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IDENTIFYING COMPONENT DISCOURSE PROCESSING FROM THEIR fMRI TIME COURSE SIGNATURES

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Reading is a complex task and it is accomplished by several interactive levels of skills, starting from phonological, lexical and syntactic analyses and extending to propositionalization (Perfetti & Britt, 1995) and intra-sentence integration/discourse-levels (Mason & Just 2004), which involve cognitive processing at higher/different levels such as memory and inference generation (e.g., Kintsch, 1988; Kuperberg et al., 2006; Myers & O'Brien, 1998); and Theory of Mind (understanding the thoughts of another person, e.g., Castelli et al., 2002; Mason & Just, 2009) among others. We suggest that there is evidence to support the characterization of the discourse-level processes in which a reader constructs an understanding of the meaning of larger units of text using the products of lexical and syntactic processing by utilizing regions across the cortex. We will refer to this set of processes as discourse comprehension

Network theories of discourse comprehension (e.g., Ferstl et al., 2008; Schmalhofer & Perfetti, 2007) typically specify functional roles for different brain regions by identifying which regions activate during high level comprehension tasks such as reading passages that require inferences (Jung-Beeman, 2005; Kuperberg et al., 2006; Martin-Loeches et al., 2008; Mason & Just 2006; Virtue et al., 2006, 2008; Xu et al., 2005). The general conclusion from these studies is that there are many regions that interact to support discourse comprehension. In fact, Perfetti and Frishkoff (2008, p. 172) specify in their review of the neuroimaging literature that "Of course, there should be no surprise to learn that the components of text processing are distributed rather than localized. They depend fundamentally on processes of information encoding, memory, and retrieval, along with basic left hemisphere language processes." Occasionally, a meta-analysis across data sets (Ferstl et al., 2008) will provide insight as to which regions are generalizable beyond task-specific experimental designs. Both of these techniques are excellent ways of specifying the network(s), yet as suggested here, both can leave some things unspecified. This chapter is an attempt to revisit our initial characterization of discourse networks (Mason & Just, 2006) and suggest that there is evidence to support the characterization of cognitive processes which utilize multiple regions across discourse networks. What is presented here is a data mining technique (factor analysis of the time course of activated cortical regions) that offers a novel way of determining network makeup and function.

Using the traditional approach, we (Mason & Just, 2006) put forward an integrative conceptual framework for understanding brain function specifically during discourse processing. This framework proposed that discourse comprehension involved, in addition to lexical and syntactic processing, five specialized networks: (1) a coarse semantic processing network (right middle and superior temporal); (2) a coherence monitoring network (bilateral dorsolateral prefrontal); (3) a text integration network (left inferior frontal-left anterior temporal); (4) a network for interpreting a protagonist or agent's perspective, essentially the Theory of Mind network (bilateral medial frontal/posterior right temporal/parietal); and (5) a spatial imagery network (left dominant, bilateral intraparietal sulcus). This characterization of the discourse processing framework was predominantly based on neuroimaging results, but was intended to be consistent with discourse theories that have arisen from behavioral (e.g., Kintsch, 1988; Myers & O'Brien, 1998), and neuropsychological (Grafman, 1995) as well as neuroimaging research.

This neurocognitive framework guided research from our lab, and helped integrate different activation patterns across texts and individuals into a unified whole. In the interim the framework has been adapted due to investigations of causal inferences (Mason & Just 2004), intentional inferences (Mason & Just 2011), theory of mind in text (Mason & Just 2009), inferences in autism (Mason et al., 2008), causal connectives (Prat et al., 2011), and figurative language (Prat et al., 2012). Across these tasks, the relationship of which components of the network were active depended on task. Once the components were specified, the conceptualization of the network was extended by examining the functional synchronization of the component regions. Not only were the regions activated as needed, they were recruited only when necessary (Mason & Just 2011). An internal meta-analysis of these seven studies guided by the parallel networks of discourse framework (combining group level activation results across the various passage types) resulted in a set of 20 functional regions of interest (fROIs) which has been used to examine the recruitment and synchronization of activated voxels within each fROI. The current work follows from the examination of synchronization between regions.

