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Research Report

The nature of mind wandering during reading varies with the cognitive control demands of the reading strategy

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ABSTRACT

Prior studies of mind wandering find the default network active during mind wandering, but these studies have yielded mixed results concerning the role of cognitive control brain regions during mind wandering. Mind wandering often interferes with reading comprehension, and prior neuroimaging studies of discourse comprehension and strategic reading comprehension have shown that there are at least two networks of brain regions that support strategic discourse comprehension: a domain-general control network and a network of regions supporting coherence-building comprehension processes. The present study was designed to further examine the neural correlates of mind wandering by examining mind wandering during strategic reading comprehension. Participants provided ratings of mind wandering frequency that were used to investigate interactions between the strategy being performed and brain regions whose activation was modulated by wind wandering. The results support prior findings showing that cognitive control regions are at times more active during mind wandering than during a task with low control demands, such as rereading. This result provides an initial examination of the neural correlates of mind wandering during discourse comprehension and shows that the processes being engaged by the primary task need to be considered when studying mind wandering. The results also replicate, in a different learning domain, prior findings of key brain areas associated with different reading strategies.

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1. Introduction

Mind wandering while performing a task is both common and often detrimental to task performance, and the study of the neural correlates of mind wandering and task-unrelated thoughts has been the focus of a number of recent neuroimaging studies (for a review, see Christoff (2012)). While mind wandering has been hypothesized to have benefits (Bar, 2007), it is also known to interfere with tasks such as reading comprehension; resulting in lower comprehension (Schooler et al., 2004).

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A number of terms have been used to refer to spontaneous thought unrelated to an individual's focal task, including mind wandering, task-unrelated thoughts, and stimulus-independent thought. In some cases, distinctions are drawn between these terms and in other cases they are used interchangeably. In this paper, we use the term mind wandering to refer to the occurrence of thoughts unrelated to the current task (i.e., task-unrelated thoughts).

A number of studies examining the neural correlates of mind wandering have done so by examining brain activity when no stimulus is presented to participants (e.g., Andrews-Hanna et al., 2010; Buckner et al., 2008; Christoff et al., 2004). However, recent studies have focused on using subjective reports to examine mind wandering during task performance (e.g., Christoff, 2012; Christoff et al., 2009). Using such subjective reports, Christoff and colleagues found activity associated with mind wandering in default network areas that have previously been associated with self-referential thought as well as areas including dorsal anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) that have been associated with executive control. These default network and executive control regions were also found to be functionally connected during mind wandering (Christoff, 2012). The fact that some executive control regions were more active rather than less active during mind wandering suggests that understanding mind wandering and its impact on task performance will require an examination of the cognitive processes and associated neural correlates of both task-related and mind-wandering processes.

One example of considering the processes engaged by a task and their interaction with mind wandering comes from research examining the role of rostral prefrontal cortex (rPFC) in mind wandering (Dumontheil et al., 2010). Using subjective ratings of the frequency of mind wandering during task performance, this study found that rPFC activity interacted with task demands. In comparison to a task requiring a high level of sustained attention to external stimuli, rPFC activity was higher for both a task requiring a low amount of externally-directed attention (i.e., one where mind wandering is possible due to available resources) and for a task demanding a high degree of attention to internally-directed thought (i.e., stimulus-independent thought). These results indicate that rPFC may be associated with attention to internally-directed thought regardless of whether that thought is relevant to the task at hand or is a task-unrelated thought. For example, if one were to examine the neural correlates of mind wandering by contrasting brain activity during mind wandering to activity during task performance, it would appear that mind wandering during a more externally-directed task (such as visual search) involved the rPFC while mind wandering during a more internally-directed task (such as reading comprehension) did not involve the rPFC. This issue is not just a methodological point about the logic of task contrasts involving mind wandering, but also a deeper point about the effects that mind wandering may have on task performance. Consideration of the kinds of cognitive processes utilized in a task should help to understand the interference of mind wandering with different tasks as well as neuroimaging data examining mind wandering during task performance.

Reading comprehension is a task that involves both externally-directed attention in reading the words on the page as well as a good deal of internally-directed attention to the mental representation of the text being constructed. Comprehension of an expository text is a common learning task and involves coherence building processes that manipulate mental representations of meaning in order to construct inferences and elaborations that connect the text with prior knowledge (e.g., Kintsch, 1998). A meta-analysis of neuroimaging studies of discourse processing has shown that these cognitive processes have neural correlates that include regions such as posterior cingulate cortex, medial prefrontal cortex, and temporoparietal regions near the angular gyrus (Ferstl et al., 2008). The overlap between mind wandering regions and discourse comprehension regions indicates that mind wandering and comprehension likely share many of the same cognitive processes. This overlap in processes may also indicate why mind wandering is so detrimental to comprehension.

A number of reading comprehension strategies have been identified that improve readers' comprehension of text. Some readers use these strategies naturally, and others benefit from being provided with strategy instruction (McNamara, 2007). Self-explanation is one reading strategy that focuses on the coherence building processes of inferencing and elaboration, and it 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). During self-explanation, readers explain the text to themselves by putting the text into their own words, making elaborative inferences based on their prior knowledge, and making bridging inference across sentences and paragraphs of the text. These elaborative and bridging inferences are thought to help to build coherence in a reader's representation by forming connections between propositions in their mental representation, or situation model, of the text that would not have been formed automatically (Kintsch, 1998; McNamara, 2004). Other less effective strategies that readers could employ are rereading the text and paraphrasing the text by putting the text into their own words (Chi et al., 1994; McNamara, 2004; Moss et al., 2011).

