

## An fMRI Study of Strategic Reading Comprehension

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### Abstract

While there have been neuroimaging studies of text comprehension, little is known about the brain mechanisms underlying strategic learning from text. 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 learning strategy. The present study was designed to answer the question of what brain areas are active during performance of complex reading strategies. Activation was found in both executive control and comprehension areas, and furthermore, learning gains were found to be associated with activation in the anterior prefrontal cortex (aPFC).

**Keywords:** Reading Strategies; fMRI; Cognitive Control

### Introduction

The importance and difficulty of comprehending expository text is obvious to anyone who has tried to learn about a new field of science by reading a textbook. The complexity of text comprehension and learning processes results in large individual differences in the strategies that students engage in to understand texts and what students extract from texts (e.g., Chi, Bassok, Lewis, Reimann, & Glaser, 1989; McNamara, 2004). While there have been neuroimaging studies of text comprehension, these studies have not examined the differences in brain activity associated with different reading strategies. Thus, understanding the neural correlates of different types of strategic reading comprehension should help us to better understand both the brain mechanisms underlying comprehension as well as the way in which these strategies affect comprehension.

There have been a number of neuroimaging studies that have investigated the brain areas involved in text comprehension (e.g., Xu, Kemeny, Park, Frattali, & Braun, 2005; Yarkoni, Speer, & Zacks, 2008). These studies show that a network of neural regions are used in text

comprehension including inferior frontal and temporal areas associated with language comprehension and production as well as areas distributed throughout the temporal, parietal, and frontal cortices that appear to be associated with building coherent representations of texts.

When contrasting sentence-level processing with narrative-level processing, Xu et al. (2005) identified a network of areas including the hippocampus, caudate, thalamus, prefrontal cortex, precuneus, posterior cingulate, and angular gyrus. Hippocampal areas are likely associated with memory formation and retrieval. They hypothesized that the caudate, thalamus, and prefrontal cortex were involved in the sequencing of higher-level processes associated with reading comprehension. Medial prefrontal cortex, precuneus, and posterior cingulate were hypothesized to be involved with linking text content with global themes and other information in memory, and the angular gyrus was hypothesized to be involved in the mental scanning of spatial representations built from the text.

A number of the areas 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, Andrews-Hanna, & Schacter, 2008). Some studies of discourse processing have noted this overlap between the default network and areas active during comprehension (e.g., Xu et al., 2005; Yarkoni, Speer, Balota, McAvoy, & Zacks, 2008). The default network has been associated with self-referential processing and the generation of coherent mental representations (Hassabis & Maguire, 2007). If the reader's goal is to form a coherent representation of the text, then these processes would be involved in all forms of comprehension including strategic reading comprehension.

Reading comprehension strategies improve readers' comprehension of text. Some readers use strategies naturally, and others benefit from being provided with strategy instruction. Self-explanation is one reading strategy

that has been shown to be effective at improving readers' comprehension when students are trained or prompted to use it (Chi et al., 1994; McNamara, 2004).

Because instructing readers to self-explain 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 reading strategies with demonstrated effectiveness. SERT includes five component reading strategies: comprehension monitoring, paraphrasing, elaboration, bridging, and prediction (McNamara, 2004). 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. The process of putting text into one's own words helps to activate relevant semantic knowledge in long-term memory and prepares the reader to make further inferences. Inferences are necessary in most text comprehension situations because most 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 and the reading strategies help 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).

Because self-explanation is a strategy that enhances 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 have been shown to be active in a variety of tasks involving executive control (Chein & Schneider, 2005; Cole & Schneider, 2007). This control network includes dorso-lateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), pre-supplementary motor area (pSMA), dPMC, anterior insular cortex (AIC), inferior frontal junction (IFJ), and posterior parietal cortex (PPC). These areas have been shown to be active in a variety of tasks involving executive control (Chein & Schneider, 2005; Cole & Schneider, 2007). Because learning strategies such as self-explanation are effortful and complex, we hypothesize that this executive control network will be active during self-explanation. We expect lower levels of activation for less complex learning strategies that do not involve as much effort and management of complex information, such as simple paraphrasing or rereading of information.

The present study contrasted these three learning strategies—rereading, paraphrasing, and self-explaining—differing in complexity and effectiveness. Rereading is commonly used as a reading strategy but has been found to be less effective than self-explanation and is often used as a control condition to evaluate the effectiveness of self-explanation training (Chi et al., 1994). Paraphrasing a text to put it into one's own words is another learning strategy that could be used to aid comprehension. It was predicted that more complex strategies would show more engagement of the executive control network as well as greater activation of areas that previous studies have associated with text 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. In addition to examining activation associated with each learning strategy, this study will examine if there are areas that are associated with measurable learning gains.

