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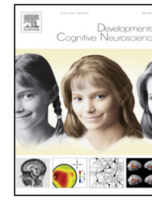

The direct segment of the arcuate fasciculus is predictive of longitudinal reading change

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ABSTRACT

Structural coherence across the arcuate fasciculus has previously been related to reading skill, but the arcuate may be divisible into distinct subtracts which support different functions. Here, we examine longitudinal data from 30 children between the ages of 8 and 14 to determine whether initial coherence in any of the arcuate's subsections is predictive of changes in reading across a longitudinal interval of approximately three years. The arcuate was divided using probabilistic tractography; mean fractional anisotropy across each subtract was extracted for each participant. Time 1 to Time 2 change in reading skill (identification, fluency score average) was significantly and uniquely predicted by only direct fronto-temporal arcuate segment coherence. Participants with lower direct segment FA demonstrated decreases in reading scores, potentially reflecting lessened improvements due to continued inefficient processing. These results were consistent in the older and younger halves of the sample. As such, we demonstrate that it is specifically the direct segment of the arcuate that may support and be predictive of reading skill both initially and longitudinally across development.

The left arcuate fasciculus is one of the most studied white matter tracts in the brain and has been demonstrated to support language skills such as semantic comprehension, phonological sensitivity, and most importantly here, reading (Friederici, 2009). From a functional-anatomical perspective, the arcuate fasciculus serves to connect the temporal lobe and the inferior frontal gyrus, with potential branches stopping in the posterior temporal lobe or inferior parietal lobule. As such, it thus provides a physical connection between regions critically involved in phonological or linguistic processing (see Gazzaniga, 2009), including reading. While connectivity across the arcuate has been related to concurrent reading abilities (see Vandermosten et al., 2012b), whole arcuate coherence has not been consistently predictive of longitudinal reading outcomes in school-aged children (e.g., Hoeft et al., 2011). Recently, it has been proposed that the arcuate may be composed of several separable subtracts that support different functions (Catani et al., 2005), but the longitudinal relationship between initial connectivity in these subsections and future reading ability has not previously been explored. We here aim to determine the relationship between early arcuate connectivity in these three arcuate subsegments, as compared to that across the whole tract, and outcome reading skill in a sample of typically developing children with a range of reading abilities to determine whether these proposed functional relationships are subtract specific and predictive across a multi-year interval.

Fractional anisotropy, or FA, indicates the degree and direction of the diffusivity of water within a voxel. Voxels along major white matter tracts should have a high degree and directionality, as water can diffuse easily in one primary direction. A high FA is taken to reflect high tract coherence, where the individual axonal fibers cohere and travel together; high coherence is thought to indicate increased functional connectivity and processing efficiency, as information can thus travel more effectively along the tract between gray matter regions (Roberts et al., 2013). As such, increased FA generally co-occurs with, or may have a causal relationship with, increased skill.

Left arcuate FA has been consistently demonstrated to be positively correlated with concurrently measured reading and reading-related skills, including word identification (Hoeft et al., 2011; Yeatman et al., 2012), reading fluency (Gold et al., 2007; Nagy et al., 2004), phonological awareness (Saygin et al., 2013; Yeatman et al., 2011), and composite measures of reading ability (Gullick and Booth, 2014). Further, significant differences in arcuate connectivity have been found between reading-skill groups: both

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adults and children with dyslexia demonstrate decreased fractional anisotropy in the left arcuate (see Vandermosten et al., 2012b for a recent review). As such, reading ability across development may be in part supported by the arcuate.

There is currently some debate within the neuroanatomical literature as to the taxonomy of the arcuate and its potential subtracts. Most prominently, Catani et al. (2005) demonstrated three individual segments: a direct, or long, segment is proposed to make the temporal–parietal–frontal arc, while an anterior section connects frontal and parietal only and a posterior section parietal and temporal only. Other groups have proposed similar subdivisions, such as the two-segment model from Glasser and Rilling (2008), with two parallel frontal to superior versus middle temporal tracts, and the four-segment model from Makris et al. (2005), which was based on non-human primate work and finds segments generally similar to those of Catani et al. (2005). Wakana et al. (2007) has also demonstrated that the superior longitudinal fasciculus, which may be synonymous with the arcuate (Friederici, 2009) or may be a parallel tract (Duffau, 2008), can similarly be reproducibly subdivided into at least an SLF and SLFt (temporal) section. As such, a distinction between frontal–temporal and frontal–parietal sections within the arcuate is consistent with current reports from multiple methodologies, with temporo-parietal segments also demonstrated in some cases.