The following research will examine processing of the discourse network by conducting an exploratory factor analysis of the time course, with respect to fixation, of functional regions of interest during reading. Specifically, the time course of activation was examined when participants read multiple sentence passages which contained a potential inference (or non-inference control). These inferences were based on either a character's intention or physical causality. The passages were followed by a comprehension probe. Examples of the two types are presented here (see Mason and Just (2011) for a more complete description):

> *Protagonist Intention Inference Passage*
> Brad had no money but he just had to have the beautiful ruby ring for his wife. Seeing no salespeople around, he quietly made his way closer to the ring on the counter. He was seen running out the door. Were there any salespeople near Brad?
>
> *Physical Causality Inference Passage*
> While playing in the waves, Sarah's Frisbee went flying toward the rocks in the shallow water. While searching for it, she stepped on a piece of glass. Sarah had to wear a bandage on her foot for a week. Was Sarah searching for her beach ball?

Factor analysis is a data extraction/reduction technique[1] which offers new insights into brain imaging investigations of discourse comprehension by establishing that a fROI can be part of a group of regions that are supporting a component cognitive process at the same point in time. A time course corresponding to each factor can then be reconstructed in order to interpret the function of the component cognitive process. A simplistic example of what is referred to here as a component cognitive process, and might be extracted as a factor, would be a shared neural response across a set of regions associated with answering a probe question. Interpretation of the factor will depend upon the traditional roles of the set of similarly responding regions, their strength of association (or factor loadings), and the reconstructed time course of the factor. This approach enabled us to group cortical regions into four component cognitive processes: (1) Integration and synthesis of intentional inferences; (2) Interrogating memory of passage to answer probe; (3) Sentence level integration and potential generation of forward inferences; and (4) Structure building/Establishing the text model. However, this technique is not intended to supplant traditional techniques and, in fact, network theories (e.g., Ferstl et al., 2008; Mason & Just 2006) are necessary in order to interpret the data driven factor analysis as it was for these four factors.

In this case, common components from the time course of activated voxels in 20 functional regions of interest across 4 passage types (intentional inference/control and physical causality inference/control) were extracted. The 4 factors which account for at least 10% of the variance across the 80 time courses (20 fROI x 4 conditions) are presented here. In this data-reduction technique, the extraction of factors is dependent upon the input in both the temporal region of the input (whole passage in this case) as well as passage type. Restricting the analysis to a smaller temporal region, for example the probe, or to a specific condition would likely result in a different set of factors. In the future, more specific hypothesis about within passage networks could be examined by limiting the data, or conversely more general examinations could occur by expanding the data set to other experiments. Here the approach is to examine the discourse network across a set of similar passage-probe stimuli. An example of the raw time course in the left superior temporal (averaged over activated voxels and passages) is presented in Figure 10.1. It is superimposed with a boxcar function representing the experimental paradigm that has been shifted 4 seconds to allow for the hemodynamic delay.

In the following 4 sections, the extracted factors will be presented. A time course corresponding to the factor was then reconstructed under the assumption that each time point can be estimated given the factor loadings and the original time courses values from the (fROI X condition) components(Just et al., 2010).[2] For each factor, the underlying cognitive component is interpreted based on three considerations: (1) the timing of the fluctuations in the component time course (e.g., increase at sentence onset, decrease at offset), (2) the experiment conditions (e.g., intention vs. physical) which load heavily on the component, and (3) common cognitive roles that have been hypothesized for the fROIs which load heavily on the component. The resulting factors are presented in the order of percentage of variance accounted for across the 80 time courses