The results of an initial exploration of the neural correlates of strategic reading comprehension found that a combination of cognitive control and discourse comprehension regions are activated during performance of effective reading strategies (Moss et al., 2011). This prior study examined three reading strategies: rereading, paraphrasing, and self-explaining. The results supported the notion that effective reading strategies involve a combination of intentional cognitive control along with engagement of coherence-building processes. Paraphrasing and self-explanation were found to engage a network of regions comprising a cognitive control network more so than did the rereading strategy. This domain-general network of brain areas have been shown to be active in a variety of tasks involving executive control, and includes DLPFC, anterior cingulate cortex/pre-supplementary motor area (ACC/pSMA), anterior insular cortex (AIC), posterior parietal cortex (PPC), inferior frontal junction (IFJ), and dorsal pre-motor cortex (dPMC) (Chein and Schneider, 2005; Duncan, 2010).

In addition to an increase in control network activation, Moss et al. (2011) found that a set of areas including bilateral angular gyri, posterior cingulate cortex, and the right middle temporal gyrus were more active during self-explanation than during paraphrasing. These regions have been found to be active during discourse comprehension processes including coherence-building inference processes (Ferstl et al., 2008; Xu et al., 2005; Yarkoni et al., 2008). These results suggest that self-explanation, the most effective strategy examined, further engages coherence-building processes that aid in the construction of a good situation model of the text's content.

Using these prior results concerning the role of the cognitive control network in strategic reading comprehension, it is possible to hypothesize about the neural correlates of mind wandering that could be observed in this network during different reading strategies. During rereading, a strategy known to be low in engagement of the cognitive control network, mind wandering would lead to increases in activity in cognitive control regions of interest (ROIs) such as the ACC and DLPFC that have been identified in prior research on mind wandering (Christoff et al., 2009). Rereading has been shown to engage cognitive control ROIs significantly less than other reading strategies (Moss et al., 2011). In contrast, strategies that engaged the cognitive control network to a greater degree, such as paraphrasing and self-explanation, would not show increases in activation in cognitive control ROIs. Therefore, this cognitive control hypothesis would support the argument by Christoff et al. (2009) that they found mind-wandering related activation in control regions while others had not because of their use of experience sampling as opposed to contrasting two tasks which differ in their propensity to encourage mind wandering. In other words, if tasks that lead to a higher propensity for mind wandering also always have lower cognitive control demands, then contrasting the high- and low-mind-wandering tasks would also be contrasting a high- and low-cognitive-control task. Therefore, it would always appear that cognitive control regions decrease in activity during mind wandering. However, using some form of experience sampling eliminates the need to contrast different tasks and therefore allows for the detection of increases in activity in cognitive control ROIs when mind wandering in fact leads to greater control demands than the task itself, such as in rereading. In contrast, the paraphrasing and self-explanation strategies that activate the control network to a greater degree should show either no change or a decrease in activation in these cognitive control ROIs during mind wandering.

The present study closely follows the methodology of earlier work on the neural correlates of strategic reading comprehension by contrasting three learning strategies—rereading, paraphrasing, and self-explaining—differing in complexity and effectiveness (Moss et al., 2011). We sought to replicate prior findings about the regions activated by these educationally important learning strategies using expository texts about a different text topic. The main difference from the prior study is a focus on mind wandering, a common issue that undermines learning in many students. To this end, participants were asked to provide a self-rated frequency of mind wandering out while reading and performing the reading strategies. These subjective ratings were used to

examine whether there were brain regions that were associated with mind wandering.

One additional important new feature of the current study was that the texts that participants read included diagrams along with the text in contrast to the prior study that used texts without accompanying diagrams. The prior study began with the relatively simple context of only text. But, such a situation rarely exists in science learning situations. Expository text in textbooks is usually accompanied by illustrations intended to aid in comprehension, and self-explanation has often been studied in contexts including diagrams such as in learning to solve physics problems (e.g., Chi et al., 1989). It is therefore important to examine whether the neural correlates identified in our prior work generalize to situations in which both text and diagrams are present. Behavioral studies of self-explanation have shown that including accompanying diagrams with the text increases the number of inferences that readers make (Ainsworth and Loizou, 2003). If diagrams increase the ease with which inferences are made, then it may be the case that the neural correlates of self-explanation would be associated with less activation when diagrams are present. In addition, areas associated with visual processing should be more active during reading strategies involving diagrams because of the visuospatial processing required to interpret the diagrams and relate them to the text.

2. Results

2.1. Behavioral results

The proportion correct on the pretest and posttest were used to calculate a learning gain score adjusting for the fact that questions already answered correctly on the pretest cannot be improved upon, gain=(posttest−pretest)/(1−pretest), (Cohen et al., 1999). Due to time constraints, two of the fMRI participants did not complete the posttest.

The gain scores for the behavioral and imaging participants did not differ on any of the three conditions (for all comparisons, $p>.09$), so the data for these two groups were combined. Planned comparisons showed that rereading gain ($M=.30$, $SD=.23$) did not differ from paraphrasing ($M=.35$, $SD=.24$), $t<1$. As expected, self-explanation led to greater learning ($M=.41$, $SD=.21$) than rereading, $t(36)=2.30$, $p=.028$, Cohen's $d=.38$. However, self-explanation learning gains, despite being the largest among the three groups, did not differ significantly from paraphrasing, $t(36)=1.50$, $p=.14$. Prior research has generally found self-explanation to be more effective than paraphrasing (Moss et al., 2011). The fact that 2.7 of the 15 self-explanations for each participant contained only paraphrasing and that learning was assessed with multiple choice questions instead of short answer questions may explain why a stronger advantage for self-explanation was not found.