These arcuate subtracts are proposed to support distinct functions, based on their gray matter endpoints. The anterior segment is hypothesized to support articulatory processing and the direct section reading (Catani et al., 2005). Vandermosten et al. (2012a) reconstructed these segments in individual control and dyslexic participants through a series of waypoint and exclusion planes with deterministic tractography; mean FA across only the direct segment was positively related to contemporary phonemic awareness skill. In contrast, mean FA in the posterior segment was related to speech-in-noise perception; anterior FA was not related to any of the measured skills. Yeatman et al.'s (2011) probabilistic tracking of the left arcuate effectively included only the direct segment, with anterior and posterior segments referred to as "coherently oriented non-arcuate fibers" tracked from their nodes, and also found that FA in their direct segment was related to phonological awareness skill at that timepoint, though negatively so: participants with higher FAs (and thus lower radial diffusivities) demonstrated lower phonological skills. Interestingly, Thiebaut de Schotten et al. (2014) noted that FA specifically in the posterior segment increased with the late acquisition of literacy in an adult ex-illiterate population, potentially indicating lexical (semantic) and non-lexical (phonemic) processing (see also Myers et al., 2014). This literature establishes initial relationships between particular reading skills and subtract connectivities measured at the same time point.

While these concurrent structure (arcuate)–function (reading skill) relationships have been consistently demonstrated in sizable samples of children across a wide age range, the results from longitudinal investigations of the whole arcuate have been mixed. Hoeft et al. (2011) found that while initial FA in the left superior longitudinal fasciculus (explicitly stated to include the arcuate) was related to initial word identification standard scores for control participants, it was not predictive of longitudinal changes in standard scores over 2.5 years in either dyslexics or controls. Right hemisphere superior longitudinal fasciculus coherence, however, was predictive of reading gains in children with dyslexia, potentially reflecting compensatory use of right hemisphere systems parallel to those typically found on the left side (e.g., Eden et al., 2004). However, this study examined the tract as a whole without segmenting it into subsections: if only particular segments of the arcuate support reading, its longitudinal impact may not be seen when coherence is collapsed across segments.

More recently, Yeatman et al. (2012) found that Time 2 good readers (initial ages 7–12) tend to show increases in arcuate connectivity across the three-year testing period, while poor readers showed decreases in connectivity, indicating that the arcuate's role in reading may be preserved and even strengthened with practice and experience. While an individuals' rate of arcuate FA change was predictive of reading scores (both initial and average across time points), the predictive power of initial FA on final reading score or change in ability was not tested. These developmental changes were also not related to subsections. Similarly, Myers et al. (2014) demonstrated that change in temporo-parietal coherence from kindergarten to third grade were related to outcome reading scores; post-hoc tractography demonstrated that one of the significant clusters contained both superior corona radiata and direct arcuate fasciculus fibers; anterior streamlines were also included in a subsample of their subjects. The second cluster contained posterior arcuate fibers. This work indicates that changes in the arcuate are critical for successful early reading. However, the impact of initial coherence itself on behavioral outcomes or reading improvement was not examined. As such, early arcuate connectivity may impact later reading ability, but this relationship has not yet been clearly described. To our knowledge, no studies have compared the prospective impact of individual differences in subdivision connectivities on reading outcome, which may be critical for reconciling the previous conflicting whole arcuate results.

Strong connectivity across the arcuate may thus be critical for successful reading, both initially and perhaps longitudinally, but whether this relationship is specific to a subsection or general across the arcuate as a whole remains to be seen. We thus aimed to determine whether Time 1 initial FA across the whole arcuate or in any of the direct, anterior, or posterior segments was predictive of changes in reading from Time 1 to Time 2, in comparison to the predictive ability of Time 1 behavioral measures of performance. This design allows for determination of which sections may be particularly important for successful reading development, and how neural structure may impact educational outcomes beyond what can be predicted by standardized behavioral measures, further specifying the role of these arcuate subsections and informing a causal relationship to behavioral outcomes.

1. Methods

1.1. Participants

Participants were 30 (13 females) children recruited from the Chicago metropolitan area. At Time 1, children's ages were between 8;1 and 13;8 years (*mean* = 10;7 years); Time 2 ages were between 10;1 and 16;9 years (*mean* = 13;9 years). Gap period between testing sessions was between two and four years (*mean* = 33.2 months; see Table 1 for demographic and score information). Children were all right-handed native English speakers with normal hearing and normal or corrected-to-normal vision, and no history of neurological or psychiatric illness or disorder. Informed consent was obtained from participants and their parents, and all procedures were approved by the Institutional Review Board at Northwestern University.

1.2. Standardized testing

Children participated in standardized testing sessions at both Time 1 and Time 2 to ensure that all participants were of at least average IQ and reading ability. Tests included the Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999), using two verbal (vocabulary, similarities) and two performance (block design, matrix reasoning) subtests; the Woodcock-Johnson III Tests of