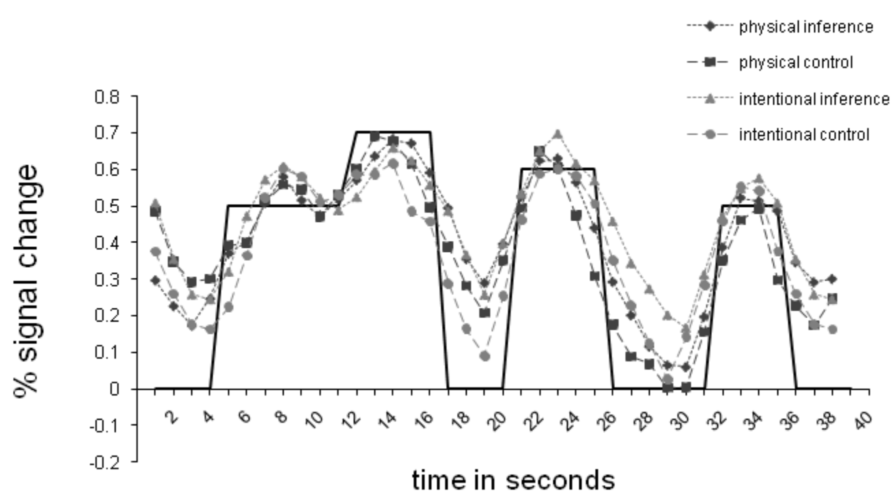

Figure 10.1. The time course for the left superior temporal fROI is presented as an example. The paradigm is presented as a boxcar function and shifted corresponding to the hemodynamic delay. The first bimodal rise corresponds to processing sentences 1 and 2, the second rise corresponds to sentence 3 and the fourth rise corresponds to the probe.

Factor 1 - Integration and Synthesis of Intentional Inferences

The largest common component across the ROIs corresponds to integration and synthesis of intentional inference accounting for ~32% of the variance. That this component accounts for a large percent of the variance is perhaps unsurprising since the manipulation of characters' intentions was a main component of the experimental design. Additionally, all the passages were narratives requiring protagonist monitoring even when an explicit intention based inference was not necessary. The time course of this component indicates an onset of processing during the 2nd half of reading the inference sentence and extends into the probe. This can be seen in Figure 10.2. The temporal location of the onset of processing is a limiting factor in the possible cognitive functioning. Here, the lack of a response early on limits the interpretation to what the reader is doing at the end of the passage. Combined with the information that the primary network loadings were on the intention passages, leads to the interpretation of Factor 1 as supporting an intentional inference. From the example passage, the reader could be completing the inference that Brad stole the ring. As indicated in the shaded circles on the brain image, this time course critically involved the Protagonist Network (Mason & Just 2009; 2011). We have proposed a critical Protagonist Network for in narrative comprehension involving the medial frontal gyrus and the right temporo-parietal junction. As suggested by Mason and Just (2011) the ability to understand the goals and intentions of a protagonist as well as other characters in a story is essential for a reader to understand a story. Thus, engagement of a social processing system, particularly a Theory of Mind cortical network, is expected during the reading of any narrative (Martin & Weisberg, 2003; Moll et al., 2002; Nichelli et al., 1995; Xu et al., 2005). Often, in social and developmental psychology, "Theory of Mind" refers to the ability to think about the mental state of another person (Gallagher & Frith, 2003; for a review, see Saxe et al., 2004). In this case, the involvement of this "Theory of Mind" network supports the understanding of protagonist intentions and synthesis into the discourse representation.

The loading of primary language network fROIs (left inferior frontal gyrus and left superior temporal gyrus, extending from the posterior region down to the temporal pole) on Factor 1 is indicative of a reciprocal nature of basic language processing and inference integration. This conclusion that that areas of the brain that are active during sentence comprehension also support the comprehension of connected text was reached by Perfetti and Frishkoff (2008) as well and it is consistent with activation of these regions during narrative comprehension as contrasted with baseline in the majority of discourse imaging papers.

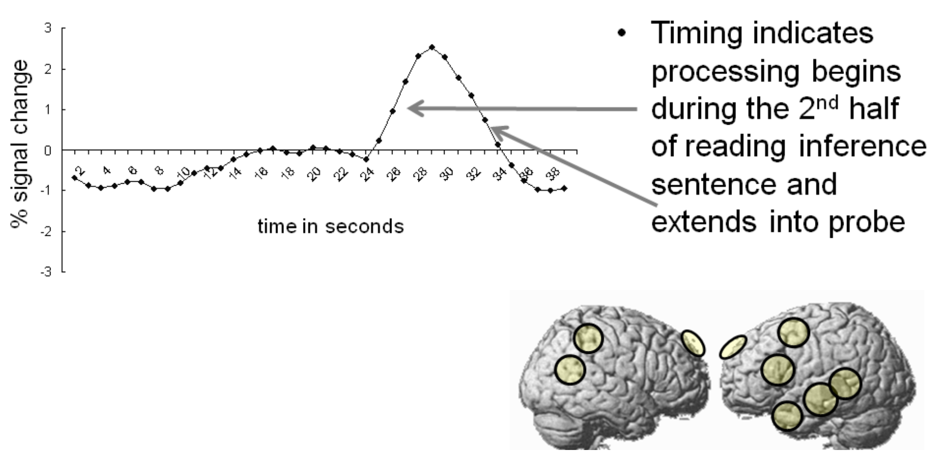

Figure 10.2. The time course and fROIs which comprise the first factor are presented.