The average time spent reading just before rereading ($M=23.24$ s, $SD=4.88$ s), paraphrasing ($M=23.15$ s, $SD=5.71$ s), and self-explaining ($M=23.96$ s, $SD=6.00$ s) did not differ, $F<1$. The time spent performing each strategy did differ, $F(2, 28)=7.86$, $p=.002$, with participants spending longer during rereading

(M=43.20 s, SD=1.21 s) than either self-explaining (M=37.51 s, SD=6.00 s) or paraphrasing (M=37.93 s, SD=6.14 s).

The mind wandering ratings across strategy conditions did not differ for the behavioral and imaging participants, F<1, so the ratings were analyzed in a set of planned comparisons combining the two groups of participants. Mind wandering ratings likely reflected mind wandering during the strategy portion of the reading task because frequency of mind wandering was rated lower for self-explanation (M=2.11, SD=.85) than for rereading (M=2.47, SD=.92), t(38)=3.00, p=.005, and paraphrasing (M=2.35, SD=.78), t(38)=2.92, p=.006. Mind wandering ratings for paraphrasing and rereading did not differ significantly, t(38)=1.06, p=.30.

An analysis was done to examine whether the three reading strategies led to verbalizations that differed in systematic ways, and thus potentially introducing a confound between processes and verbalizations contents in the strategy condition analyses. Coh-Metrix (Graesser et al., 2004) was used to examine the transcribed utterances produced by participants. Coh-Metrix analyzes text and provides a large number of variables related to the content of the texts being analyzed including syntactic variables. These variables have been shown to be well explained by eight principal components that have been described as narrativity, syntactic simplicity, word concreteness, referential cohesion, causal cohesion, verb cohesion, logical cohesion, and temporal cohesion (Graesser et al., 2011). These eight principle component scores were analyzed to determine if any of them differed significantly between the three reading strategies used here.

Paraphrasing differed from rereading on three of these components: narrativity, syntactic simplicity, and causal cohesion. Self-explanation differed from rereading on five components: narrativity, syntactic simplicity, word concreteness, referential cohesion, and causal cohesion. Self-explanation differed from paraphrasing on two components: word concreteness and referential cohesion. For each pairwise strategy contrast, the difference between the significantly different Coh-Metrix component scores was used as a covariate for the fMRI strategy difference analyses. For example, for the contrast between self-explanation and paraphrasing, the difference between the word concreteness and referential cohesion scores were used. The analyses using these covariates did not differ in terms of peaks of activation from those without the covariates, suggesting that the main activity differences were the result of the underlying strategic reading comprehension processes rather than different speech contents produced. In further support of this interpretation, no regions of activation were found to be associated with any covariate. Therefore, the analyses without the covariates are reported below.

2.2. Imaging results

2.2.1. Reading strategy contrasts

Three planned contrasts (paraphrase > reread, self-explain > reread, and self-explain > paraphrase) were conducted to examine whether the differences in activation associated with the reading strategies found previously are replicated with a new content domain and new learning strategies situation (i.e., text and diagrams together). The regions more active for paraphrasing than rereading and those more active for self-explanation than rereading were similar and are shown in Table 1. Because the results were very similar for these two contrasts, only the self-explanation > reread contrast is shown in Fig. 1. A conjunction analysis (Nichols et al., 2005) for each of the strategy contrasts was carried out examining common regions of activation in this study and our prior study of reading strategies (Moss et al., 2011). Areas in Fig. 1 that were significant in the conjunction analysis are shown in a blue scale and are also indicated in Table 1. The only regions that did not overlap with prior results were in the occipital cortex, including right lateralized activation in superior and middle occipital gyri as well as the fusiform gyrus.

The regions more active for self-explanation than paraphrasing are shown in Fig. 2 and Table 2. These results also show a high degree of overlap with those found in the prior study. Overlapping regions including the left angular gyrus and left posterior cingulate cortex are areas that have been associated with coherence building during discourse comprehension (Ferstl et al., 2008).

2.2.2. Cognitive control network

The six bilateral ROIs of the cognitive control network for each participant were computed using the line search task functional localizer. Average percent signal change in these 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 reading strategies. Bonferroni corrections were used because 12 separate ANOVAs were conducted. For ANOVAs indicating a significant difference, a series of planned paired comparisons was used to determine which strategies were significantly different. The pattern of reading strategy comparison results divides the 12 ROIs into two groups. One group did not show any differential activation for the three strategies. This group includes all of the right hemisphere ROIs except R ACC/pSMA. All of the left hemisphere ROIs and the R ACC/pSMA showed significant differences between rereading and the other two strategies, but they did not show any difference between self-explanation and paraphrasing. These results replicate those of our prior study with the only difference being that the differential activation of the control network for the non-rereading strategies was slightly more left-lateralized in this study.

2.2.3. Mind wandering

Mind wandering-related regions were identified by examining which brain regions' activity was correlated with the ratings provided by participants. The hypothesis tested was that mind wandering during rereading, a strategy typically low in control network engagement, would lead to an increase in activity in control network regions more so than the other two strategies in which the control network is typically already active. Activity in control network ROIs correlated with changes in mind wandering is shown in Fig. 4, separately for each reading strategy. Focusing on the comparison of rereading to the other strategies, control network activity shows more significant increases during mind

Table 1 – Regions significantly more active during self-explanation and paraphrasing when compared to rereading.

