	23,31	−7	−33	35	7.62
L posterior cingulate	–	No	23,31	−7	−49	28	6.76
L precuneus	–	No	7,31	−3	−69	28	5.32
R posterior cingulate	–	No	23,31	3	−49	28	6.53
R precuneus	–	No	7,31	7	−66	24	5.36
L angular g	4333	No	39	−49	−66	24	6.1
R angular/middle temporal g	2223	No	37,39	46	−66	10	5.95
Cerebellum/Subcortical							
L cerebellum	565	No		−16	−43	−18	5.03

Note. All regions within a connected cluster are presented on consecutive lines. The first row within a cluster contains the cluster size, and all regions within the same cluster contain a '–' for cluster size.

with learning gain. In addition to the areas that were active during self-explanation, these anterior prefrontal areas were more active during self-explanation trials during which material was learned well enough to be answered better on the posttest than the pretest.

Discussion

The results provide evidence that complex reading strategies engage executive control regions, semantic/comprehension regions, and bilateral aPFC. The behavioral learning results confirmed that the three reading strategies differed in effectiveness as hypothesized. With a relatively short learning period for complex science materials and a short delay between learning and test, these moderately-sized learning differences were as expected. With longer delays, there

would likely be further differentiation of results between paraphrasing and rereading as well as between self-explanation and paraphrasing.

Comparing the least complex strategy, rereading, with the next most complex strategy, paraphrasing, showed that predominantly areas known to be involved in executive control were more active for the more complex strategy. This finding is consistent with our initial hypothesis that more complex strategies would require more engagement and cognitive control. In addition to the control network, areas of activation identified in a recent meta-analysis of language processing included left pSMA and left IFG (Ferstl et al., 2008). The other active non-control regions included right lingual, right cerebellum, and portions of the basal ganglia, which have previously been seen in studies of word and sentence reading (e.g., Joubert et al., 2004; Xu et al., 2005). Based on these results, it appears that paraphrasing activates the control network and a portion of the language processing network more than rereading does.

Self-explanation when contrasted with rereading activated the same regions as paraphrasing as well as additional areas including left superior frontal gyrus near the dorsal median wall, left precuneus, left MTG, and the thalamus. Many of these areas including premotor cortex and the thalamus are known to be active during word and sentence processing (e.g., Xu et al., 2005). Areas such as dmPFC, the precuneus, and MTG have been linked to coherence building processes including inferencing (Ferstl and von Cramon, 2001, 2002; Ferstl et al., 2008; Friese et al., 2008). In particular, Maguire et al. (1999) found the same area of the precuneus to be more active during the second reading of a narrative passage, and they hypothesized that this area might be associated with the processing of episodic memories while further developing a mental model of the text. The self-explanation strategy was designed to promote coherence building processes, and these results support the link between these brain regions and coherence building cognitive processes.

