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A 10-year longitudinal fMRI study of narrative comprehension in children and adolescents

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ABSTRACT

Comprehension of spoken narratives requires coordination of multiple language skills. As such, for normal children narrative skills develop well into the school years and, during this period, are particularly vulnerable in the face of brain injury or developmental disorder. For these reasons, we sought to determine the developmental trajectory of narrative processing using longitudinal fMRI scanning. 30 healthy children between the ages of 5 and 18 enrolled at ages 5, 6, or 7, were examined annually for up to 10 years. At each fMRI session, children were presented with a set of five, 30 s-long, stories containing 9, 10, or 11 sentences designed to be understood by a 5 year old child. fMRI data analysis was conducted based on a hierarchical linear model (HLM) that was modified to investigate developmental changes while accounting for missing data and controlling for factors such as age, linguistic performance and IQ. Performance testing conducted after each scan indicated well above the chance ($p<0.002$) comprehension performance. There was a linear increase with increasing age in bilateral superior temporal cortical activation (BAs 21 and 22) linked to narrative processing. Conversely, age-related decreases in cortical activation were observed in bilateral occipital regions, cingulate and cuneus, possibly reflecting changes in the default mode networks. The dynamic changes observed in this longitudinal fMRI study support the increasing role of bilateral BAs 21 and 22 in narrative comprehension, involving non-domain-specific integration in order to achieve final story interpretation. The presence of a continued linear development of this area throughout childhood and teenage years with no apparent plateau, indicates that full maturation of narrative processing skills has not yet occurred and that it may be delayed to early adulthood.

Introduction

The development of narrative comprehension skills is critical for communication. Listening to stories is a daily routine for many children and children who are already in preschool are able to create stories that contain basic plot elements. As children develop, story structure becomes more elaborate and complex, including main and subplots. Narrative skills are not just important to oral communication, but are also linked to later literacy skills, including reading comprehension and written language skills (Chang, 2006; Griffin et al., 2004; Silliman, 1989). This is not only true for children developing language and literacy skills in a typical fashion, but also for children who have a reading disability (Westerveld and Gillon, 2010; Westerveld et al., 2008). Furthermore, deficits in oral narrative skills are found for a wide range of developmental disorders that affect children, including attention deficit hyperactivity disorder (Lorch et al., 1998), Down syndrome (Bird et al., 2008), language impairment (Copmann and Griffith, 1994), learning disability (Schneider et al., 1997; Wright and Newhoff, 2001), and Williams syndrome (Marini et al., 2010). Likewise, children with acquired disabilities,

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including traumatic and focal brain injury also show deficits involving narrative skills (Chapman et al., 2004; Kennedy and Nawrocki, 2003).

The ability to comprehend a story involves coordination of a number of basic linguistic skills including phonological, semantic, and syntactic processing along with the ability to accumulate information over time and draw links between separate propositions. Narrative competence clearly rests on a base of strong linguistic skills. However it is also the case that more general cognitive skills, like verbal working memory (Karasinski and Weismer, 2010) and processing capacity and speed (Montgomery et al., 2009) predict narrative skills. Further, children who produce complex and high quality narratives tend to have strong general cognitive skills (Curenton, 2011). Thus, both the cognitive and linguistic capacity of the child influences performance on narrative tasks (Curenton, 2011; Karasinski and Weismer, 2010; Montgomery et al., 2009).

Given the complexity of narrative processing, and the range of skills that contribute to its development, it should not be surprising that the development of narrative skills has a protracted trajectory. Differences in narrative comprehension with age are readily detected in the early school years with increases in the number of story elements that are recalled and an increased ability to draw inferences (Vieiro and Garcia-Madruga, 1997) as well as an improved ability to make connections between story elements (Brown et al., 2011). Even in the middle school years children appear to still be acquiring narrative comprehension skills relative to that of adults (Bohn-Gettler et al., 2011).