Regions	BA	Self-explanation – reread					Paraphrase – reread				
		Cluster size (mm³)	x	y	z	peak t	Cluster size (mm³)	x	y	z	peak t
Frontal cortex											
L inferior frontal g	13/44/45	38448	−46	23	14	18.50[a]	28053	−46	20	5	9.39[a]
L middle frontal g	9	–	−43	23	35	8.16[a]	–	−40	23	29	6.84[a]
L anterior cingulate g	24/32	–	−4	20	35	9.73[a]	–	−6	13	43	8.81[a]
L precentral g	6	–	−37	2	38	10.93[a]	–	−37	2	38	8.67[a]
L SMA	6	–	−7	8	59	11.77[a]	–	−4	11	56	10.90[a]
R SMA	6	–	2	8	56	7.98[a]	–	2	8	59	8.23[a]
R anterior cingulate g	24/32	–	11	20	38	9.11[a]	810	11	23	35	7.32[a]
Parietal cortex											
L inferior parietal	7	5022	−28	−46	38	7.43					
L inferior parietal	40						675	−46	−43	47	5.49[a]
L superior parietal	7	–	−22	−70	41	6.31[a]					
L superior parietal	7	540	−7	−64	56	5.88[a]	783	−13	−70	56	5.63[a]
R superior parietal	7	486	17	−61	56	6.32	702	23	−61	38	4.94[a]
Occipital cortex/ Cerebellum											
R fusiform g	19	17118	26	−64	−7	6.46	5589	35	−61	−13	4.32
R cerebellum		–	23	−61	−28	10.91[a]	–	26	−67	−34	9.49[a]
R middle occipital g	18/19	–	38	−88	5	7.72	2052	35	−91	14	7.26
R superior occipital g	18/19	–	26	−79	23	5.44	513	26	−70	23	6.12
R cerebellum		–	38	−55	−43	5.40					
L middle occipital g	7/19						2673	−28	−67	29	7.22[a]
R cerebellum		567	2	−43	−19	8.85[a]					
Subcortical											
L caudate		4833	−13	−1	20	9.04[a]					
L thalamus		486	−4	−13	−7	5.72[a]					
L pallidum							1728	−16	−1	5	7.72[a]
R pallidum							729	14	2	2	8.81[a]

[a] Regions that were significantly active in the conjunction analysis examining common patterns of strategic reading comprehension activation in the current study and a prior study.

wandering for the rereading strategy in right IFJ, right dPMC, and bilateral ACC. These results support this control network hypothesis and show that the association with mind wandering is somewhat right lateralized.

3. Discussion

The present study had two primary goals: examining mind wandering during strategic reading comprehension and replicating prior results on the neural correlates of strategic reading comprehension. The first goal was to examine the neural correlates of mind wandering by determining whether there were cognitive control regions that showed an amplitude-modulated BOLD response correlated with participants' subjective ratings of mind wandering. Based on prior work on mind wandering, a cognitive control hypothesis was examined that stated that regions associated with cognitive control would become more active during mind wandering while rereading. Using a different subjective-report methodology, Christoff et al. (2009) found that areas including DLPFC were more active during mind wandering, and that the DLPFC activity was correlated with activation in regions of the default network, which have been shown in many tasks to be anti-correlated (Christoff, 2012; Fox et al., 2005; Mason et al., 2007; McGuire et al., 1996). Rereading was hypothesized to be likely to show increases in cognitive control areas during mind wandering while the other strategies may not because, as the results of this study and prior work show, the cognitive control network is significantly less active while rereading than while paraphrasing or self-explaining. Indeed, mind wandering during rereading was
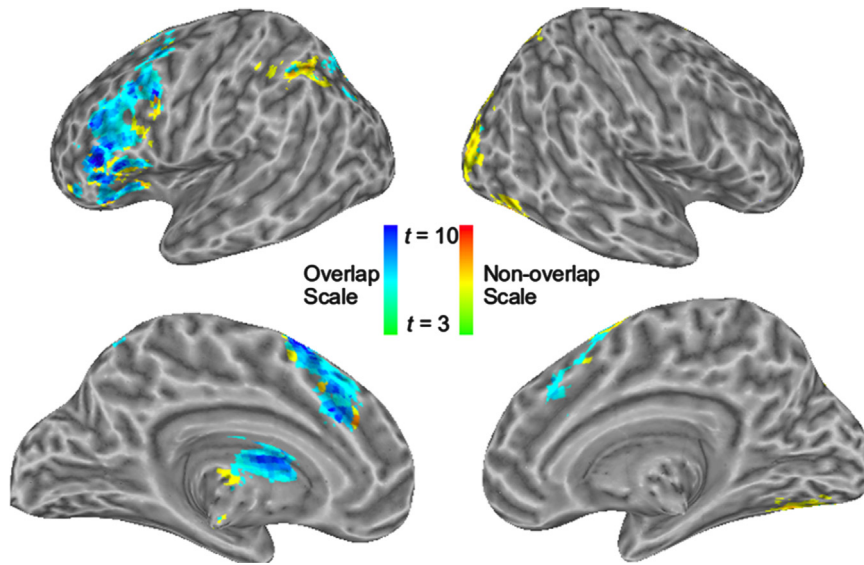
Fig. 1 – Statistical map for group analysis of areas more active in self-explanation than during rereading. Corresponds to list of regions in Table 1. Areas shown in the blue color scale overlapped with prior results from the same contrast from Moss et al. (2011) based on a conjunction analysis.
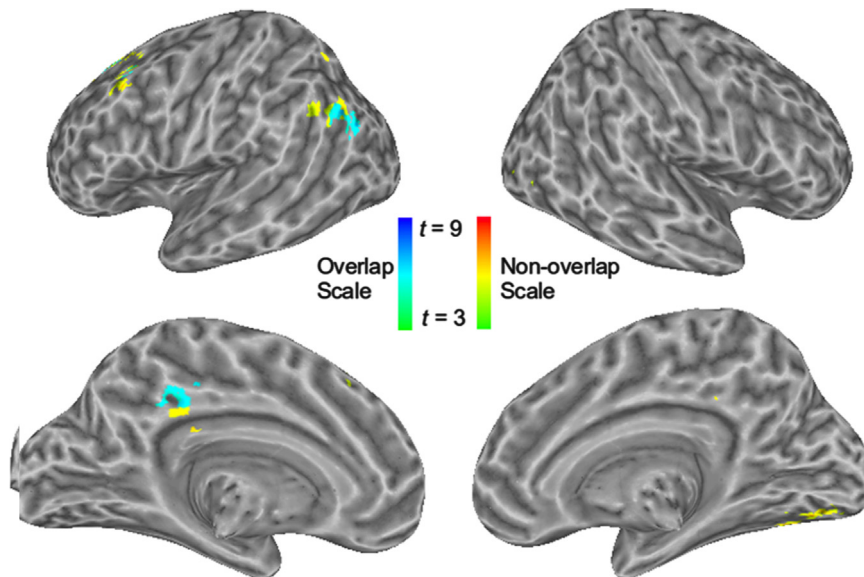

