This is the accepted version of the manuscript published by Elsevier in *Journal of the American Academy of Child and Adolescent Psychiatry*, yet to be allocated a doi.

**White Matter Microstructure in Youths with Conduct Disorder: Effects of Sex and Variation in Callous Traits**

**Running Head: White Matter in Conduct Disorder**

**Keywords:** Conduct disorder, callous-unemotional traits, diffusion tensor imaging (DTI), sex differences, FemNAT-CD.

**Abstract = 248**

**Article Body = 4933 (inc. headings, sub-headings etc. but not reference to Table/Figure inclusion) Limit is 4500**

**References = 63**

**Facebook (approximately 50-100 words):**

Study using a large sample of youths from the @FemNATCD project reveals differences in the brain’s white matter pathways in youths with conduct disorder. Sex and callous traits (e.g. reduced empathy and guilt) were identified as important factors to consider when examining white matter in conduct disorder. These differences in the brain’s structural connections might explain the results of previous functional neuroimaging studies in conduct disorder showing abnormal activity in different regions of the brain that are structurally connected to each other.

**Twitter (no more than 280 characters):**

Using neuroimaging data from the @FemNATCD project, this article in #JAACAP finds that youths with severe antisocial behavior show structural differences in the white matter pathways of the brain which were partly driven by callous traits @jackcrogers @SCAN\_lab @IMH\_UoB @TheCHBH @UoB\_SoP <link to article>

**Lay Summary:**

Different parts of the brain are connected structurally by white matter fiber tracts. Using data from the FemNAT-CD study, we investigated differences in these white matter tracts in youths with severe behavior problems, diagnosed as conduct disorder. We found significant differences between conduct disordered and typically-developing youths in white matter across a number of tracts, including the corpus callosum which connects the two hemispheres of the brain. We also found that sex and callous traits (e.g., reduced empathy and guilt) explained some of the white matter differences seen in youths with conduct disorder. These findings add to the evidence base showing that conduct disorder is associated with changes in the wiring map of the brain.

**ABSTRACT**

**Objective:** Studies using diffusion tensor imaging (DTI) to investigate white matter (WM) microstructure in youths with conduct disorder (CD) have reported disparate findings.Weinvestigated WM alterations in a large sample of youths with CD, and examined the influence of sex and callous-unemotional (CU) traits.

**Methods:** DTI-data were acquired from 124 youths with CD (59 female) and 174 typically-developing (TD) youths (103 female) aged 9-18 years. Tract-based spatial statistics tested for effects of diagnosis and sex-by-diagnosis interactions. Associations with CD symptoms, CU traits, a task measuring impulsivity, and the impact of comorbidity and age- and puberty-related effects were examined.

**Results:** Youths with CD exhibited higher axial-diffusivity in the corpus callosum and lower radial-diffusivity and mean-diffusivity in the anterior thalamic radiation relative to TD youths. Females and males with CD exhibited opposite changes within the internal capsule, fornix, posterior thalamic radiation and uncinate fasciculus. Within the CD group, CD symptoms and callous traits exerted opposing influences on corpus callosum axial-diffusivity, with callous traits identified as the unique clinical feature predicting higher axial-diffusivity and lower radial-diffusivity within the corpus callosum and anterior thalamic radiation, respectively. In an exploratory analysis, corpus callosum axial-diffusivity partially mediated the association between callous traits and impulsive responses to emotional faces. Results were not influenced by symptoms of comorbid disorders and no age- or puberty-related interactions were observed.

**Conclusion:** WM alterations within the corpus callosum represent a reliable neuroimaging marker of CD. Sex and callous traits are important factors to consider when examining WM in CD.

**INTRODUCTION**

Conduct disorder (CD) is characterized by aggressive, antisocial and oppositional/defiant behaviors during childhood and adolescence1 and impairments across social, cognitive, and affective domains.2 Meta-analytic evidence from functional (fMRI) and structural (sMRI) MRI studies has shown abnormal neural responses3 and volume reductions4 across a number of cortical and subcortical regions critical for emotion processing and regulation, decision-making, executive functions and empathy. However, diffusion tensor imaging (DTI) findings on white matter (WM) microstructure in youths with antisocial behavior have been inconsistent in both the nature and loci of reported effects.5 Methodological factors, as well as demographic and clinical features of the samples, may have contributed to the inconsistent findings and lack of replication.5

