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Fiber tracking of the frontal aslant tract and subcomponents of the arcuate fasciculus in 5–8-year-olds: Relation to speech and language function

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ABSTRACT

Long association cortical fiber pathways support developing networks for speech and language, but we do not have a clear understanding of how they develop in early childhood. Using diffusion-weighted imaging (DWI) we tracked the frontal aslant tract (FAT), arcuate fasciculus (AF), and AF segments (anterior, long, posterior) in 19 typical 5–8-year-olds, an age range in which significant improvement in speech and language function occurs. While the microstructural properties of the FAT and the right AF did not show age-related differences over the age range we investigated, the left AF evidenced increasing fractional anisotropy with age. Microstructural properties of the AF in both hemispheres, however, predicted receptive and expressive language. Length of the left FAT also predicted receptive language, which provides initial suggestion that this pathway is important for language development. These findings have implications for models of language development and for models of the neurobiology of language more broadly.

1. Introduction

Two fundamental problems facing researchers exploring the neurobiology of speech and language and its development are the establishment of a comprehensive map of the fiber pathways comprising the network's structural connectivity, and the establishment of the functional relevance of the various fiber pathways to specific linguistic domains. Indeed, understanding connectivity of the speech/language network can provide critical insights into function. Before the advent of diffusion-weighted imaging (DWI), studying human brain connectivity was challenging because it required exploration of either lesioned tissue or postmortem tissue (Catani & Thiebaut de Schotten, 2012). These challenges have been overcome to some degree with DWI, which allows the mapping of fiber pathway connectivity *in* vivo, and has even allowed the tracking of new pathways (Brauer, Anwander, Perani, & Friederici, 2013; Dick, Bernal, & Tremblay, 2014; Dick & Tremblay, 2012; Gierhan, 2013). However, despite considerable progress, there is still much to be learned about the fiber pathways supporting speech and language development. This is particularly the case for the period of early childhood, as this age-range is typically under-represented in empirical studies of fiber pathway development. This under-representation occurs despite the fact the age range between 5- and 8-years is a time of rapid change in several complementary areas of speech and language development: phonological processing, articulation, receptive language, and expressive language. For example, between 5- and 8-years, children improve articulation and phonological skill. About 50% of 5-year-olds still show phonological error patterns (gliding, cluster reduction, stopping, and fronting), which are seen less frequently in 7–8-year-olds (Dodd, Holm, Hua, & Crosbie, 2003; Dodd, Hua, Crosbie, Holm, & Ozanne, 2010). Children also show improvement in higher-level receptive and expressive language over this age range (Chomsky, 1969; F. Dick, Wulfeck, Krupa-Kwiatkowski, & Bates, 2004; Kendeou, Van den Broek, White, & Lynch, 2009). Thus, while there is extensive development at the behavioral level, less is known about the underlying white matter supporting speech and language development in 5-to-8-year-olds.

In fact, there is no work investigating the development of an intriguing new pathway identified by DWI, the frontal aslant tract (FAT; Catani et al., 2012, 2013; Ford, McGregor, Case, Crosson, & White, 2010; Kinoshita et al., 2014; Klein et al., 2007;

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Kronfeld-Duenias, Amir, Ezrati-Vinacour, Civier, & Ben-Shachar, 2014; Oishi et al., 2008; Vassal, Boutet, Lemaire, & Nuti, 2014; Vergani et al., 2014). The pathway's putative connectivity linking the posterior inferior frontal gyrus, *pars opercularis* (IFGOp) and the pre-supplementary/supplementary motor area (pre-SMA and SMA), two regions known for their roles in speech and language function, suggests that the tract could play an important part in the development of these domains. Some brain-behavior correlations support this contention. For example, Catani et al. (2013) reported, in a sample of people with primary progressive aphasia (PPA), that microstructure of the FAT is associated with verbal fluency performance. Vassal et al. (2014), using intraoperative electrostimulation and DWI, showed that stimulation of the FAT induced speech arrest, with normalization of speech occurring when stimulation stopped. In addition to replicating the electrostimulation findings by Vassel et al., Kinoshita et al. (2014) reported that resection of the FAT was associated with transient speech initiation disorders. Finally, microstructure of the FAT is associated with fluency deficits in adults who stutter (Kronfeld-Duenias et al., 2014). The emerging evidence thus suggests that the FAT may play a role in speech and possibly in its development. However, the FAT has never been characterized in children, and its functional relevance to speech and language is still under investigation. The first aim of the present study is to characterize this pathway in young children and explore its potential relevance to speech and language function.