Fig. 2 – Statistical map for group analysis of areas more active in self-explanation than during paraphrasing. Corresponds to list of regions in Table 2. Areas shown in the blue color scale overlapped with prior results from the same contrast from Moss et al. (2011) based on a conjunction analysis.

associated with somewhat right-lateralized increases in cognitive control regions including ACC, IFJ, and dPMC. Although not statistically significant in all regions, all of the right hemisphere ROIs in Fig. 4 show numerically greater increases in activity with mind wandering during rereading than the left hemisphere ROIs.

Therefore, the results support the cognitive control hypothesis that mind wandering is associated with increases in cognitive control regions in tasks with low cognitive control demands. The use of a functional localizer task to localize the cognitive control regions was critical to being able to examine the activation of these regions in focused ROI analyses in which the ROI was defined independently of the analysis of strategies and mind wandering.

The right-lateralized nature of the increases in the control network deserves further comment. One possible reason for this right lateralization is that the rereading task is minimally engaging control processes that are primarily left-lateralized due to language specialization. Lateralization of activity in the cognitive control network has been shown to depend on the type of task or modality of stimuli being processed (Stephan et al., 2003; Yeung et al., 2006). Therefore, the left lateralization of control network activity that can be seen in Fig. 3 for all reading strategies could be due to the nature of the task and corresponding mental representations being processed. Even for rereading, the strategy with the least control network activation, the left hemisphere ROIs tend to be more active than the corresponding right hemisphere ROIs

Table 2 – Regions significantly more active during self-explanation than paraphrasing.

Regions	BA	Cluster size (mm³)	x	y	z	peak t
Frontal cortex						
L middle frontal g	6/8	4212	−40	14	44	6.18
L superior frontal g	6/8	–	−19	29	50	5.80[a]
Parietal cortex						
L angular g	39	2916	−43	−70	26	5.40[a]
L superior parietal	7	–	−37	−67	47	6.35
L cingulate g	31	918	−4	−28	35	5.39[a]
Occipital cortex/cerebellum						
R fusiform g	19	3537	20	−67	−10	5.84
R cerebellum		–	17	−82	−25	3.97

[a] Regions that were significantly active in the conjunction analysis examining common patterns of strategic reading comprehension activation in the current study and a prior study.
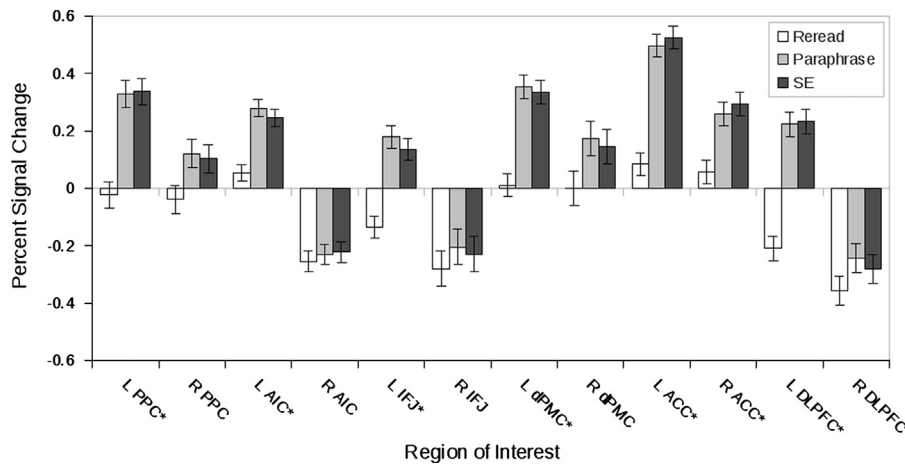

Fig. 3 – Activation in the cognitive control network regions during each of the three reading strategies. A '*' indicates that the ROI shows a difference between rereading and the other two strategies.
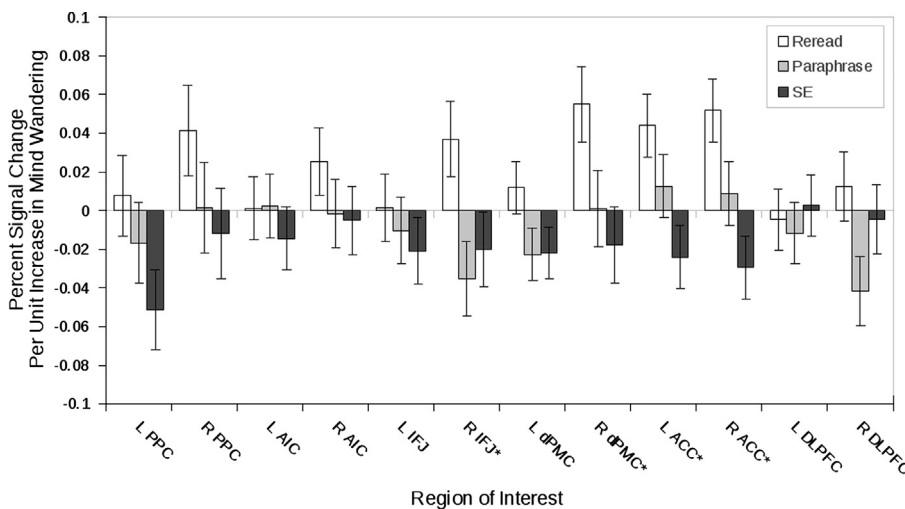

Fig. 4 – Activation change in cognitive control network ROIs associated with changes in mind wandering rating for each of the reading strategy conditions. A '*' indicates that the ROI shows a difference between rereading and the other two strategies.

