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Dimensions of Attention Associated with the Microstructure of Corona Radiata White Matter

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Abstract

Mirsky proposed a model of attention that included these dimensions: *focus/execute*, *sustain*, *stabilize*, *encode*, and *shift*. The neural correlates of these dimensions were investigated within corona radiate subregions in healthy youth. Diffusion tensor imaging and neuropsychological assessments were conducted in 79 healthy, right-handed youth aged 4–17 years. Diffusion tensor imaging maps were analyzed using standardized parcellation methods. Partial Pearson correlations between neuropsychological standardized scores, representing these attention dimensions, and diffusion tensor imaging measures of corona radiate subregions were calculated after adjusting for gender and IQ. Significant correlations were found between the *focus/execute*, *sustain*, *stabilize* and *shift* dimensions and imaging metrics in hypothesized corona radiate subregions. Results suggest that greater microstructural white matter integrity of the corona radiata is partly associated

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with attention across four attention dimensions. Findings suggest that white matter microstructure of the corona radiata is a neural correlate of several, but not all, attention dimensions.

Keywords

corona radiata; attention; focus/execute; shift; sustain; stabilize; encode; diffusion tensor imaging; diffusion tensor imaging; neuropsychology; Mirsky

Introduction

The neuropsychologist Allan F. Mirsky proposed a model that provides a multicomponent view of attention by synthesizing data from typically developing children, healthy adults, adult neuropsychiatric patients with brain lesions, and anatomical data from animal lesion studies. The Mirsky model that includes the following key dimensions of attention: *focus/execute*, *sustain*, *stabilize*, *encode*, and *shift*¹. The *focus/execute* dimension, or selective attention, is attention that focuses and acts on one aspect of a stimulus. The *sustain* dimension refers to the ability to stay on-task and avoid distracting stimuli. The *encode* dimension refers to the ability to store information while acting on that information. The *shift* dimension encompasses flexibility of attention and the capacity to adjust to change. Mirsky did not originally propose the *stabilize* or variability dimension of attention in 1991. In 1999, he added this to the *sustain* dimension, renaming it *sustain* and *stabilize* attention elements². The *stabilize* dimension refers to the ability to maintain attention consistently throughout the performance of a task². This neuropsychiatric multidimensional conceptualization of attention has received empirical support from factor analysis studies³. Evidence suggests that these dimensions of attention mature with increasing age⁴. In a factor analysis of the Mirsky model in healthy children, aged 7 to 13 years, Kelly (2000) reported that response speed, impulsivity, sustaining ability (*sustain*), and shifting ability (*shift*) increase with age⁴.

Mirsky proposed that these dimensions of attention were linked to specific brain structures and functions². The *focus/execute* dimension was specifically linked to the neurobiological functions of the superior temporal gyrus, inferior parietal cortex, and corpus striatum. The *sustain* and *stabilize* dimensions were considered to be related to midbrain structures. The *encode* dimension was linked to the functions of the hippocampus and amygdala. Lastly, the *shift* dimension was associated with the functions of the prefrontal cortex.

Recently, the neurobiological basis of Mirsky's model of attention has been empirically tested using modern human imaging methods in adults, although there have been fewer studies in children. These investigations resulted in an expansion of the neurobiological basis of the Mirsky's model of dimensions of attention. Although the *sustain* dimension was initially considered to be related to midbrain structures¹, functional magnetic resonance imaging and positron emission tomography studies have identified parietal activation during tasks measuring the *sustain* dimension in adults^{5,6}. More recently, diffusion tensor imaging, a well-accepted magnetic resonance imaging method for assessing the degree of microstructural maturation of white matter tracts has been used to determine the association of dimensions of attention with specific white matter tracts^{7,8}. One widely studied diffusion

tensor imaging measure is fractional anisotropy, a scalar measure from 0–1 that reflects the tendency for water motion to occur in a preferred direction as opposed to random motion; this measure increases with age, suggesting more mature microstructural fibers⁹. Other measures are: the radial diffusivity, a measure of the minor eigenvectors of the diffusion tensor; the apparent diffusion coefficient, which measures the rate, as opposed to the directionality, of microscopic water motion; and axial diffusivity, a measure of the major eigenvector of the diffusion tensor indicating water diffusion parallel to the dominant axonal orientation; these are thought to reflect less organized microstructural fibers and decrease with age and maturity, and increase with brain lesions⁷.