The control network was not more active for self-explanation than it was for paraphrasing. The benefits of self-explanation over paraphrasing were clear in the behavioral learning results, but were associated with areas outside of the control network. Because these areas are defined as control areas by the fact that they show practice-related decreases as more automatic processing occurs (Chein and Schneider, 2005), then the activation of the control network may be
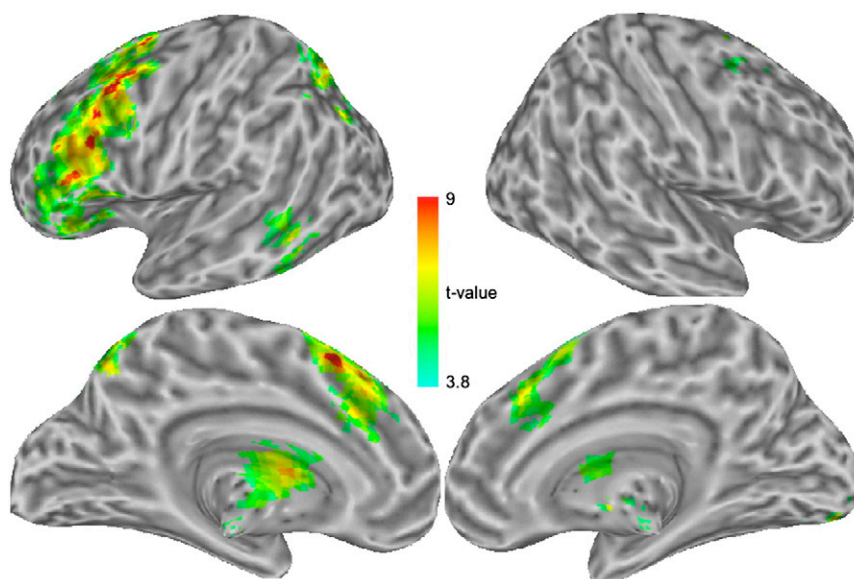
Fig. 4. Statistical map for group analysis of areas more active in self-explanation than reread projected on to cortical surface ($p < .001$, minsize = 490 mm^3). Corresponds to list of regions in Table 3. Activation map is very similar to paraphrase–reread contrast map (see supplementary materials).
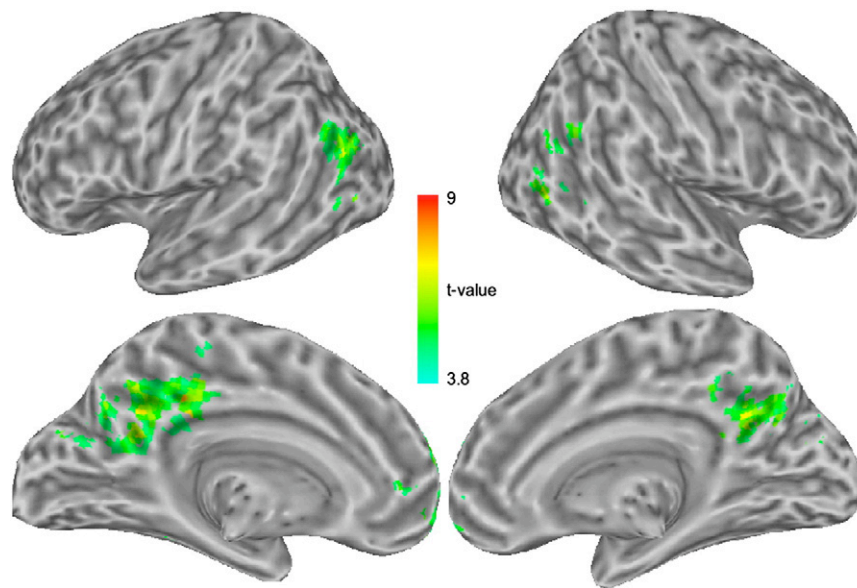
Fig. 5. Statistical map for group analysis of areas more active in self-explanation than paraphrase projected on to cortical surface ($p<.001$, minsize $= 490$ mm^3). Corresponds to list of regions in Table 2.

seen as an indication of the amount of controlled processing required. The effectiveness of self-explanation was never expected to be solely due to the controlled effort involved, but it is interesting that the more effective complex reading strategy requires a similar amount of effort as a less effective one.

The contrast of self-explanation with paraphrase yielded activation in bilateral vmPFC (anterior cingulate and orbital gyri), bilateral dmPFC (superior frontal gyrus), bilateral precuneus, and left PCC which were all identified in a meta-analysis of studies contrasting coherent with incoherent text (Ferstl et al., 2008). Also, the bilateral angular gyrus activation found in this contrast is close to the superior temporal sulcus region found in the same meta-analysis. The overlap between this contrast and the meta-analysis shows that the regions more active in self-explanation than paraphrasing are the same regions known to be involved in coherence building processes while reading. Most of the studies included in the meta-analysis used narrative texts or sentences, so this overlap also indicates that the processing of expository text involves similar brain regions as the coherence building processes that occur for narrative texts. The only area identified by Ferstl et al. (2008) that was not seen in this contrast is the aTL. The lack of aTL activation is also consistent with other studies that have examined inferencing in discourse comprehension (Kuperberg et al., 2006). Ferstl et al. (2008) hypothesize that this region may be associated with producing a semantic propositional

representation, and it could be that this process is equally important for rereading, paraphrasing, and self-explaining which is why it was not seen in our results.