## 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 during the scanning session.

### Materials and Design

Three biology texts that were matched on length were selected along with a set of 15 short-answer questions for each text. Text and question difficulty were equated using data from a pilot study in which students answered the questions before and after reading and self-explaining the texts. The texts were separated into 12 paragraphs, each containing 2-4 sentences. Each participant performed all three learning strategies: rereading, paraphrasing, and self-explaining. Each participant was instructed to use a given learning strategy to read all of a given text. The assignment of learning strategies to texts was counterbalanced across participants. The order in which participants performed the strategies was randomized. Each text was presented over three blocks consisting of four paragraphs each. Each block of paragraphs for each of the texts was presented before the next block of paragraphs for each text (e.g., Text1-Block1, Text2-Block1, Text3-Block1, Text1-Block2, ...).

### Procedure

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

**Session 1** During the first session, participants were given up to 30 minutes 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 provides high school students with instruction and practice on how to self-explain texts using the five SERT strategies described in the introduction. iSTART is described in greater detail by McNamara and colleagues (2004). iSTART training took approximately 90 minutes.

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. Participants were presented with paragraphs from a practice text that was 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 learning 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 learning strategy aloud. The participants then reread, paraphrased, or self-explained the text and pressed a button.

The paraphrasing and self-explanation strategies were 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 self-explanation 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 seconds, which was determined from a pilot study in which participants applied the three strategies to the same texts.

**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, which gave the participants additional practice self-explaining. fMRI data was collected for the remainder of the session. All tasks were presented using E-Prime (Psychology Software Tools, Inc., Pittsburgh, PA) 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.

A 30-second rest period was placed before and after each block of 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 blocks with each block consisting of 4 paragraphs (3 blocks for each text/learning strategy pair). Following these 9 learning blocks, participants were presented with a posttest for each text. Although the posttest was collected in the scanner, we do not examine this fMRI data in this paper.

After the posttest, participants were presented with a line search task that served as a functional localizer to localize activity in control areas. The task involved detecting a target line orientation by monitoring lines of differing orientation in four locations on the screen. The lines in these four locations changed over time, and the participants were asked to press a button when one of the locations matched the target orientation. This task has been used in prior research on executive control (Cole & Schneider, 2007).

In order to increase statistical power in the learning comparison across learning strategy conditions while constraining the number of fMRI participants, a second group of 14 behavioral participants participated using the same learning strategy paradigm outside of the scanner.

## Data Acquisition and Analyses

Structural and functional images were collected on a whole body Siemens Trio 3-T scanner at the University of Pittsburgh during a 2-hour scanning session. The functional runs were acquired as 39 oblique-axial slices parallel to the AC-PC plane using a T2\*-weighted echo-planar imaging pulse sequence (TE = 25 ms, TR = 2000 ms, FOV = 21, thickness = 3.5 mm, flip angle = 76, in-plane = 3.28 mm<sup>2</sup>).

The raw neuroimaging data were preprocessed and analyzed using the AFNI software package (Cox, 1996). All functional images were realigned to the first image of each run, which were aligned to the first run of each participant. The images were then transformed into Talairach space (Talairach & Tournoux, 1988). For visualization, statistical maps were mapped onto the cortical surface using Caret (Van Essen et al., 2001).

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. At the individual participant level, general linear models were fit to the data using a set of boxcar functions for the conditions of interest convolved with a standard hemodynamic response function. Each group-level analysis used a mixed effects model with participants treated as a random factor.

The line search task was used to define participant-specific regions of interest (ROIs) for the six bilateral areas

of the control network. Local peaks of activation corresponding to the anatomical location of the control net areas were used to identify each ROI. All statistically significant voxels within a sphere of radius 15 mm from the peak were included in the ROI.

## Results

### Behavioral Results

The proportion correct on the pretest and posttest were used to calculate a learning gain score, where  $\text{gain} = (\text{posttest} - \text{pretest}) / (1 - \text{pretest})$ . This gain score adjusts for the fact that questions already answered correctly on the pretest cannot be improved upon on the posttest (Cohen, Cohen, Aiken, & West, 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 analyses 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  $d = 0.4$ . With a relatively short learning period for complex science materials and a short delay between learning and test, these moderately-sized condition differences in learning were as expected.