Reaction time, a method used to measure the *sustain* dimension, has been associated with the microstructure of white matter regions such as the anterior corona radiata and the anterior internal capsule, while processing speed, another aspect of the *sustain* dimension, has been associated with increased fractional anisotropy values in the posterior corona radiata in children¹⁰ and adults^{10–13}. The *stabilize* dimension, or variability, has been found to significantly correlate with the microstructure of the right anterior corona radiata in adults, in that patients with traumatic brain injury who made more errors showed lower fractional anisotropy values¹⁴. Through principal component analysis, associations were identified between the *encode* dimension and bilateral occipital, bilateral superior parietal, bilateral dorsolateral prefrontal, and dorsal anterior cingulate areas in adults^{1, 15}. The *encode* dimension of attention also has been associated with left superior corona radiata microstructure in children¹⁰.

The corona radiata is a key white matter structure of the default mode network, a complex network important to attention regulation^{16–18}. The corona radiata is located cephalad to the internal capsule and radiating white matter tracts for the corpus callosum to the cortex. These reflect the right and left anterior, posterior, and superior sections of the cerebral cortex and include afferent and efferent fibers¹⁹. Factors in Mirsky's Model of Attention show that these dimensions of attention mature with increasing age⁴. Similarly, corona radiata diffusion tensor imaging measures of fractional anisotropy increase with age, while apparent diffusion coefficient decrease; the direction of both these measures suggest greater white matter microstructural maturity with age²⁰. These studies suggest that the microstructure of this white matter region as measured by corona radiata fractional anisotropy increases during "sensitive periods," with an 11% increase observed between childhood (ages 8 to 12 years) and young adulthood (age 21 to 27)²¹.

Therefore, the primary goal of this study was to examine the relationship of the dimensions of Mirsky's Model of Attention, *focus/execute*, *sustain*, *stabilize*, *encode*, and *shift*, and the microstructure of the corona radiata in healthy typically developing children and adolescents. To our knowledge, no study has simultaneously considered all five dimensions of attention as hypothesized by Mirsky^{1, 2} with respect to their relationships with the white matter microstructure of the bilateral anterior, superior, and posterior segments of the corona radiata as measured by all diffusion tensor imaging measures in healthy children and adolescents. Given Mirsky's Model of Attention, we hypothesized that: the *focus/execute* dimension would be significantly associated with the white matter microstructure of the left and right superior corona radiata which reflects axons from the superior temporal gyrus,

inferior parietal cortex, and corpus striatum; the *sustain* dimension would be significantly associated with the white matter microstructure of left and right anterior, superior and posterior corona radiata, reflecting bottom up projections from the midbrain and top down projections from the parietal cortex; the *stabilize* dimension would be significantly associated with the white matter integrity of microstructure of the right and left anterior corona radiata, reflecting bottom up projections from the midbrain and top down projections from the prefrontal cortex; the *encode* dimension would be significantly associated with the white matter microstructure of the entire corona radiata, reflecting bilateral occipital, bilateral superior parietal, bilateral dorsolateral prefrontal, and dorsal anterior cingulate areas; and that the *shift* dimension would be significantly associated with the white matter microstructure of left and right anterior corona radiata, reflecting top down projections from the prefrontal cortex. To the best of our knowledge, our study is the first to empirically test Mirsky's model in healthy children as reflected in diffusion tensor imaging measures as most studies only focused on fractional anisotropy values. Consequently, we also planned an exploration of the relationship between all corona radiata diffusion tensor imaging measures and all five dimensions in Mirsky's Model of Attention.

Methods

Participants

Seventy-nine right handed children and adolescents, ages 4 to 17 years, participated (Table-1). Participants were recruited from the community, with overall socioeconomic status falling within the middle stratum and ranging from classes I to V as measured by the Hollingshead Four factor index where higher numbers reflect higher socioeconomic status.