Another pathway that is important to understanding the development of speech and language is the arcuate fasciculus (AF; historically called the superior longitudinal fasciculus/arcuate fasciculus; SLF/AF). In contrast to the FAT, there is a substantial literature on the AF, an important fiber pathway that forms the substrate of the dorsal speech/language pathway connecting the frontal, inferior parietal, and temporal regions (Dick et al., 2014; Hickok & Poeppel, 2007) involved in auditory-motor mapping (Saur et al., 2008), processing speech (Maldonado, Moritz-Gasser, & Duffau, 2011), and syntax (Friederici, Bahlmann, Heim, Schubotz, & Anwander, 2006; Wilson et al., 2011). One issue with studying the pathway in children is the sometimes-inconsistent anatomical definition and nomenclature, and the fact that historically the arcuate component was not dissociated from other components of the SLF (Brauer et al., 2013; Fernández-Miranda et al., 2014; Glasser & Rilling, 2008; Makris et al., 2005). Despite the inconsistency in definition, the most widely-cited model in the literature on development of the pathway is that of Catani and colleagues (Catani & Thiebaut de Schotten, 2012; Catani, Jones, & ffytche, 2005; Thiebaut de Schotten et al., 2011). In this model, the focus is on the perisylvian connectivity of three subcomponents of the AF: (1) the anterior component, analogous to the third subcomponent of the SLF (SLF III; Makris et al., 2005), proposed to connect the supramarginal gyrus to the inferior frontal gyrus, (2) the long segment, proposed to connect the posterior superior and middle temporal cortex to the inferior frontal gyrus and ventral premotor cortex, and (3) the posterior segment, proposed to connect the posterior superior and middle temporal regions to the angular gyrus. Many studies have shown asymmetries in the AF in typical adults (Barrick, Lawes, Mackay, & Clark, 2007; Catani et al., 2007; Fernández-Miranda et al., 2014; Glasser & Rilling, 2008; Nucifora, 2005; Parker et al., 2005; Powell et al., 2006; Thiebaut de Schotten et al., 2011; Upadhyay, Hallock, Ducros, Kim, & Ronen, 2008; Vernooij et al., 2007), with differences in the lateralization profile of each of the three AF segments.

Similar studies have been conducted in typical children with a focus on understanding age-related differences and developing laterality of the AF (Barnea-Goraly et al., 2005; Brauer, Anwander, & Friederici, 2011; Brauer et al., 2013; Eluvathingal, Hasan, Kramer, Fletcher, & Ewing-Cobbs, 2007; Giorgio et al., 2008; Lebel & Beaulieu, 2009; Lebel & Beaulieu, 2011; Oishi, Faria, Yoshida, Chang, & Mori, 2013; Schmithorst, Wilke, Dardzinski, & Holland, 2002; Tamnes et al., 2010; Tiwari et al., 2011; Urger et al., 2014; Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012; Yeatman et al., 2011). The findings of age-related differences of the pathway are mixed. For example, Schmithorst et al. (2002) found increased anisotropy with age over the left hemisphere AF from 5- to 18-years, but this was not replicated in a different sample of 6–17-year-olds (Eluvathingal et al., 2007). To explain the lack of findings of maturation of FA, Eluvathingal et al. suggested that the AF likely undergoes "substantial maturation before the age of 6 years to support basic proficiency in speech..." (p. 2765). However, when the different segments of the AF were examined, and when different measures were used (namely radial and axial diffusivity measures expected to decline with age), Eluvathingal et al. did report significant negative correlations with age. These patterns were found in all three segments bilaterally. This suggests some potential for maturation of these pathways during early childhood, which would fit with the age-related differences in speech and language that occur at the behavioral level.

The findings for age-related differences in laterality are also mixed. In a study of 5- to 17-year-olds, Urger et al. (2014) reported no significant laterality of their defined SLF and AF tracts, a finding that is consistent with Tiwari et al. (2011). Eluvathingal et al. (2007) reported left laterality of the long segment, and right laterality of the posterior segment, but they reported no evidence for differences in lateralization associated with age. Similarly, in a large sample ranging in age from 5 to 30 years, Lebel and Beaulieu (2009) reported that the majority of participants showed left lateralization of the AF (assessed with FA and number of streamlines), which was uncorrelated with age. Thus, they suggested that "arcuate fasciculus lateralization is present in early childhood" (p. 3568). However, their sample had very little representation of children in the early childhood years (less than 5% of the sample was comprised of children 5- to 8-years of age). Consequently, it is difficult to make a strong statement, based on the available data, about the development of laterality of the AF in this younger age range.

Only a handful of these studies have related development of the AF to behavioral measures of speech and language. Measures of the tract microstructure and laterality have been related to general verbal IQ or vocabulary measures (Lebel & Beaulieu, 2009; Peters et al., 2012; Schmithorst, Wilke, Dardzinski, & Holland, 2005; Urger et al., 2014), and to speech processing in noise (Schmithorst, Holland, & Plante, 2011). For example, after controlling for age and sex, Urger et al. (2014) reported an association between left (but not right) AF microstructure and expressive (but not receptive) language. Similarly, Lebel and Beaulieu (2009) reported an association between left lateralization and phonology and vocabulary. These studies are important, and evidence an association between AF white matter microstructure and speech and language function, but the limited representation of young children in the samples does not allow for a detailed understanding of the development of these fiber pathways in early childhood.

In order to expand our current understanding of the development of these pathways in younger children, we used DWI in 19 5–8-year-olds to assess specific age-related differences in the microstructure properties of the FAT and AF white matter tracts, and relate these properties to behavioral measures of speech and language. First, we predicted that we would be able to track the FAT in young children, and we further predicted that, given the known age-related differences in speech and language function over this age range, the FAT would show age-related differences. The predictions regarding age-related differences for the AF were more exploratory for this age range—some studies show asymmetric age-related differences across hemispheres