Factor 2 - Interrogating Memory of Passage to Answer Probe

Each passage is followed by a comprehension probe. This aspect of the design is reflected in a factor corresponding to the interrogation of memory of a passage in order to correctly respond to the probe (~22% of the variance). This interpretation is strongly reflected in the time course. The timing indicates a processing onset in response to the probe appearing on the screen. The processing drops after onset of new item (seen in Figure 10.3). Also consistent with this condition independent interpretation is that this factor has primary loadings on all types of passages regardless of inference source (intention or physical) or even presence of an inference or an explicit statement (control).

As indicated in the accompanying fROI mapping, the primary network loadings were on regions which have been known to correspond to memory (hippocampus and fusiform; see Squire & Schacter, 2002) as well as the left superior temporal gyrus. The left superior temporal ROI is localized in traditional Wernicke's area and has been traditionally associated with comprehension based semantics (for reviews see Bookheimer, 2002; Price, 2000).

Also present is the left anterior temporal gyrus. This region has been suggested to be a center of propositionalization in text processing (Ferstl et al., 2008). Propositionalization in text involves extracting semantically based content units out of the individual words in the text (Kintsch & van Dijk, 1978; Kintsch, 1988; Perfetti & Britt, 1995). A heavy loading on this time course possibly indicates a component of directly interrogating the text base in order to correctly respond to the probe.

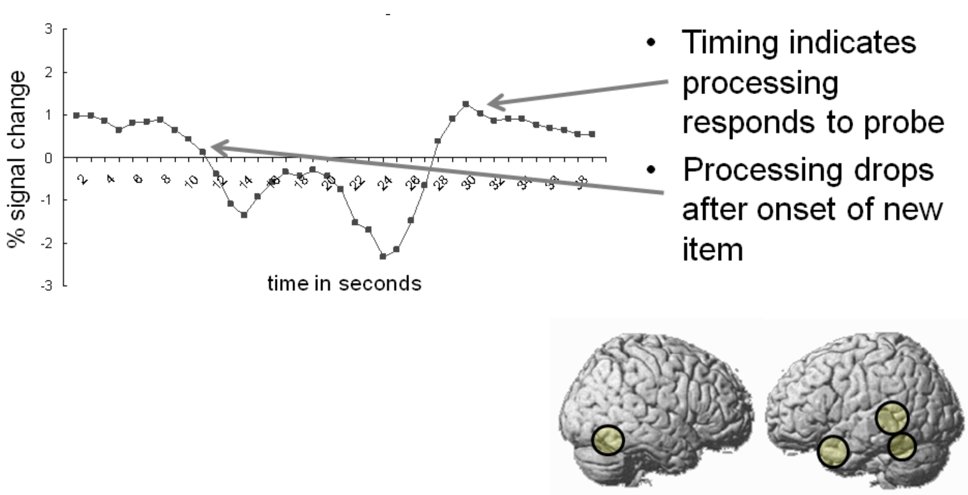

Figure 10.3. The time course and fROIs which comprise the second factor are presented.

Factor 3 - Sentence Level Integration and Potential Generation of Forward Inferences

The third Factor is involved in the integration of sentences during the processing of a text. It is also consistent with the potential generation of forward inferences due to the slightly larger increases following the forward inference sentence in the passage (~20% variance). The time course leads to this conclusion based on the bimodal function which rises at the offset of the first sentence and the offset of the second sentence (shown in Figure 10.4). While integration presumably occurs at the end of the third sentence and the probe, these rises are accounted for by the previous two factors. In further support of the integration interpretation, the loadings are primarily on the right hemisphere in the temporal gyrus regardless of passage type. This is consistent with work which proposed a right hemisphere role in integration processing (Long & Baynes, 2002; Mason & Just 2004; Schmalhofer & Perfetti, 2007).