All participants received a comprehensive neuropsychological, psychiatric, and developmental history to rule out the presence of any medical, neurodevelopmental, psychiatric disorders, or severe trauma and child maltreatment history. To examine psychiatric diagnoses and trauma history, the Kiddie Schedule for Affective Disorders and Schizophrenia-Present and Lifetime Version (KSADS-PL)²² was administered to all caregivers and youth. Because multiple sources of information are needed to gather accurate maltreatment history and related symptoms, we requested and reviewed archival records (e.g., pediatric records, school attendance records, birth records, forensics records) as sources of mental health, birth history, trauma history, and pediatric health²³. If information from these data sources produced evidence meeting any of the exclusionary criteria below, the participant was excluded. KSADS-PL interviewer training and modifications were previously described²⁴.

Exclusion criteria included: IQ<70; a disability that made a comprehensive interview of the child difficult; a significant medical illness and/or daily prescription medication use; lifetime history of any DSM IV-TR Axis I psychiatric disorders, substance use disorders, or learning disability; documented brain injury or neurologic disorder; left-hand dominance based on measures of psychomotor skills, autism spectrum disorder; birth weight under 5 pounds, or severe prenatal compromise or neonatal intensive care unit stay; significant prenatal exposure to alcohol or illicit drugs, documented history of involvement with child protective services for abuse and/or neglect, interview data that made report to child protective services

professionally necessary, or severe trauma history; and any contraindications to safe magnetic resonance imaging. The university institutional review board approved the study. All legal guardians gave informed consent and youth assented prior to participation in accordance with the guidelines of the Helsinki Declaration.

Measures

All subjects had a comprehensive neuropsychological evaluation, which included examination of attention-related tasks. Mirsky's model of attention characterizes attention as an organized, componential system. The measures used in the neuropsychological evaluation were configured to fit Mirsky's model and included: Connors' Continuous Performance Test-II ²⁵, Wisconsin Card Sorting Test ²⁶, and Woodcock-Johnson Achievement Test III ²⁷. Connor's Continuous Performance Test Errors of Omission measured the *focus/execute dimension*. The Hit Response Time and Variability scores from the Connor's Continuous Performance Test-II represented the *sustain* and *stabilize* dimensions of attention, respectively. The Calculation score from the Woodcock-Johnson III Achievement Test represented the *encode* dimension. The Perseverative Responses score from the Wisconsin Card Sorting Task characterized the *shift dimension*. Participants also received the age-appropriate version of the Wechsler scale ^{28, 29} to generate a two-factor intelligence quotient score. Standardized scores are reported in Table-1.

Magnetic Resonance Imaging Acquisition

Magnetic resonance imaging was performed with a Siemens Trio 3.0 Tesla magnetic resonance imaging system (Trio, Siemens Medical Systems) running version VA 24 software. Diffusion tensor imaging was performed using a single-shot echo-planar imaging pulse sequence. Imaging parameters were echo time=90 ms, repetition time=7200 ms, bandwidth of 1346 Hz/pixel, acquisition matrix of 128×64, field of view of 220 mm, and contiguous 3-mm slice thickness. All axial slices were acquired parallel to the anterior commissure-posterior commissure line. Images were acquired with diffusion weighting in each of 6 different directions, all with a b-value (diffusion weighting factor) of 1000. An image with no diffusion weighting (b-value of 0) was acquired as reference. The set of seven diffusion weighted images was acquired a total of 4 times for retrospective averaging to improve image quality, and then averaged together after the magnitude-image reconstruction.

