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Cortical regions supporting reading comprehension skill for single words and discourse

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ABSTRACT

A substantial amount of variation in reading comprehension skill is explained by listening comprehension skill, suggesting tight links between printed and spoken discourse processing. In addition, both word level (e.g., vocabulary) and discourse–level sub-skills (e.g., inference-making) support overall comprehension. However, while these contributions to variation in comprehension skill have been well-studied behaviorally, the underlying neurobiological basis of these relationships is less well understood. In order to examine the neural bases of individual differences in reading comprehension as a function of input modality and processing level, we examined functional neural activation to both spoken and printed single words and passages in adolescents with a range of comprehension skill. Data driven Partial Least Squares Correlation (PLSC) analyses revealed that comprehension skill was positively related to activation in a number of regions associated with discourse comprehension and negatively related to activation in regions associated with executive function and memory across processing levels and input modalities.

1. Introduction

While the contributors to variation in reading comprehension ability in both children and adults have been well-studied behaviorally, the underlying neurobiological basis of this variation is less well understood. Progress in this area has been hindered by a reliance on off-line measures of reading comprehension, such as standardized assessments or comprehension questions, which do not support the investigation of comprehension processes as they unfold. In addition, such measures likely recruit other strategic test-taking or problem solving skills which may not be intrinsic to comprehension processes themselves. The current study addresses this gap by tracking neural activity (BOLD signal) during natural text comprehension in a task-free environment so that task processing demands cannot artificially drive relations among the dimensions of interest.

Research on variability in reading comprehension skill has been heavily influenced by the Simple View of Reading (Gough & Tunmer, 1986), which suggests that reading comprehension is the product of decoding (word and non-word reading) and listening comprehension. Indeed, regression models testing the Simple View have been found to account for as much as 77% of variance in reading comprehension (e.g., Adlof, Catts, & Little, 2006; Braze, Tabor, Shankweiler, & Mencl, 2007; García & Cain, 2014; Joshi, Ji, Breznitz, Amiel, & Yulia, 2015; Sparks & Patton, 2016; Tunmer & Chapman, 2012). A natural extension of this view is the notion that once word decoding is mastered, reading comprehension ability will be solely determined by an individual's oral language ability (i.e., listening comprehension). This is consistent with high correlations observed between reading and oral language comprehension (r = .50–.75; Braze et al., 2007; Diakidoy, Stylianou, Karefillidou, & Papageorgiou, 2005; Tighe & Schatschneider, 2014; Tunmer & Chapman, 2012; Wise, Sevcik, Morris, Lovett, & Wolf, 2007).

A wealth of behavioral evidence supports this approach. To begin with, listening comprehension has a strong influence on reading comprehension ability throughout development (Hogan, Adlof, & Alonzo,

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2014). It is related to reading comprehension over and above reading fluency in first grade, a time when word reading skill is still developing (Kim, Park, & Wagner, 2014). Reading and listening comprehension are highly correlated and the skills important for both are largely overlapping (Adams, Bourke, & Willis, 1999; Verhoeven & van Leeuwe, 2008). These include both word-level processing skills (phonological and lexical-semantic processing) and higher-level linguistic skills such as word-to-text integration, parsing, and inference making (Babayigit & Stainthorp, 2014; Diakidoy, et al., 2005). In addition, a few studies suggest that functional activation during comprehension is largely modality-independent, especially for complex sentences or passages (Braze et al., 2011; Constable et al., 2004). Despite these findings, there has only been one exploration of the relationship between reading comprehension skill and neural activation as a function of processing modality (spoken versus printed).

Shankweiler et al. (2008) examined how activation during listening and reading comprehension relates to many different reading-related skills. Their participants listened to or read sentences in the scanner. They found that convergence in activation across modalities increased with reading comprehension skill in dorsal IFG, such that more-skilled comprehenders showed similar activation while reading and listening while less-skilled comprehenders showed more modality-specific activation in this region. This effect persisted even after taking into account individual differences in listening comprehension, decoding, and vocabulary. However, another goal of this study was to investigate effects related to processing syntactically and pragmatically anomalous sentences. Thus, the stimuli were somewhat artificial in nature. In the present study, we seek to replicate and extend this study by examining how reading comprehension skill relates to neural activation during comprehension of naturalistic spoken and printed texts.