This factor also loads on the primary language regions (left inferior frontal gyrus and left superior temporal gyrus), but only for the inference passages. This pattern reflects an additional workload in primary language regions when an inference is potentially generated, perhaps reflecting a reciprocal relationship. Optional or elaborative inferences tend to be more reliably drawn by high capacity readers (Just & Carpenter, 1992; Long et al., 1997). This additional loading for inferences in the second sentence in the left hemisphere may reflect additional capacity in those regions for high span readers. This hypothesis is tentative and would require further research, but would be consistent with the conclusions of Prat et al. (2011).

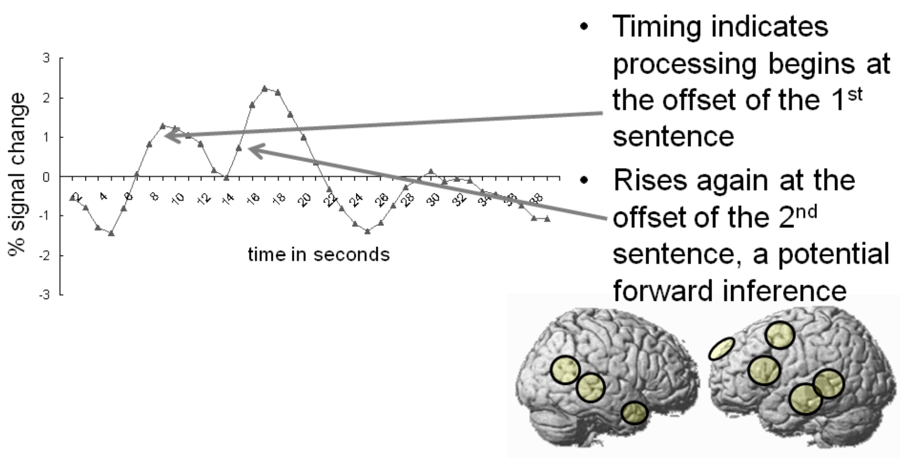

Figure 10.4. The time course and fROIs which comprise the third factor are presented.

Factor 4 - Structure Building/Establishing the Text Model

Establishing a text model is an essential part of comprehending any passages (Kintsch 1988; Gernsbacher, 1990). This process will be heavily involved at the beginning of a passage and likely will update with each additional sentence. This pattern fits the time course of the fourth Factor (accounting for ~13% of the variance) as seen in Figure 10.5. The onset of processing is fairly large for the first sentence and each additional sentence is accompanied by a rise in the function. Although this would be expected for all passages, primary loadings occurred for the physical causality passages (both inference and explicit); it is likely that this component is less in the intentional passages due to some overlap with protagonist monitoring (additional factors that account for less than 10% of the variance load on the intention passages).

This network loads heavily on two right hemisphere regions that have been suggested to be involved in propositionalization and text model establishment (Robertson et al., 2000; Schmalhofer & Perfetti, 2007). These regions could be expected to be involved early on in the passage to provide a foundation (Tomitch et al., 2004). Much like the other factors, this time course also loads on the primary language fROIs in the left hemisphere (left superior temporal gyrus and left inferior frontal gyrus). This is also consistent with most text imaging work that suggests the primary language networks activate in context sentences (Martin-Loeches et al., 2008; Mason & Just 2004, 2011; Virtue et al., 2006; Xu et al., 2005).