MR Image processing and analysis

The images were processed using the MRistudio software suite comprised of the following analysis software tools: 1) DtiStudio (www.mristudio.org, Johns Hopkins University); 2) DiffeoMap (www.mristudio.org, Johns Hopkins University); and 3) ROEditor (www.mristudio.org, Johns Hopkins University). A very detailed description of the work flow and methods used were based on the work of Faria et al. ³⁰. Briefly, the raw diffusion-weighted images were first co-registered to the b0 image using the 12-mode affine transformation of Automated Image Registration function ³¹ in DtiStudio to correct for eddy current distortion ³² and subject motion. The maps for fractional anisotropy, apparent diffusion coefficient, axial diffusivity, and radial diffusivity were derived and then skull-

stripped utilizing ROIeditor in which a skull-stripped b0 mask was applied to the fractional anisotropy, apparent diffusion coefficient, axial diffusivity and radial diffusivity maps.

We then normalized the image parameters of our resultant skull stripped subject image to the image parameters (e.g., image width, height, field of view, slice thickness, etc.) of the Johns Hopkins University “Eve” atlas. Our resampled, skull stripped subject image then served as the template to linearly transform the Johns Hopkins University –diffusion tensor imaging-Montreal Neurological Institute “Eve” single-subject atlas in an effort to maintain the integrity of each individual subject’s brain.

The linearly transformed “Eve” atlas was further transformed non-linearly using Large Deformation Diffeomorphic Metric Mapping, utilizing the subject’s brain as the template. Due to the reciprocal mathematical relationship of diffeomorphic metric mapping, the resultant linear transformation matrix and the resultant large deformation diffeomorphic metric mapping transformation matrix (non-linear transformation matrix) were then applied to the Johns Hopkins University White Matter Parcellation Map II utilizing nearest neighbor interpolation. The relevant diffusion tensor imaging metrics were then derived by applying this transformed Johns Hopkins University White Matter Parcellation Map II onto the fractional anisotropy, apparent diffusion coefficient, axial diffusivity and radial diffusivity maps of each subject. The modification of our study from that of Faria et al.,³⁰ was that, in our study, the atlas (“Eve” atlas) data was transformed to each individual subject’s data, whereas in the Faria et al. study³⁰, both b0 and fractional anisotropy images were used to register the subject data to the “Eve” atlas. The applied White Matter Parcellation Map II segments each individual subject’s brain into 130 regions, and from these, we only examined the following hypothesized bilateral regions for our analysis: anterior corona radiata; superior corona radiata; and posterior corona radiata (Figure-1).

Data Analysis

Demographic analysis showed a wide spread of IQ scores in the sample, ranging from 74 to 150. This range of age and IQ scores, along with reported gender differences in white matter development, indicated the need to adjust for age, IQ, and gender in the correlational design³³. To control for age, all of the neuropsychological measures were standardized for age and converted to z-scores. Scores from the Connor’s Continuous Performance Test-II were reversed scored so that higher scores represented better performance for all five dimensions of attention.

To address the research questions, partial Pearson correlations controlling for IQ and gender were conducted between five age-adjusted neuropsychological dimensions of attention measures, representing aspects of Mirsky’s model of attention, and the left and right segments of the anterior, superior and posterior corona radiata.

To ensure the validity of the brain measures, simple pairwise partial Pearson correlations were conducted between age and each segment of the corona radiata. As expected from the literature²⁰, fractional anisotropy significantly increased with age (range of $r=.26$ to $.36$; $p<.05$), except the right anterior corona radiata ($r=.19$, $p=.09$); while radial diffusivity (range of $r=-.35$ to $-.66$; $p<.01$), apparent diffusion coefficient (range of $r=-.35$ to $-.67$; $p<.01$), and

axial diffusivity (range of $r = -.26$ to $-.58$; $p = .02$) significantly decreased with age in each segment of the corona radiata in all analyses. These results support previous findings that corona radiata white matter microstructure is significantly related to age^{20, 21} and further support the validity of our diffusion tensor imaging analyses.

Our group and clinical comparisons were limited, hypotheses-driven and planned. Therefore, multiple comparison adjustments were not necessary³⁴ and $p < .05$ was used for these comparisons. However, since we also planned an exploration of the relationship between all corona radiata diffusion tensor imaging measures and all five dimensions in Mirsky's Model of Attention that were without specific hypotheses related to Mirsky's model, only comparisons considered significant were correlations where $p = .01$ in order to account for multiple comparisons (e.g., five neuropsychological dimensions of attention measures) and to lessen the number of correlations due to chance. We made this latter adjustment because all diffusion tensor imaging measures in a particular structure are mathematically related to one another.