The angular gyrus, PCC, and precuneus have been associated with relating text to prior knowledge and the use and manipulation of mental models (Maguire et al., 1999; Mellet et al., 2002; Xu et al., 2005). The areas active in the MTG in self-explanation are also similar to areas that have been found when people draw inferences during text comprehension (Virtue et al., 2006). These are exactly the kinds of cognitive processes that a reading strategy such as self-explanation is assumed to engage to support deep comprehension of the text.

An open question is whether there is a special role for right hemisphere language processing regions in comprehending discourse. Some neuroimaging and neuropsychological studies have found that the right hemisphere may be more important for discourse comprehension and making inferences than the left hemisphere (e.g., Beeman and Chiarello, 1998; Jung-Beeman, 2005; Lehman-Blake and Tompkins, 2001; Mason and Just, 2004; St George et al., 1999). The evidence is mixed as some studies, including a recent meta-analysis, have not found a differential level of activity in the right hemisphere during discourse comprehension (e.g., Ferstl and von Cramon, 2001, 2002; Ferstl et al., 2008; Kuperberg et al., 2006). Visual inspection of Figs. 4 and 5 also shows that if anything activity is left lateralized. In many cases, regions are activated bilaterally, but the right hemisphere
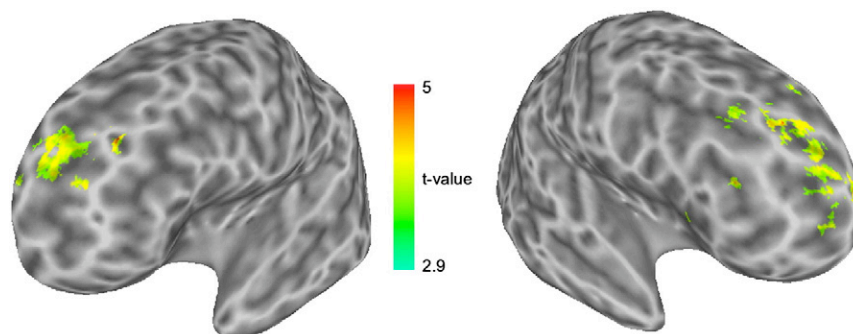
Fig. 6. Statistical map for areas linearly related to measurable learning gains during self-explanation projected on to cortical surface ($p<.01$, minsize $= 1496$ mm^3). Corresponds to list of regions in Table 3.

Table 3
Local maxima of regions showing activation for learning regressor ($p < .01$, minsize = 1496 mm^3).

Regions	Cluster Size (mm^3)	BA	x	y	z	Peak t
R inferior frontal gyrus	4560	46	35	28	18	5.11
R superior frontal gyrus	–	10	23	53	15	4.86
R superior orbital gyrus	–	10	23	41	0	4.21
R middle frontal gyrus	–	9	31	45	31	4.10
L superior frontal gyrus	2148	10	−18	43	21	5.05
L middle frontal gyrus	–	9,10	−33	39	28	4.86

Note. All regions within a connected cluster are presented on consecutive lines. The first row within a cluster contains the cluster size, and all regions within the same cluster contain a '–' for cluster size.

was not differentially activated for self-explanation than for either of the other two strategies even though self-explanation should lead to more inferences than the other strategies. The evidence in the literature for a special role of the right hemisphere in inferencing is mixed, but our results are consistent with other work on inferencing in discourse comprehension (e.g., Kuperberg et al., 2006) as well as the meta-analysis by Ferstl et al. (2008) that do not show differential right hemisphere activity.

While the activation shown while performing self-explanation seems to be associated with coherence building processes as expected, it is interesting to note that the contrast between self-explanation and paraphrase is not a subset of the regions active for the self-explanation–reread contrast. This pattern of results indicates that activation of many of the regions in the self-explanation–paraphrase contrast was similar to the reread condition. Many of the regions in the self-explanation–paraphrase contrast are part of the default network (Buckner et al., 2008; Raichle et al., 2001). There are a number of possible interpretations for the highly consistent pattern of activity that defines the default network, but many of these explanations focus on an internal mode of thought that is stimulus independent self-guided thought (Buckner et al., 2008). These stimulus-independent thoughts have been associated with lapses in attention (Weissman et al., 2006) and mind wandering (Christoff et al., 2009), but this mode of thought is also thought to have adaptive purposes (Bar, 2007; Hassabis and Maguire, 2007). One explanation for our results is that during rereading participants were engaging this same network for the purposes of self-directed thought or mind wandering instead of processing text. Rereading is not a particularly demanding task especially because our participants repeated the same paragraph two or more times in a row so that they spent the same amount of time rereading as self-explaining and paraphrasing. This less demanding strategy could have left enough time and attention free that mind-wandering occurred to some degree while rereading.