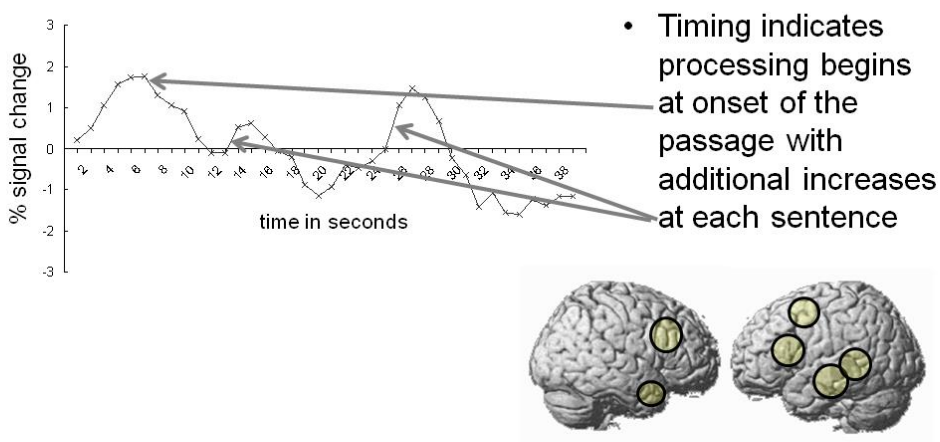

Figure 10.5. The time course and fROIs which comprise the fourth factor are presented.

Benefits from the Factor Analysis Approach

Combined, these factors indicate that information may be extracted from a set of fROIs beyond those which activate, when they activate, and the synchronization among and across the fROIS. Specifically, cognitive component processes may be supported by several regions (e.g., hippocampus and left superior temporal gyrus for the interrogating memory factor) and may activate in response to workload in connected fROIs (e.g., the primary language network fROIs in the Integration and synthesis of intentional inferences network). The factor analysis approach has the utility of extracting information across the cortex that is in some sense lost in examining raw time courses of activation for an entire passage.

The factor analysis approach is meant to enhance our understanding of the discourse network and not supplant previous approaches. Interpretation is both exploratory and highly context-depended. It is reliant on *a priori* specified fROIS that arose from previous conceptualizations of the discourse network. Furthermore the grouping of regions and factor loadings must be interpreted in the light of theory. For example, the loadings of the intentional inference passages and the Protagonist Network fROIS (medial frontal and right temporo-parietal junction) on Factor 1 enable the interpretation as integration and synthesis of intentional inferences.

A potential future utility of this approach is the specification of the discourse network as a function of an individual's reading ability or working memory capacity. Prat et al. (2007) described three system-level properties that characterize the brain activation of high-capacity readers: (1) greater efficiency (accomplishing the same task with less activation); (2) greater adaptability (more modulation of activation as a function of variation in the task demand); and (3) higher inter-center synchronization (higher functionally coordination). A number of studies in this lab have begun to approach the understanding of language processing as a function of individual differences (Buchweitz et al., 2009; Prat et al., 2011; Prat & Just, 2011) The factor analysis approach could naturally group component process that load on individual differences. It may expand our understanding of what fROIs activate as a function of ability and the component processes that remain unaffected at the individual level.

In summary, cortical-based discourse theories can benefit from a factor analysis approach to reduce the data-rich fMRI results. Specifically, a dynamic network based account can be enhanced by hypothesizing that specialized regions may be multi-functional and utilized in more than one cognitive component of discourse comprehension. In this instance, a data set which supported the existence of a Protagonist Network (Mason & Just 2011) was used to specify some underlying components to discourse comprehension beyond monitoring and inference synthesis yet still is consistent with that theory. The factors that arose were interpreted as: (1) Integration and Synthesis of Intentional Inferences; (2) Interrogating memory of passage; (3) Sentence level integration and potential generation of forward inferences; and (4) Structure Building/Establishing the text model. This exploratory analysis has the potential of enhancing our conceptualization of cortical-based discourse processing models particularly through the use in investigations of individual differences.

Notes

1 This Factor Analysis was performed similarly to that present in Koshino et al. (2005). For each participant, a mean time-course was computed across activated voxels in each ROI. An exploratory factor analysis (e.g., Peterson et al., 1999) was then performed for each group separately. Our logic behind the factor analyses was that each factor would represent a large-scale network among brain regions corresponding to some functions (e.g., Mesulam, 1990, 1998). Factors that had eigenvalues of 1.0 or above were retained. In this case, an eigenvalue corresponds to the equivalent number of ROIs that the factor represents. Factor loadings represent the degree to which each of the ROIs correlates with each of the factors, and ROIs that had factor loadings of 0.4 or greater were taken into consideration in interpretation.

2 The reconstruction of a time course for each of the four factors is analogous to the second level analysis in Just et al. (2010). In this case the factor profile is a vector across the time points of the

hemodynamic response as opposed to words in their analysis. Thus, the factor profile can be solved for given the time course and factor loadings of each ROI x condition vector.

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