Results

Correlations between the focus/execute dimensions of attention and the corona radiata

We hypothesized the following: that the *focus/execute* dimension would be significantly associated with the white matter microstructure of the left and right superior corona radiate. Our results showed that this hypothesis was supported. The *focus/execute* dimension of attention was significantly and positively associated with bilateral superior corona radiata fractional anisotropy, and significantly and negatively associated with the right corona radiate apparent diffusion coefficient and radial diffusivity values and left superior corona radiate apparent diffusion coefficient and axial diffusivity values (Table-1).

We also found that the *focus/execute* dimension was significantly and positively associated with right and left posterior corona radiate fractional anisotropy, and significantly and negatively associated bilateral posterior corona radiate apparent diffusion coefficient and radial diffusivity values. All correlations were of moderate magnitude. The *focus/execute* dimension did not significantly correlate with the anterior corona radiata measures.

Correlations between the sustain dimensions of attention and the corona radiata

Given Mirsky's Model of Attention, we hypothesized that the *sustain* dimension would be significantly associated with the white matter microstructure of left and right anterior, superior and posterior corona radiate. Our results showed that this hypothesis was supported in part. The *sustain* dimension of attention was significantly and positively associated with left superior corona radiata fractional anisotropy values. Further, we found that the *sustain* dimension was significantly and negatively associated with the right and left anterior, right superior, and right and left posterior corona radiate apparent diffusion coefficient measures. We also found that the *sustain* dimension was significantly and negatively associated with only the right and left anterior axial diffusivity measures. Further, we found that the *sustain* dimension was significantly and positively associated with left posterior superior corona radiate, and significantly and negatively associated with the right superior corona radiate

apparent diffusion coefficient measures and right posterior corona radiate radial diffusivity measures.

Correlations between the stabilize dimensions of attention and the corona radiata

Given Mirsky's Model of Attention, we hypothesized that the *stabilize* dimension would be significantly associated with the white matter microstructure of the right and left anterior corona radiate. Our results showed that his hypothesis was supported, particularly for the left anterior corona radiate. We found that the *stabilize* dimension significantly and negatively associated with the right and left anterior corona radiate apparent diffusion coefficient and radial diffusivity measures. Further, we found that the *stabilize* dimension was significantly and negatively associated with left corona radiate axial diffusivity measures. Small to moderate correlations were demonstrated. The *stabilize* dimension of attention was not significantly associated with bilateral anterior corona radiata fractional anisotropy values.

We also found that the *stabilize* dimension was significantly and positively associated with left posterior corona radiate fractional anisotropy values; and significantly and negatively associated right superior corona radiate apparent diffusion coefficient and bilateral superior corona radiate radial diffusivity values.

Correlations between the encode dimensions of attention and the corona radiata

Given Mirsky's Model of Attention, we hypothesized that the *encode* dimension would be significantly associated with the white matter microstructure of the entire corona radiate. Our results showed that his hypothesis was not supported.

Correlations between the shift dimensions of attention and the corona radiata

Given Mirsky's Model of Attention, we hypothesized that the *shift* dimension would be significantly associated with the white matter microstructure of left and right anterior corona radiate. Our results showed that his hypothesis was supported for the right but not the left anterior corona radiate. The shift dimension was significantly and negatively associated with the right anterior corona apparent diffusion coefficient and axial diffusivity values.

However, the *shift* dimension of attention was significantly and negatively associated with the bilateral superior and posterior corona apparent diffusion coefficients. Further, the *shift* dimension of attention was significantly and negatively associated with the right superior and bilateral posterior corona radial and axial diffusivity values. All correlations were moderate in strength.