(see Fig. 3). It is possible that these activation increases in cognitive control ROIs in the right hemisphere during mind wandering reflect the engagement of these less utilized control regions such that mind wandering can occur without influencing the ability to continue rereading the text aloud. This explanation may mean that the right hemisphere ROIs

would show less functional connectivity with the left hemisphere ROIs, but evaluating this hypothesis requires that the periods of mind wandering be more tightly localized in time than the current data allow.

Controlled processing during mind wandering is likely needed because many of the thoughts that individuals self-report during mind wandering include planning and thoughts about upcoming social events or interactions that require the use of control resources to sequence thought (Klinger, 2012, 1996; Schooler et al., 2004; Smallwood et al., 2007). However, the increase in control network activity interacted with the demands of the task at hand, such that similar increases were not observed for strategies requiring greater use of control resources. This task interaction implies that the neural correlates of mind wandering and maybe even the types of thoughts that occur during mind wandering depend to a large extent on the task being pursued.

In contrast to rereading (or paraphrasing), self-explanation incorporates explicit coherence-building processes such as elaborative and bridging inferences (McNamara, 2004; Moss et al., 2011). These coherence-building processes produce increases in activation in the posterior cingulate cortex and the angular gyrus that are also a subset of the default network (Ferstl et al., 2008; Ferstl and von Cramon, 2001). Therefore, because mind wandering is known to be associated with increased activity in the default network (Christoff, 2012; Christoff et al., 2009; Mason et al., 2007), then mind wandering might be particularly disruptive for a strategy such as self-explanation. However, this overlap in processing regions between mind wandering and coherence-building comprehension processes may also be the reason that self-reported mind wandering was lower in self-explanation than the other two strategies. The combined activity of the cognitive control network and these coherence-building regions in the strategic and controlled processing of self-explanation may make this type of reading strategy effective both in terms of learning and in terms of avoiding distraction by task-unrelated thoughts.

One potential inconsistency with our interpretation that the right-lateralized mind-wandering modulation of activity in the cognitive control network during rereading is due to the left-lateralized demands of the reading comprehension strategies is the activity of the right IFJ. The right IFJ is not differentially activated by the three reading strategies (see Fig. 3), but it is modulated by mind wandering during rereading more than in the other two strategies (see Fig. 4). Therefore, the explanation of increased cognitive control activity in paraphrasing and self-explanation being the reason for only the rereading strategy showing increases in cognitive control does not explain why there is not increased mind-wandering activity in the right IFJ for paraphrasing and self-explanation. Given the role of the right IFJ in cognitive inhibition (Aron et al., 2004; Levy and Wagner, 2011), the increased activity in this region during frequent mind wandering could have been due to attempts to suppress wandering thoughts. The IFJ and other cognitive control regions have been shown to be associated with inhibiting or suppressing memory retrieval (Anderson et al., 2004; Aron et al., 2004). The increased engagement of these control regions associated with inhibition and monitoring may therefore be due to the engagement of processes to try to suppress task-unrelated thoughts while rereading. These additional processes may not have been used during the other two strategies due to low mind wandering frequency or due to the lack of control resources needed to engage these processes (due to the relatively high activation of control regions during paraphrasing and self-explanation).

These two interpretations of increased cognitive control activation during rereading are not mutually exclusive. The increase in control regions could be due to more activation of control regions during mind wandering than in the original rereading task in addition to increased attempts to monitor for and inhibit task-unrelated thoughts. At this point, further research would be needed to examine each of these interpretations because the function of many regions in the cognitive control network including the IFJ is still an active area of investigation (e.g., Duncan, 2010; Levy and Wagner, 2011). The current results do highlight the importance of future research in examining the role of different brain networks in mind wandering, and the need to consider the demands of the task being studied while examining mind wandering.

The second goal of the present study was to test whether prior results on the neural correlates of reading strategies depended on the nature of the learning materials or whether there were domain-general brain regions that were also active in a different content domain and with the addition of more authentic text/diagram integration. The neural correlates of rereading, paraphrasing, and self-explanation were contrasted, and the results provided a strong replication of prior work (Moss et al., 2011), suggesting that the pattern of activation differences was in fact driven by strategy differences rather than differences in the content being read. In particular, the cognitive control network was shown to be more active for paraphrasing and self-explanation reflecting the use of controlled processing during performance of these strategies. Regions associated with coherence-building processes such as inferencing during the construction and maintenance of a situation model were found to be more active during self-explanation than paraphrasing. These regions include the angular gyrus and posterior cingulate cortex, which have been shown to be reliably activated by coherence building during discourse comprehension across a number of studies (Ferstl et al., 2008).