The current study used DTI to investigate WM microstructure in the largest sample of female and male youths with CD recruited to-date and compared them to age- and puberty-matched typically-developing (TD) females and males. Tract-based spatial statistics (TBSS)6 were used to examine WM microstructure at the *whole-brain* level and within *specific regions-of-interest (ROIs)*. We adopted this approach because we had *a priori* hypotheses regarding the loci of expected group differences, and wanted to compare our results to existing DTI literature on CD in which both approaches have been used. However, we also sought to identify previously undetected effects owing to our large and mixed sex sample. To measure diffusion within WM tracts, fractional anisotropy (FA) was computed, reflecting differences in microstructural properties such as axon density and degree of myelination.7 FA is a function of axial diffusivity (AD) and radial diffusivity (RD) values, such that FA increases when AD increases and/or RD decreases, and vice-versa. When observing changes/differences in FA, the changes in AD and/or RD can help with the biological interpretation. For example, greater axon density will manifest as increased FA and decreased RD. Axonal breakdown will lead to decreased FA and decreased AD, whereas demyelination will show up as decreased FA and increased RD.7 Mean diffusivity (MD) is the rate of diffusion averaged over all orientations and is thought to provide a marker of neuronal damage in cell bodies and axonal fibers.8 We used these four indices to characterize differences in microstructure across WM tracts between CD and TD groups. All analyses (whole-brain and region-of-interest) were also conducted on mode of anisotropy, but no significant effects were observed (see Table S13).

The primary aim of the study was to test for effects of CD diagnosis on these DTI indices. Recent studies9-13 have reported increased FA or AD within the uncinate fasciculus and/or corpus callosum in youths with CD compared to TD youths. Lower RD within the uncinate fasciculus12 and the corpus callosum13 has been reported in males with CD. Finally, decreased MD within the right uncinate fasciculus (defined as a ROI) was also reported for females with CD11 compared to TD controls. As such, we predicted higher FA or AD and reduced RD or MD (believed to reflect increased microstructural integrity7) within the uncinate fasciculus and corpus callosum in youths with CD compared to TD youths. However, we note that several studies have also reported the opposite pattern of results (i.e., reduced FA and AD, and increased RD and MD) across a number of other WM tracts.14,15 Therefore, we also predicted differences in FA, AD, RD and MD within other association, commissural, projection and thalamic tracts but did not make predictions regarding the direction of these effects.

Our second aim was to test for sex-by-diagnosis interactions. Given known sex differences in the CD phenotype,16 its etiology,17 as well as rates of WM maturation in TD youths,18 WM diffusivity may differ between females and males with CD. To date, however, most studies on CD have focused only on males9,10,13,19 or females alone.11 Three studies12,14,20 have included mixed-sex samples but were underpowered to test for sex-by-diagnosis interactions, thereby contributing to the inconsistencies in the literature. These data highlight the need to investigate similarities across the sexes as well as testing for potential sex-specific effects.5 In this context, we made no *a priori* hypotheses regarding differences between males and females with CD in terms of the location or direction of changes across the DTI indices.

Our third aim was to examine the impact of callous-unemotional (CU) traits (i.e., reduced empathy and guilt, combined with shallow emotions and the callous use of others; see the “limited prosocial emotions” specifier for CD in DSM-51) on WM alterations associated with CD. Indeed, several studies14,20 have failed to account for heterogeneity within CD in relation to CU traits, which might have contributed to inconsistent findings across studies. Two recent studies showed that CU traits influenced the pattern of WM differences in youths with CD.21,22 Furthermore, fMRI and sMRI studies have revealed that the unique variance associated with CD symptoms and CU traits shows opposing relationships with neural activity and gray matter volume in cortical23 and subcortical structures.24,25 Interestingly, two recent fMRI studies of empathy in youths reported that the callous subcomponent of CU traits was the strongest predictor of group differences in neural response26 and connectivity.27 Hence, we hypothesized that CD symptoms and CU traits (or the callous subcomponent) might show opposing associations with WM microstructure in youths with CD.