Discussion

This study investigated the relationship between the diffusion tensor imaging measures of white matter microstructure in specific regions of the corona radiata with Mirsky's Model of dimensions of attention in healthy children and adolescents. Significant correlations were found between the *focus/execute*, *sustain*, *stabilize* and *shift* dimensions of attention and diffusion tensor imaging metrics in hypothesized subregions of corona radiata. However, no association was found with the *encode* dimension. These findings suggest that greater

microstructural white matter integrity of the corona radiata is, in part, associated with better attention functioning across four of the dimensions of Mirsky's model of attention. Most correlations were of moderate magnitude. Our findings suggest that white matter microstructure of the corona radiata is a neural correlate of several, but not all, dimensions of attention and expands the neurobiological basis of Mirsky's model. The originality of this work stems from both the interpretation of the diffusion tensor imaging findings in the context of Mirsky's framework for understanding attention along with the use of an automatic method for segmenting the corona radiata in diffusion tensor imaging analysis.

The corona radiata is composed of ascending and descending fibers that relay information to and from the cerebral cortex, and its connections map throughout the cortex, overlapping with known attention pathways. Our findings build on previous work in cognitive control and attention³³ where positive associations with better cognitive performance were positively associated with the mean fractional anisotropy of the entire corona radiata in typically developing children³³. The results reported here are in concordance with Mirsky's proposed neural correlates of *focus/execute*.

The sustained attention dimension was connected to midbrain structures according to Mirsky. However, we found significant associations between sustain and anterior, superior, and posterior corona radiata. Our diffusion tensor imaging results in children and adolescents agree with functional magnetic resonance imaging and positron emission tomography studies that have identified parietal activation during tasks measuring the *sustain* dimension in adults^{5, 6}.

Mirsky did not speculate in detail about the neural correlates of *stabilize*, so our findings add to current understanding of brain-behavior relationships as the *stabilize* dimension of attention showed significant association with left anterior, bilateral superior, and left posterior corona radiata.

Additionally, in accordance with Mirsky's original neurological underpinnings for the *encode* dimension of attention whose neurobiological basis was subcortical and related to amygdala and hippocampal functions, we did not uncover any significant relationships between *encode* and diffusion tensor imaging measures of the corona radiata. We suspect that this lack of an association may be related to our measure of encoding. Perhaps the use of an arithmetic calculation task was too complex to parse out the relationship between encoding and the corona radiata, and a different measure may have served to uncover such as relationship.

Mirsky and colleagues found the *shift* dimension to be correlated mainly with the prefrontal cortex, which fits with current understanding of executive function¹. Our findings support Mirsky's model by showing a significant relationship between the *shift* dimension and the anterior corona radiata. Our findings also add to the neurobiological basis of the *shift* dimension by showing significant relationships bilaterally between the *shift* dimension and the superior and posterior corona radiata diffusion tensor imaging measures. This finding corroborates data where authors found activation of the posterior parietal cortex of primates during set-shifting³⁵.

The primary focus of this paper was examining brain-behavior correlates of the corona radiatae and a specific set of attention functions as proposed in the Mirsky's model. In addition to our hypotheses, it is important to note that attention and related executive functions are not only multidimensional in their behavioral manifestations, but also in their underlying neural networks. The corona radiatae and its associations may reflect only one possible set of neural connections for the different dimensions of attention. For example, Menon and Uddin (2010)³⁶ described the relationship between the cognitive functions of saliency, set-shifting, and attentional control and the underlying anterior region of the insula—a limbic brain structure that has been implicated in both cognitive and emotional regulation. Similarly, Petersen and Posner (2012)³⁷ have evolved their model of attention showing involvement of the anterior cingulate, anterior insula and prefrontal cortices in a variety of attentional controls in their model. Relatedly, studies of individuals with ADHD have implicated structural anomalies in both cortical and subcortical structures as well as the cerebellar regions encompassing both white and gray matter. Further, Makris et al. (2007)³⁸ examined cortical thickness and surface area in individuals with ADHD and found cortical thinning in the right hemisphere cortical network that mediates attention and executive controls including the inferior parietal lobe, dorsolateral prefrontal cortex, and the anterior cingulate cortex. Taken together, when combined with our current findings implicating the corona radiata in different dimensions of attention, these studies point to the complexity of the underlying neural networks involved in attention in typically developing children and adolescents.