In addition, there was activation in the fusiform gyrus and the middle and superior occipital gyri in the current study that was not present in the prior study. One likely reason for this fusiform activity was the inclusion of diagrams that accompanied the text. These regions are known to be involved in the ventral visual processing stream and in the maintenance of information in visual working memory (Courtney et al., 1996; Rissman et al., 2004). Interpreting the diagrams and linking the content of diagrams to the content of text requires the maintenance of relevant spatial information in working memory along with linking that information into the current situation model being constructed for the text (e.g., Hegarty and Just, 1993). Further, the activation observed in this study was right lateralized. The diagrams were presented on the right half of the screen, so this lateralization seems unlikely to be due to the visual hemifield in which the information was presented. There is some evidence that the right occipitotemporal regions may exhibit

less abstract or holistic processing, and therefore the lateralization may be due to the specific nature of the processing being used with the diagrams (Koutstaal et al., 2001; Marsolek, 1995). It may be that the process of integrating diagrams with text requires processing of multiple specific visuo-spatial features rather than processing the whole of the diagram as a complete entity abstracted from perceptual details.

Overall, the reading strategy results provide a strong replication and extension of prior results, and the mind wandering results support the cognitive control hypothesis and indicate that the neural correlates of mind wandering depend upon the task in which the wandering is occurring. The results raise a number of interesting hypotheses that could be pursued in future work. In particular, the main limitation of the current work is that mind wandering was not localized in time but instead was based on a single rating occurring immediately after the paragraph the participant read. One possibility is that methods relying on self-caught mind wandering and experience sampling (e.g., Christoff et al., 2009) could be combined with reading strategies in a future study to further evaluate the hypotheses explored in this study.

4. Experimental procedures

4.1. Participants

Fifteen right-handed, native English speakers were recruited from the University of Pittsburgh and Carnegie Mellon University communities (12 female, M age=20.7 years; SD=1.8; range=18–25). None of the participants had taken a college physics course. A group of 24 behavioral-only participants (15 female, M age=19.7 years; SD=1.5; range=18–24) recruited from the same population also completed the study outside of the MRI in order to increase statistical power in the pretest/posttest comparison while constraining the number of fMRI participants. All participants were paid for their participation.

4.2. Materials

Three new texts that taught three separate introductory physics topics were constructed. Each text consisted of 15 topic-related paragraphs, each containing 2–4 sentences. The topics of the texts were DC circuits, pulley systems, and classical mechanics (i.e., forces and motion of objects). For each text, 13–14 diagrams that corresponded to individual paragraphs were also constructed such that almost every paragraph had an accompanying diagram. A set of 15 multiple-choice questions that tested the content of each text was also created. A series of pilot studies involving a total of 34 participants were used to refine the materials to ensure that all three texts and accompanying tests were of equivalent difficulty.

4.3. 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 15-paragraph text was divided into three sections of five paragraphs each. Each of these five-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. Each section of five paragraphs for each of the three texts was presented before the next section of paragraphs for each text. For example, this organization implies that the first and second sections of a particular text were separated by a section of each of the other two texts (e.g., Text1-Section1, Text2-Section1, Text3-Section1, Text1-Section2, Text2-Section2, …). The sections 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).

4.4. Procedure

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

4.4.1. Session 1

During the first session, participants were given up to 30 min to complete a pretest that included all of the questions for each of the three texts. Participants then completed a 90-min iSTART session that provided instruction on how to self-explain using reading strategies.

iSTART, described in greater detail by McNamara and colleagues (Levinstein et al., 2007; McNamara, 2004; McNamara et al., 2004), provides students with instruction and practice on how to self-explain texts using the five Self-Explanation Reading Training (SERT) strategies: comprehension monitoring, paraphrasing, elaboration, bridging, and prediction. These reading strategies are designed to improve the quality of the students' self-explanations and enhance reading comprehension. 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.

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 head tracking system to present feedback to the participant regarding head movement. The simulator practice was done to screen for claustrophobia, to train participants to perform the experiment without excessive head motion (talking aloud), 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, instructions were presented on the screen indicating the reading strategy to use for that block.

During the practice and the MRI session, 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. After participants completed the learning strategy for a particular paragraph, they were presented with the following prompt: "How often did you catch yourself zoning out and thinking about other things when reading the last paragraph?". Along with the prompt was a scale at the bottom of the screen from 1 indicating "None of the time" to 5 indicating "All of the time". The finger associated with each response was displayed below the response scale, and participants pressed a button on the response glove to indicate their response.

Because the paraphrasing and self-explanation strategies were introduced within iSTART, participants were provided only brief reminder instructions at the start of each block 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.

4.4.2. 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 a 30-min iSTART practice session for additional practice self-explaining. fMRI data was collected for the remainder of the session. All tasks were presented using E-Prime (Schneider et al., 2002). To verify strategy use within each condition during scanning, 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.

The first task presented to the participants in the MRI was a line search task that served as a functional localizer to localize activity in control areas (Saxe et al., 2006). This task has been used in prior research on executive control (Cole and Schneider, 2007) and also as a functional localizer in a similar reading strategy study (Moss et al., 2011). Participants received instructions on how to complete this task just before the start of fMRI data acquisition. One yellow line of a particular orientation was presented in each quadrant of the screen surrounding a fixation cross. During the line search task, the line in each of the four locations changed orientation every 2 s. Each line changed orientation one at a time in a clock-wise fashion such that there was one orientation change every 500 ms. The task involved detecting a target line orientation by monitoring the lines. The target was always a 65° line shown to participants before each search task block, and there were three angles of distractor lines: 85°, 45°, and 155°. The participants' task was to press a button with their left index finger when the target was present. The first response recorded after a target but before 2000 ms post-target was counted as a hit. All other responses were counted as false alarms.

An additional control task (to be contrasted with the line search task) was also presented with almost identical visual stimuli except that the participants' task was to press their left index finger every time the central fixation cross blinked. In this control task, four lines were present on the screen but they did not change orientation. The central fixation cross blinked the same number of times as there were targets in the line search task. Each participant completed two data acquisition runs of this task, and each run consisted of 4 blocks of the control task and 4 blocks of the line search task. Each run always began with the control task and then alternated between blocks of line search and control until the end of the run. Each block of the line search and control tasks began with 6 s of encoding whether the task was search or control, followed by 30 s of the task (control or line search), followed by a 6 s delay before the next block began. The entire task lasted 336 s.