In addition to our three central aims, we conducted two follow-up analyses and one exploratory analysis. First, disorders that frequently co-occur with CD (e.g., attention-deficit/hyperactivity disorder (ADHD), mood and anxiety disorders and substance abuse) are also associated with WM alterations in the corpus callosum and the uncinate fasciculus.28-31 We therefore systematically assessed the impact of symptoms of comorbid disorders in our sample, predicting that group differences in WM microstructure might be partly explained by these symptoms. Second, given the large age range of our sample (9-18 years) and suggestions that relationships between CD and WM may differ by age5,9,20 or pubertal stage,32 we tested for age-by-diagnosis and puberty-by-diagnosis interactions. Finally, given that self-reported impulsivity has been shown to positively correlate with FA within the corpus callosum in CD youths,13 we conducted an exploratory analysis aiming to extend this finding by relating WM microstructure to performance on an objective, laboratory-based measure of impulsivity: the emotional Go/No-Go task.33 We hypothesized that in youths with CD, corpus callosum FA or AD would be positively correlated with impulsive responses on this task.

**METHOD**

## Participants and Measures

A total of 124 (59 females) youths with CD and 174 (103 females) TD youths aged 9–18 years were included as part of the Neurobiology and Treatment of Adolescent Female Conduct Disorder study (FemNAT-CD), a European multi-site study investigating sex differences in CD (https://www.femnat-cd.eu/). Thirty participants (16 with CD) were included in a previous DTI study comparing CD and TD females.11 However, excluding those participants (N=30) did not alter the main effects (data available upon request). Participants and their parents/main-caregivers were interviewed separately using the Kiddie-Schedule for Affective Disorders and Schizophrenia-Present and Lifetime version (K-SADS-PL34). Interviews were conducted by trained staff at each site to assess for CD and other common comorbid disorders using DSM-IV-TR criteria.35 Further details regarding participant demographics, socioeconomic status, inclusion/exclusion criteria and inter-rater reliability of diagnoses are provided in Supplement 1, available online.

CU traits were assessed using the parent-report Inventory of Callous-Unemotional traits (ICU),36 a standardized measure including callous (α=.74), uncaring (α=.79), and unemotional subscales (α=.85). An estimate of full-scale IQ was obtained using the two-subtest (vocabulary and matrix reasoning) version of the Wechsler Abbreviated Scale of Intelligence37 or the same subtests from the Wechsler Intelligence Scale for Children.38 Participants were classified as either pre/early or mid/late/post pubertal using the Pubertal Development Scale.39 Across all sites, written informed consent/assent was obtained from all participants and their parents according to site-specific ethical requirements (see Supplement 2 and 3, available online, for information on imputation procedures for missing data and ethical approvals).

**Emotional Go/No-Go Task**

Impulsivity was operationalized using the number of commission errors (false-alarm rates expressed as a %) on an emotional Go/No-Go task33 (see Supplement 4 and Figure S1 available online for further details regarding task design, response coding, convergent validity check and testing procedures).

# DTI Data Acquisition and Pre-processing

Diffusion-weighted images were acquired across four sites (Tables S1-S2, available online) and subsequently pre-processed using the FMRIB Software Library (FSL) diffusion toolkit40 (see Supplement 5 and 6 for details regarding site qualification procedures, acquisition parameters, image processing, movement and distortion correction).

**Statistical Analyses**

We used ANOVAs (post-hoc pairwise comparisons with Bonferroni correction, p<.05) and Chi-Square tests to compare diagnostic groups (CD vs. TD) on demographic and clinical variables (Table 1 and Supplement 1 available online).

*[Table 1 here]*

Within FSL,40 separate general linear models with a 2 (diagnosis: CD *vs.* TD) x 2 (sex: male *vs.* female) factorial design were fitted to the FA, AD, RD and MD diffusion indices to test for main effects of diagnosis and sex-by-diagnosis interactions. Age and IQ were included as covariates of no interest (see Supplement 7 for results of analyses without including IQ as a covariate of no interest and for an IQ-matched subsample). Additional factorial analyses were conducted entering mean-centered age as continuous covariates into the GLM. This enabled investigation of age-related differences between CD and TD youths (age-by-diagnosis interactions) as well as potential interactions with sex (age-by-diagnosis-by-sex interactions). Finally, in separate analyses, puberty scores were included as continuous covariates enabling investigation of potential puberty-related differences between youths with CD and TD youths and potential interactions with sex. For the models testing for age and puberty effects, IQ was included as a covariate of no interest (see Supplement 8, available online, for further details). Details of how between-site variability was accounted for within all statistical models are provided in Supplement 9, available online.