Our study has a number of design strengths including having strict inclusion criteria, excluding participants with lifetime mental disorders, severe traumas, or learning disabilities, and ensuring no prenatal confounds by examining prenatal and birth records. Four diffusion tensor imaging measures acquisitions were performed to optimize image quality. All subjects were scanned on the same dedicated research scanner using the same imaging protocol throughout the duration of the study. This consistency strengthens the accuracy of comparison in our data.

Our investigation has a number of limitations. Although we believe that our correlation coefficients are sufficiently powered, our limited sample size could have prevented us from discovering a greater number of associations between the dimensions of attention and diffusion tensor imaging measures. Second, we chose neuropsychological assessments that are commonly implemented and known to be strong indicators of attention, yet a possibility exists that we could have obtained different relationships with our diffusion tensor imaging measures had we selected an alternate set of cognitive tests. Third, we adjusted for age, gender and IQ in our partial correlations, but it would be useful to understand whether these same associations could be replicated with a longitudinal design and with clinical samples of children and adolescents. Fourth, current research has noted that increasingly accurate results of scalar diffusion parameters are obtained with a greater number of diffusion-encoding gradient directions³⁹. Lastly, additional study limitations are the lack of diffusional kurtosis and diffusion spectrum imaging data collection which extends conventional diffusion tensor imaging methods by improving the resolution of intra-voxel fiber crossings and thus the fiber tractography of white matter^{40, 41}. However, given the young age of our population, we did not believe that the extra scanning time to obtain the

diffusional kurtosis and diffusion spectrum imaging data collection were feasible for this age group. However, these methods have evolved and should be considered in future studies of cognitive function and white matter maturation. Nevertheless, accurate results are still obtained with less than 12 diffusion-encoding directions, and the current findings are not obviated by the lesser number of directions used to collect our diffusion tensor imaging variables^{42, 43}.

The findings reported here, showing significant correlations between Mirsky's model of dimensions of attention with regional diffusion tensor imaging corona radiata values in a healthy sample of children and adolescents, add to our understanding of healthy brain development. Studies examining neurocognitive and underlying neurological pathways in healthy children are necessary for enhancing our understanding of relationships between white matter microstructural integrity and function. To our knowledge, our study is the first to examine and report significant associations of Mirsky's model of dimensions of attention with diffusion tensor imaging corona radiata measures in a healthy, well-characterized sample of children and adolescents. This study provides important preliminary data that increase our understanding of targeted brain-behavior relationships in developmentally healthy children and adolescents. Furthermore, it paves the way towards future study of these relationships in pediatric populations with diseases and disorders, such as attention deficit hyperactivity disorder, learning disabilities, and psychiatric disorders.

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Anterior Corona Radiata

Superior Corona Radiata

Posterior Corona Radiata

Figure 1. Corona Radiata Parcellation. An automated parcellation technique was used to distinguish the anterior, superior, and posterior corona radiata segments as shown in the sagittal, axial, and coronal planes.

Table 1

Sample Characteristics with Neuropsychological Standardized Scores

Sample	
N	79
Age in years *	11.66 ± 3.59
Range	4.17 – 17.92
Gender (Females/Males)	41/38
Race (White/ African American or biracial)	34/45
Intelligence quotient *	111.85±16.88
Range	74 – 150
Socioeconomic status ^a	46.52 ± 12.63
Range	14 – 66
Connors' Continuous Performance Test-II T-Scores	
Errors of Omission *	48.7 ± 8.5
Range	41.5 – 84.7
Hit Response Time *	45.3 ± 10.1
Range	26.0 – 70.7
Variability *	49.4 ± 10.7
Range	31.3 – 76.2
Wisconsin Card Sorting Test	
Perseverative Reponses Standard Score *	113 ± 16.4
Range	69 – 145
Woodcock-Johnson Achievement Test III	
Calculation Standard Score *	113.4 ± 11.5
Range	82 – 135

* Given as mean ± standard deviation

^a Includes parent's education and occupations by the Hollingshead Four factor index, where higher numbers represented higher socioeconomic status.