Following the line search and line-search control task, participants began the task of reading and using the reading strategies on the three physics texts. The only difference from the MRI simulator procedure was that a 30-s 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 fMRI runs with each run consisting of five paragraphs (3 runs while performing each of the 3 strategies). Due to the self-paced nature of the task, each run was variable with the average run lasting 410 s (SD=49 s). Following these 9 learning runs, participants were presented with a posttest for each text. Participants were informed at the beginning of session 2 that a performance incentive of $0.25 for each posttest question answered correctly would be provided in order to encourage them to learn as much as they could from the texts. Although the posttest was collected in the scanner, we do not examine the posttest fMRI data in this paper.

The behavioral-only participants completed the same procedure with the only differences between the groups

was 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 or the MRI simulator training.

4.5. 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-h 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 mm³) 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=29 ms, TR=2000 ms, FOV=21, slice thickness=3.5 mm with no gap, flip angle=76, in-plane resolution=3.28 × 3.28 mm).

The raw neuroimaging data were preprocessed and analyzed using the AFNI software package (Cox, 1996). Preprocessing included high-pass filtering, 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. Estimated motion was examined in order to exclude time points during which excessive motion occurred from statistical analysis. Overall, the training in the MRI simulator in session 1 was successful at helping to minimize motion. Displacement and rotation within a data collection run were less than 2 mm or 2° in all directions except for inferior–superior displacement and pitch rotation, and in these directions motion was less than 3 mm or 3°. 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 with isometric 3 mm voxels (Talairach and Tournoux, 1988).

Prior to analyzing the data with a voxel-wise general linear model, MELODIC from the FSL software package (Beckmann and Smith, 2004) was used to reduce noise. MELODIC is a probabilistic ICA method that has been used for this kind of noise reduction (e.g., Smith et al., 2010). Similar to Smith et al. (2010), the top 10% of ICA components correlated with motion estimates, high-frequency noise and discontinuous spikes in the data were removed. The time course for each component was correlated with motion to determine the components to remove based on motion. High frequency noise components were eliminated by rank ordering the components by the frequency at which their power was highest (using a Fourier transform) and removing the top 10% of these components. Finally, the top 10% of components showing the greatest TR-to-TR signal change (i.e., a discontinuous spike) were also removed. Comparison of analyses with and without this noise reduction step did not differ greatly, but this step did increase the peak t-statistics for most clusters.

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 3dClustsim, which allows for determination of cluster size using Monte Carlo simulations. The threshold used in the analyses reported here was an uncorrected p-value of .001 and a cluster threshold of 16 contiguous voxels in Talairach space. At the individual subject level, general linear models (GLMs) were fit to the data using a set of boxcar functions for the conditions of interest convolved with a standard hemodynamic response function (Boynton et al., 1996). Each group-level analysis, unless otherwise noted, was done using a mixed effects approach where the average and variance (i.e., beta and t-statistic) at the individual participant level were used in the group analysis (Chen et al., 2012).

4.5.1. Line search functional localizer

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. The line search fMRI data were not spatially smoothed for this analysis. ROIs corresponding to the control network regions were defined on the basis of each subject's statistical map for the line search condition contrasted with the control condition (line search > control). An uncorrected p-value of .05 used to identify the peak t-stat in the clusters corresponding to the DLPFC, anterior cingulate cortex/pre-supplementary motor area (ACC/pSMA), anterior insular cortex (AIC), posterior parietal cortex (PPC), inferior frontal junction (IFJ), and dorsal pre-motor cortex (dPMC). These regions were identified by anatomical landmarks and also by finding the peak of activity in the search task that was closest to coordinates reported by Cole and Schneider (2007). All statistically significant voxels within a sphere of radius 15 mm from the peak were included in the ROI (with the constraint that the sphere could not cross the longitudinal fissure). These ROIs were then used to examine relative activation associated with each of the three reading strategies.

4.5.2. Reading strategy and mind wandering analyses

Regressors for reading, self-explanation, rereading, and paraphrasing were included in the GLMs. For the self-explanation and paraphrasing regressors, the audio recordings were used to determine whether a participant used one of the self-explanation strategies other than paraphrasing for each paragraph. If no strategy other than paraphrasing was used then the strategy for that paragraph was classified as a paraphrase instead of a self-explanation. On average for each participant, 2.73 of 15 self-explanations were reclassified as paraphrasing. Two independent coders scored the data, and agreement was good (88% agreement; Cohen's kappa=.63). Disagreements were resolved through discussion with a third coder.

In addition, the mind wandering ratings that each participant provided for each paragraph were converted to standardized z-scores to correct for individual differences in the range of the scale used, and then these standardized ratings were used to create an amplitude modulated regressor for each participant for the reading, self-explanation, paraphrasing,

and rereading regressors. Modulated regressors for both the reading and strategy components of the task were both included because the participants were asked to rate the frequency of mind wandering across both of these components of the task after each paragraph. These modulated regressors were formed by convolving a boxcar function whose value was determined by the deviation of the standardized rating from the mean of the standardized rating (rating minus mean rating) with a hemodynamic response function (e.g., Buchel et al., 1998). By creating modulated regressors using the deviation from the mean, the correlation of the modulated regressor for a given condition with the non-modulated regressor for that condition was minimal. These modulated regressors were included with the non-modulated strategy regressors in the subject-level GLMs. Beta coefficients for the mind wandering regressors were analyzed within each of the ROIs identified by the line search functional localizer.

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