Given the importance of narrative development for normal children, and its wide-spread presence in the face of pediatric disorders, understanding of the neural mechanisms supporting this skill as it develops could be of considerable benefit from a range of perspectives. Previous imaging work has established that narrative comprehension is supported by a bilateral (left more than right) network that includes frontal, temporal and cingulate areas. These areas are involved not only in working memory and theory-of-mind processes but also in comprehension and production of language and causal-temporal ordering of information (Holland et al., 2007; Karunanayaka et al., 2007; Kobayashi et al., 2007; Long and Baynes, 2002; Mar, 2004; Schmithorst et al., 2006). Although narrative comprehension overall appears to be represented fairly symmetrically in both hemispheres, the participation of the non-dominant for language hemisphere may be increasing in response to the complexity of the contextual information (Xu et al., 2005). In contrast to bilateral cortical involvement in narrative comprehension, the left perisylvian areas are typically engaged in language production and are more involved in linguistic processes that become progressively more left-lateralized with age (Schmithorst et al., 2006; Szaflarski et al., 2006a, 2012). Further, there may be some degree of change in lateralization of narrative comprehension as the participants continue processing the story with left-hemispheric language areas involved more at the onset of the story (linguistic component) and right-hemispheric language areas showing more activation at the outset of the story. This is postulated to be related to representation and synthesis of the heard sentences into a coherent whole (Xu et al., 2005). The notion of the bilateral cortical involvement in narrative processing is in agreement with previous studies suggestive of the presence of the right hemisphere dominant network for higher order language processing (Meyer et al., 2000) and increased right hemispheric involvement with improved semantic processing (Donnelly et al., 2011).

A recent cross-sectional study of narrative comprehension in children ages 5–18 revealed multiple neural components and functionally connected regions that participate in the narrative comprehension (Schmithorst et al., 2006). These authors described several stepwise processes and the participation of various anatomical and functional brain areas. The first step in narrative comprehension was bilateral acoustic processing mediated via superior temporal gyri followed by semantic processing in bilateral superior temporal gyri (Friederici et al., 2003). A left-lateralized fronto-temporal language network is recruited, either related to covert speech generation (Schmithorst et al., 2006; Szaflarski et al., 2006a,b), syntactic processing at the sentence level, or semantic decision and subvocal rehearsal (Bullmore et al., 2000). Next, the information is reprocessed in the bilateral superior temporal gyri (non-domain-specific integrative process) with the final higher-order semantic processing occurring in the bilateral angular gyri (Schmithorst et al., 2006). This model provides a snapshot of the anatomical and functional components of narrative comprehension but it has not fully addressed the developmental aspect of narrative processing by children and adolescents. Although the available cross-sectional data (Schmithorst et al., 2006) can suggest what the developmental trajectory might be, the *gold standard* for establishing developmental patterns is longitudinal data. Therefore, by using a within-participant methodology and longitudinal fMRI study design, we sought to characterize the dynamic changes that occur during the maturation of the brain modules involved in the narrative comprehension (rather than narrative production) in children between the ages of 5 and 18 years. The hypothesis guiding this work, based on the available literature, was that there would be bilateral increase in the involvement of the predominantly temporal regions in narrative comprehension as the children mature related to improved access to the individual words, retrieval of their meaning, and integration of information from semantic storage to discourse production (Ahmad et al., 2003; Kuperberg et al., 2006; Long and Baynes, 2002). This is in contrast to single word and narrative production that has been shown to involve predominantly the left frontal and temporo-parietal regions (Gaillard et al., 2003; Karunanayaka et al., 2010; Long and Baynes, 2002; Troiani et al., 2008).

Materials and methods

Participants

In 2000, from a larger cohort of children enrolled in a cross-sectional study of normal language development (RO1 HD38578), we recruited 30 participants ages 5–7 (16 female) to take part in a longitudinal component of the study. A detailed description of the longitudinal cohort, scanning and data analysis methods is provided elsewhere (Karunanayaka et al., 2011b; Szaflarski et al., 2006b, 2012). Here, we provide a brief description of the methods focusing on the unique aspects of the longitudinal analysis of narrative comprehension. The enrolled children were followed annually (fMRI) or biannually (neurocognitive data collection) for up to 10 years. Some children were scanned less than 10 times due to later enrollment, braces or other metallic artifacts or due to moving to another part of the country/not being available for scanning anymore (Table 1). All participants were native English speakers and had normal neurological examination prior to study enrollment. As part of the IRB-approved exclusion criteria any children with abnormal neurological examination or history of neurological problems (e.g., migraine headaches or head trauma) were excluded. All informed consent procedures were approved by the Institutional Review Board of the Cincinnati Children's Hospital Medical Center in adherence to the Declaration of Helsinki.

Behavioral testing

All children received a battery of norm-referenced tests including *Oral and Written Language Scales* (OWLS) at the time of the first scan and then in years 3 and 5 of the study and *Wechsler Intelligence Scale for Children — III* (WISC-III) at the time of the first fMRI study visit (Carrow-Woolfolk, 1996). In year 6, the neurocognitive battery and post-scan questionnaire were expanded to allow detailed assessments of neurocognitive development during the second five-year period of the longitudinal study. Test results from years 6 to 10 are not reported here. WISC-III and OWLS scores and task performance are expected to