An important component in any such investigation is examining the multiple different levels at which variation may occur. Many skills at multiple levels of processing contribute to reading comprehension ability. For example, decoding skill often explains significant variance in reading comprehension ability, especially in young readers (Kendeou, van den Broek, White, & Lynch, 2009; Perfetti & Hogaboam, 1975). However, even after decoding has been taken into account, many other skills make significant contributions to reading comprehension ability. These include other word-level abilities, such as vocabulary (Braze et al., 2007; Cain & Oakhill, 2014) and morphosyntax (Chik, man, Ho, C. S. han, Yeung, P. sze, Wong, Y. kai, Chan, D. W. ock, Chung, K. K. hoa, & Lo, L. yan. , 2012) as well as higher-level and domain-general skills such as inference-making (Cain, Oakhill, & Bryant, 2004) and executive function (Sesma, Mahone, Levine, Eason, & Cutting, 2009). These skills each account for unique variance in reading comprehension across the distribution of comprehension ability (Language and Reading Research Consortium, & Logan, 2017), suggesting that individual differences in reading comprehension could be related to processing ability at any or all of these different levels. Consequently, the goal of the current study is twofold. First, we seek to identify common and distinct neural bases for comprehension across modalities (speech versus print) and processing levels (single words vs. passages). Second, we explore how individual differences in reading comprehension (measured offline) are associated with activation as a function of these processing levels and modalities.

Multiple regions support passage comprehension. Comparisons of text comprehension to rest, a simple perceptual baseline, or to unconnected text (e.g., word lists) most consistently show activation in bilateral middle and superior temporal gyri (MTG/STG) and bilateral anterior temporal lobe (ATL) across studies (Ferstl, Neumann, Bogler, & von Cramon, 2008). A meta-analysis of studies looking at semantic and syntactic comprehension in spoken and written tasks found that studies most often showed activation in regions in and around the left inferior frontal gyrus (IFG), including pars opercularis, pars triangularis, and precentral gyrus, This study also found activation in left MTG extending into the left STG (Rodd, Vitello, Woollams, & Adank, 2015). These two meta-analyses indicate that comprehension across modalities includes temporal and frontal regions, with text comprehension showing more bilateral activation.

Similarly, recent meta-analyses indicate overlapping regions for comprehension of language across processing levels. Houdé et al., (2010) conducted a meta-analysis on 16 studies where participants completed a variety of reading-related tasks at various levels of processing while in the scanner. These studies revealed many regions consistently activated during reading in the left frontal, temporoparietal, and occipitotemporal regions. Specifically, the putative Visual Word Form Area (VWFA) in left occipitotemporal (OT) cortex was consistently activated across all studies. In addition, IFG and precentral gyrus were implicated. Regions in the inferior, middle, and superior temporal gyri as well as inferior parietal gyrus show consistent activation, as does a cluster in bilateral supplementary motor area (SMA). A later meta-analysis looking at activation during various reading tasks at the word and sentence levels in both adults and children showed similar consistency in patterns of activation (Martin, Schurz, Kronbichler, & Richlan, 2015). Studies of both adults and children exhibited convergent activation in left OT, left IFG (specifically pars opercularis and pars triangularis), bilateral SMA, and left posterior parietal cortex. Temporal activation was seen more in children than adults, specifically in STG. Adults showed more convergence than children in left frontal regions, left middle occipital gyrus, cerebellum, and ventral OT. These results indicate that word and sentence/passage reading involves activation in left OT, left IFG, bilateral SMA, and left posterior parietal cortex.

Despite the wealth of behavioral studies investigating individual differences in reading comprehension and recent studies looking at the neural bases of comprehension, relatively few studies have explored the neural bases of individual differences in reading comprehension skill. However, some existing work supports the view that variation in spoken language processing skill and variation in reading comprehension skill are linked at the neurological level. For example, amount of activation in regions that have been associated with language processing (e.g., IFG, STG, MTG) during both listening and reading comprehension tasks is related to overall reading comprehension ability. In particular, reading comprehension skill has been shown to be related to print-speech activation overlap in IFG (Shankweiler et al., 2008). Activation during spoken narrative comprehension in left inferior frontal gyrus (IFG) is correlated with reading comprehension ability (Horowitz-Kraus, Vannest, & Holland, 2013). Reading comprehension skill is also associated with activation in left middle and superior temporal gyri (MTG/STG) during printed sentence and passage processing (Aboud, Bailey, Petrill, & Cutting, 2016; Van Ettinger-Veenstra, McAllister, Lundberg, Karlsson, & Engström, 2016; Yarkoni, Speer, & Zacks, 2008). These neural findings converge with behavioral results showing great overlap between spoken and printed comprehension at the passage level.

Studies of brain-behavior relationships for single word processing have identified similar regions, suggesting that individual differences in reading comprehension skill similarly modulate neural activation across the sentence, passage, and word levels. For example, one study found that reading comprehension is negatively related to activation in left IFG and left fusiform gyrus when processing semantically-related printed words (Malins et al., 2016). In addition, Welcome and Joanisse (2012) found that during word reading, activation in the left MTG is negatively related to reading comprehension skill. Further, individuals with particularly poor reading comprehension despite typical decoding skill have been found to have atypical functional connectivity between IFG and parahippocampal regions during a lexical decision task (Cutting et al., 2013). Thus, across studies, the regions that link offline reading comprehension skill and online single word and passage comprehension are largely overlapping.

The studies summarized here implicate associations between reading comprehension skill and neural activation during both word

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