The verbal protocols were transcribed, and the self-explanation for each paragraph was coded for whether it contained each of the five techniques comprising self-explanation. Agreement between two independent coders was reliable, 89% agreement (Cohen's kappa = .66). The self-explanation coding was used to determine whether participants were performing the strategy that they had been instructed to perform. 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

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-participant 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 the self-explanation coding process described above to determine the condition. If a participant did not use any self-explanation strategy other than paraphrasing during a self-explanation, then it was classified as being a paraphrase. 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 so only the reclassified analysis is reported.

The areas more active for self-explanation compared to rereading are shown in Figure 1. The areas in the contrast between paraphrasing and rereading were a subset of these areas. Self-explanation and paraphrase both involve greater activation of the control network. These areas include DLPFC, IFJ, AIC, ACC/pSMA, PPC, and dPMC. The results are consistent with the notion that control activity increases with more complex learning strategies.

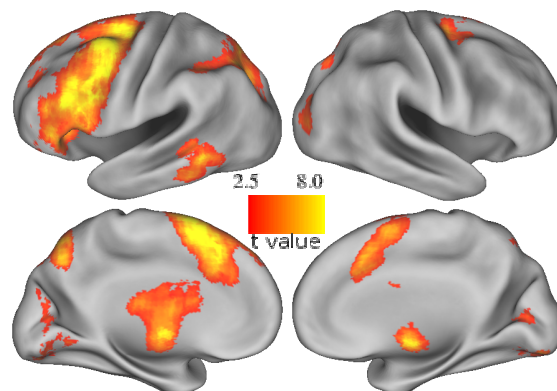


Figure 1. Areas more active while self-explaining than while rereading.

However, the contrast between the self-explanation and paraphrase conditions shows a different pattern of results as seen in Figure 2. These areas included posterior cingulate, precuneus, angular gyrus, middle temporal gyrus, and aPFC. Many of these areas are known to be part of the default network (Buckner et al., 2008). These results indicate that control areas do not account for the differential learning when using self-explanation and paraphrasing.

Analysis of areas that were active in the line search task indicated that all six areas of the control network were active, as expected. The amount of activation in control areas during performance of the learning strategies was examined by using the active voxels in a participant's line search task to identify ROIs for that participant. Average percent signal change was examined in these areas for each of the three learning strategies relative to the rest condition. For the average activation averaged across all ROIs, self-explanation and paraphrase both activated control areas more than reread,  $F(1,20) = 8.94$ ,  $p = .007$ ,  $F(1,20) = 18.40$ ,  $p < .001$ , respectively. However, self-explanation and paraphrase did not differ in control area activation,  $F(1,20) = 2.45$ ,  $p = .13$ . This analysis of control areas is consistent with the findings shown in Figures 1 and 2. Self-explanation and paraphrase do not differ in control activation.

The previous analysis examined areas that were active when participants were self-explaining. However, an alternative approach is to examine those times when it led to measurable learning. Thus, a separate analysis was conducted to examine whether there were brain regions with

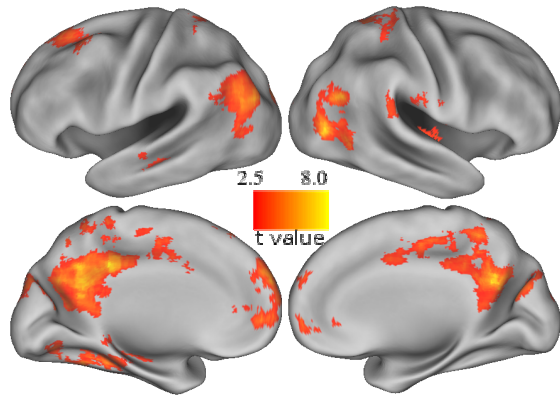


Figure 2. Areas more active while self-explaining than while paraphrasing.

activity associated during successful learning with self-explanation over and above that seen for self-explanation in general. This was achieved by creating 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 slide. The gain score for each slide was calculated by first determining for each question on which slide the information to answer the question was presented. Some slides may have mapped to multiple questions. In this case, the average gain across all questions mapping to that slide was calculated. The regressor for the analysis was formed by convolving a boxcar function whose value was determined by the gain score with a hemodynamic reference function. This process was used to identify brain areas exhibiting a linear relation to gain scores (Buchel, Holmes, Rees, & Friston, 1998).