At a whole-brain level, areas showing significant differences were identified using threshold-free cluster enhancement (TFCE; p<0.05 Family-Wise Error (FWE) corrected for multiple comparisons; 5000 permutations). We note that for our weakest effect (the observed sex-by-diagnosis interaction in the left internal capsule) we re-ran the analysis with 10000 permutations to ensure that the p-value still fell within the 95% confidence intervals around alpha = 0.05 of [0.0459, 0.0544].

Two WM atlases41,42 were used to label significant results. We also tested for differences in FA, AD, RD and MD within specific fiber tracts previously implicated in CD.5 These masks were created using the JHU-ICBM-DTI-81 WM atlas41 and included association, commissural and projection pathways identified by5 (see Table S3, available online, for full list of tracts). The same threshold was used for the voxel-wise permutation-based ROI analyses (see also Table S13, available online, for False-Discovery-Rate corrected and uncorrected ROI results). Contrast-wise FA, AD, RD and MD values at a whole-brain and ROI level were extracted using the *fslmeants* tool in FSL, enabling cluster-based statistical analysis and multiple regression analyses. Cohen’s *d* effect sizes based on group-means and standard-deviations are reported for the main effects and sex-by-diagnosis interactions.

Consistent with previous work,25 bivariate correlations (see Table S4, available online) and regression analyses were conducted for the CD group only within regions showing main effects of diagnosis or sex-by-diagnosis interactions. Multiple regression analyses were conducted in two steps to investigate the association between significant cluster-wise differences and dimensional measures. First, CD symptoms (derived from the K-SADS-PL34) and CU traits (ICU total score) or ICU subscales (Callousness, Uncaring, Unemotional) were entered. Second, symptom counts of comorbid ADHD, oppositional defiant disorder, generalized anxiety disorder and major depressive disorder, alcohol use/abuse and substance use/abuse, as well as a measure of handedness, were added to assess their influence. Zero-order correlation coefficients were calculated to estimate associations between WM differences observed between groups (CD and TD) and impulsivity, as measured using the emotional Go/No-Go task.33

**RESULTS**

**Whole-Brain Results**

Youths with CD exhibited significantly higher AD (p=.02) within the body of the corpus callosum (posterior aspect) in the right hemisphere compared to TD youths (Figure 1A). No areas of reduced AD and no sex-by-diagnosis interactions were identified. Youths with CD also showed lower RD in bilateral anterior thalamic radiation (left, p<.01; right, p=.01) compared to TD youths (Figure 2A) and lower MD in the left anterior thalamic radiation (p=.01) (Figure 2B). No areas showing higher RD or MD were identified, but a sex-by-diagnosis interaction in RD was observed within the left internal capsule (posterior limb; p=.04), bordering the corticospinal tract (Figure 3A). Underlying this interaction, CD females showed higher RD than TD females, whereas CD males had lower RD than TD males (Figure 3A). No significant main effects or sex-by-diagnosis interactions were observed for FA. Finally, no significant two-way or three-way interactions were observed between age, diagnosis and sex or puberty, diagnosis and sex for any DTI index (all p-values >.19; see Supplement 8 and Figure S2 available online).

*[Figures 1-3 here]*

**Regression Analyses: Effects of CD symptoms, CU traits, and Comorbid Symptoms**

In the corpus callosum, unique variance associated with CD symptoms, after controlling for ICU total score, negatively predicted AD (β=-.21, p=.02), whereas unique variance associated with CU traits did not significantly predict AD in this region after controlling for CD symptoms (β=.15, p=.12; Table S5, available online). After controlling for CD symptoms, and the uncaring and unemotional subscales of the ICU, unique variance associated with callous traits positively predicted AD (β=.33, p<.01; Figure 1B and Table S6, available online). CD symptoms still negatively predicted AD when controlling for ICU subscale scores (β= -.20, p=.03) (Figure 1B and Table S6, available online). Controlling for symptoms of comorbid disorders did not alter these results and the unique variance of those symptoms did not significantly predict AD (all p>.13; online Tables S5, S6).

In the anterior thalamic radiation, neither CD symptoms nor total ICU scores predicted RD (all p>.07; Table S7, available online). After controlling for CD symptoms, and the uncaring and unemotional subscales of the ICU, unique variance associated with callous traits negatively predicted RD (left: β=-.27, p=.03; right: β=-.30, p=.01; Figure 2A and online Table S8). Adding comorbid disorder symptoms did not alter these results and the unique variance of those symptoms did not significantly predict RD (Tables S7-S8, available online). In the left anterior thalamic radiation, neither CD symptoms nor ICU total or ICU subscale scores significantly predicted MD (all p>.06; Table S9-S10, available online). Controlling for symptoms of comorbid disorders did not alter these results and the unique variance of those symptoms did not significantly predict RD (all p>.12; Tables S9-S10, available online).