In support of this explanation of increased mind wandering during rereading, we have data from a recent fMRI study on mind wandering during reading strategies using a similar methodology as the current study (Moss et al., 2011). In this follow-up study, participants rated the frequency of mind wandering while performing the reading strategies after each short paragraph. Mind wandering ratings were significantly higher for rereading than for self-explanation ($p < .05$), and marginally higher for rereading than for paraphrasing ($p < .06$). This data suggests that some of the differences between the rereading contrasts and the self-explanation–paraphrase contrast may be due to mind wandering.

Rereading is also different from paraphrasing and self-explanation because it does not require the generation and production of new sentences as the other two strategies do. While the inclusion of covariates related to syntactic complexity did not alter the results, the covariate analysis does not completely rule out production planning and other production-related differences in the contrasts between rereading and the other strategies. In fact, the generation of new sentences beyond those contained in the text is an inherent difference between rereading and the more effective strategies. The design of this study does not permit the separation of the reread contrast results into comprehension versus production related regions. This limitation provides the basis for future work on understanding the neural correlates of strategic reading comprehension.

It has been found that the default network is anti-correlated with attentional and executive control areas (Fox et al., 2005). Effective reading strategies appear to strongly activate both executive control areas as well as default mode areas. These default mode areas likely perform similar functions during rest and during comprehension. One possibility is that effective reading strategies are explicit strategies that involve intentionally carrying out a sequence of actions, but that these strategies intentionally involve functions like memory retrieval, mental simulation, and information integration that are performed during mind wandering and other forms of self-directed thought as well.

The analysis of the areas that were correlated with the amount learned during self-explanation mainly included bilateral aPFC. That is, in addition to the activity in executive control and text comprehension areas associated with self-explanation, the aPFC was more active during self-explanation of paragraphs where measurable learning took place. Maguire et al. (1999) also found that a similar region of the left aPFC was associated with the number of idea units recalled after reading a narrative, and it was also active while listening to a second repetition of the story. They hypothesized that this area is associated with retrieval success. Alternatively, a recent theory of aPFC function refers to it as a router or gateway between modes of thought (Burgess et al., 2005, 2007). One of these modes of thought is one in which external representations (i.e., objects in the environment) drive thought, and the other mode is one in which internal representations drive thought. This gateway hypothesis might help to explain the correlation of the aPFC with learning in this study. The aPFC might be helping to coordinate the reading and processing of the text presented on the screen with the internal retrieval of memories and construction of situation models. It may also reflect the coordination of an explicit strategy with the types of internal thought normally associated with the default network. Self-explanation may be most effective in aiding learning when there is a good deal of strategic processing of internal representations.

Conclusions

This initial exploration of the neural correlates of strategic reading comprehension has shown that networks of areas associated with executive control and the manipulation of internal representations and memories underlie the effectiveness of these strategies. Self-explanation produced greater learning gains than the other two strategies, and performing self-explanation led to greater activation in areas associated with executive control as well as discourse comprehension areas involved in the maintenance and manipulation of internal representations to build coherent situation models. The results show that the benefits of self-explanation are not solely due to increased engagement of the executive control network because paraphrasing activated the control network to a similar degree. Instead, co-activation of the control network and discourse comprehension areas distinguished self-explanation from the less effective strategies. In addition, aPFC activation was associated with learning gains while performing self-explanation. Future work should explore the role of aPFC in reading strategies as well as whether these results will generalize to other texts and other types of texts, such as narratives.

Supplementary materials related to this article can be found online at doi:10.1016/j.neuroimage.2011.06.034.

Acknowledgments

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