This learning analysis identified a set of bilateral pre-frontal areas that were positively associated with learning gain. These areas are shown in Figure 3. There were no areas negatively associated with learning gains. In addition to the areas which were active during self-explanation, these pre-frontal areas were more active during self-explanation trials during which material was learned well enough to be answered correctly on the posttest.

### Discussion

The results presented here provide evidence that complex learning strategies engage executive control regions, semantic/comprehension regions, and bilateral aPFC. The behavioral learning results confirmed that the three learning strategies differed in effectiveness as hypothesized. 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 is consistent with our initial hypothesis that more complex strategies would require more cognitive control.

However, the control network was not more active for self-explanation than it was for paraphrasing. The effectiveness of self-explanation was never expected to be

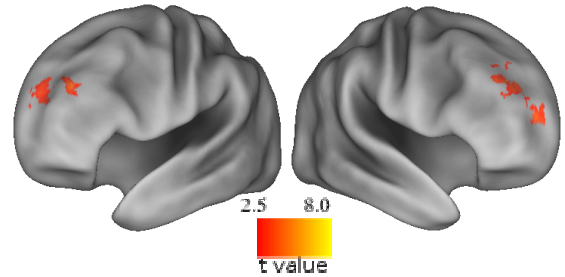


Figure 3. Areas linearly related to measurable learning gain during self-explanation.

solely due to the controlled effort involved, but it is interesting that the more effective learning strategy requires a similar amount of control activity as a less effective one.

The areas that were more active for self-explanation than the less effective strategies include areas associated with text comprehension, memory, and the default network. Areas previously shown to be associated with text comprehension that were more active during paraphrasing and self-explaining include L IFG, caudate, thalamus, PFC, bilateral precuneus, posterior cingulate, bilateral PPC, L parahippocampal gyrus, and L angular gyrus. Given that both paraphrasing and self-explanation usually lead to better comprehension than does rereading, it seems likely this network of areas are performing similar comprehension-related processing during performance of these reading strategies. In particular, the bilateral angular gyrus, right PPC, bilateral precuneus, bilateral posterior cingulate, left fusiform gyrus, and left parahippocampal gyrus were most active only in the self-explanation condition. Of these areas, PPC, left fusiform, and right precuneus have been previously been implicated in the construction and updating of situation models (Yarkoni et al., 2008). The angular gyrus, posterior cingulate, and precuneus have been associated with relating text to prior knowledge and the use and manipulation of mental models (Xu et al., 2005). The areas active in the MTG active in self-explanation are similar to areas that have been found when people draw inferences during text comprehension (Virtue, Haberman, Clancy, Parrish, & Jung Beeman, 2006). These are exactly the kinds of cognitive processes that a strategy such as self-explanation is supposed to engage to support deep comprehension of the text.

A number of the areas more active in the self-explanation condition than in the paraphrase condition are considered to be part of the default network that is active in the absence of goal-directed activity (e.g., Buckner et al., 2008). The areas of the default network typically include mid-orbital cortex, angular gyrus/inferior parietal, lateral temporal cortex, and the hippocampus. These areas were highly active during self-explanation. One hypothesis about the default network is that it is associated with an internal stimulus-independent mode of thought (Buckner et al., 2008). These stimulus-independent thoughts have been associated with lapses in attention and mind wandering (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009), but this mode of

thought is also thought to have adaptive purposes including retrieval of episodic and semantic memory along with the generation of coherent and use of coherent mental representations (e.g., Hassabis & Maguire, 2007). The retrieval of prior knowledge and the generation of coherent representations during the use of reading strategies likely make use of these same brain areas.

The analysis of the areas active during self-explanation that were correlated with the amount learned mainly included bilateral aPFC. That is, in addition to the activity in executive control and default network areas associated with self-explanation, the aPFC was more active during self-explanation of paragraphs where measurable learning took place. The aPFC is active during performance of a number of higher-order tasks, but a recent theory of aPFC function refers to it as a router or gateway between modes of thought (Burgess, Dumontheil, & Gilbert, 2007). One mode of thought is one in which external representations 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 internal thought processes associated with the default network. Self-explanation may be most effective when there is strategic processing of internal representations.

This initial exploration of the neural correlates of strategic reading comprehension has shown that a network of areas associated with executive control and the manipulation of internal representations and memories underlie the effectiveness of these strategies. Future work should explore the role of aPFC in reading strategies as well as whether these results will generalize to other texts.

### Acknowledgments

This work was supported by The Defense Advanced Research Projects Agency (NBCH090053). The views, opinions, and/or findings contained in this article are those of the authors and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense. Approved for Public Release, Distribution Unlimited.

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