Table 2

Pairwise Partial Pearson Correlation Coefficients and p-values of Corona Radiata Diffusion Tensor Imaging Measures with Mirsky's Model of Dimensions of Attention Neuropsychological Measures (Standardized for Age) and Adjusting for the Effects of Gender and IQ.*

	Focus/ Execute	Sustain	Stabilize	Encode	Shift
Right Anterior Corona Radiata					
Fractional Anisotropy	.08 (.52)	-.06 (.59)	.18 (.13)	-.15 (.20)	.02 (.90)
Apparent Diffusion Coefficient	-.28 (.02)	-.27 (.02)	-.24 (.04)	.03 (.80)	-.30 (.02)
Axial Diffusivity	-.22 (.05)	-.32 (<.01)	-.17 (.14)	-.08 (.49)	-.27 (.04)
Radial Diffusivity	-.25 (.03)	-.19 (.10)	-.28 (.016)	.08 (.48)	-.24 (.06)
Left Anterior Corona Radiata					
Fractional Anisotropy	-.05 (.69)	-.03 (.81)	.10 (.38)	-.13 (.27)	-.01 (.92)
Apparent Diffusion Coefficient	-.19 (.11)	-.24 (.04)	-.30 (.01)	.05 (.67)	-.19 (.14)
Axial Diffusivity	-.26 (.02)	-.30 (<.01)	-.32 (<.01)	-.04 (.71)	-.24 (.07)
Radial Diffusivity	-.12 (.32)	-.18 (.13)	-.28 (.02)	.08 (.50)	-.13 (.31)
Right Superior Corona Radiata					
Fractional Anisotropy	.29 (.01)	.19 (.10)	.23 (.05)	.04 (.76)	.17 (.19)
Apparent Diffusion Coefficient	-.27 (.01)	-.26 (.03)	-.28 (.01)	-.00 (.98)	-.41 (.001)
Axial Diffusivity	-.16 (.19)	-.18 (.13)	-.23 (.05)	-.02 (.85)	-.35 (<.01)
Radial Diffusivity	-.32 (<.01)	-.25 (.03)	-.31 (<.01)	-.00 (.99)	-.37 (<.01)
Left Superior Corona Radiata					
Fractional Anisotropy	.34 (<.01)	.23 (.05)	.26 (.03)	.09 (.44)	.09 (.47)
Apparent Diffusion Coefficient	-.26 (.03)	-.18 (.12)	-.24 (.04)	-.03 (.78)	-.34 (<.01)
Axial Diffusivity	-.11 (.30)	-.08 (.52)	-.17 (.16)	-.02 (.85)	-.30 (.02)
Radial Diffusivity	-.32 (<.01)	-.22 (.06)	-.30 (<.01)	-.06 (.64)	-.30 (.02)
Right Posterior Corona Radiata					
Fractional Anisotropy	.31 (<.01)	.22 (.06)	.23 (.05)	.05 (.65)	.29 (.02)
Apparent Diffusion Coefficient	-.33 (<.01)	-.31 (<.01)	-.25 (.03)	-.15 (.19)	-.50 (<.001)
Axial Diffusivity	-.23 (.05)	-.22 (.06)	-.21 (.08)	-.17 (.14)	-.38 (<.01)
Radial Diffusivity	-.35 (<.01)	-.30 (<.01)	-.28 (.02)	-.13 (.28)	-.49 (<.001)

	Focus/ Execute	Sustain	Stabilize	Encode	Shift
Left Posterior Corona Radiata					
Fractional Anisotropy	.36 (.001)	.17 (.15)	.36 (<.01)	.13 (.27)	.18 (.17)
Apparent Diffusion Coefficient	-.316 (<.01)	-.25 (.03)	-.19 (.10)	-.15 (.22)	-.45 (<.001)
Axial Diffusivity	-.19 (.10)	-.18 (.12)	-.09 (.42)	-.13 (.27)	-.41 (.001)
Radial Diffusivity	-.36 (.001)	-.25 (.03)	-.27 (.02)	-.15 (.22)	-.41 (.001)

*Planned comparison where p=.05 are in grey.