To explore the sex-by-diagnosis interaction observed within the posterior limb of the left internal capsule, regression analyses were conducted on females and males with CD separately. A significant negative relationship was found between unique variance associated with CD symptoms and RD (β=-.21, p=.04) for males with CD, but not females (β=.22, p=.1) when controlling for ICU total score (Table S11, available online). After controlling for ICU subscale scores, unique variance associated with CD symptoms and RD was also observed for males (β=-.22, p=.04) but not females (β=.06, p=.66) with CD (Figure 3B and Table S12, available online). Controlling for symptoms of comorbid disorders did not alter these results and the unique variance of those symptoms did not significantly predict RD in males (all p>.15; Tables S11-S12, available online).

**ROI Results**

Sex-by-diagnosis interactions were observed in AD within the left fornix and the left posterior thalamic radiation (see Figure 4A and 4B, respectively). Females with CD showed lower AD in the fornix compared to TD females, whereas males with CD showed a non-significant increase in AD compared to TD males, whilst the opposite pattern (TD females<CD females; TD males>CD males) was observed within the left posterior thalamic radiation. A significant sex-by-diagnosis interaction was also observed for left uncinate fasciculus MD (CD females>TD females; CD males<TD males; see Figure 4C). No further main effects or interactions were observed in the other ROIs for any DTI-index (Table S3, available online). No associations were detected between CD symptoms, CU traits or the ICU subscale scores, or any of the comorbid disorder symptoms and WM microstructure within the left fornix, left posterior thalamic radiation or left uncinate fasciculus.

*[Figure 4 here]*

**Associations between WM Microstructure and Impulsivity**

In a subset of the CD group for whom data were available (n=107), commission errors to emotional ‘no-go’ stimuli on the ‘Go/No-Go’ task were positively correlated with AD in the corpus callosum (*r=*0.24, p=.01) (Figure S3, available online). Furthermore, callous traits were positively correlated with commission errors to emotional ‘no-go’ stimuli (*r=*0.18, p=.05; online Figure S3). Given this pattern of results and evidence linking the corpus callosum to impulsivity in CD,13 an exploratory post-hoc mediation analysis was conducted to assess whether, in CD youths, corpus callosum AD values mediated the relationship between callous traits and impulsive responses (commission errors) to emotional faces. Callous traits, corpus callosum AD values and commission errors to emotional ‘no-go’ stimuli were modeled as the independent, mediating and dependent variables, respectively. Given that CD symptoms negatively predicted AD in the corpus callosum when controlling for ICU subscale scores, CD symptoms was included as a covariate (see43 for a similar approach). Bootstrap-mediation analysis (with 5000 bootstrap resamples of the data with replacement) was implemented with the SPSS PROCESS macro.44 Rather than providing formal p-values, statistical significance with alpha set at .05 is indicated by the 95% confidence intervals not crossing zero. Corpus callosum AD partially mediated the relationship between callous traits and impulsive responses to emotional faces, but this effect was small (indirect effect=0.14, 95% confidence intervals=[0.0019, 0.3734]; Figure S3, available online).

**DISCUSSION**

This study extends our understanding of WM microstructure in youths with CD in several important ways. First, consistent with our predictions, we demonstrated that compared to TD youths, female and male youths with CD show higher AD within the body of the corpus callosum and lower RD bilaterally (plus lower MD on the left) in the anterior thalamic radiation. Our whole-brain and ROI analyses also revealed that female and male youths with CD exhibit opposite changes in WM microstructure within the left uncinate fasciculus and multiple projection pathways in the left hemisphere. Second, partially supporting our predictions, we demonstrated that callous traits and CD symptoms exerted opposite effects on AD within the corpus callosum, with callous traits identified as the unique clinical feature predicting higher AD and lower RD within the corpus callosum and anterior thalamic radiation, respectively. Furthermore, higher AD values in the corpus callosum were associated with higher levels of impulsive responses to emotional faces and partially mediated the association between callous traits and impulsive responses, but this effect was small. Finally, no age-by-diagnosis or puberty-by-diagnosis interactions were observed and, contrary to predictions, no significant group differences or sex-by-diagnosis in FA were observed and none of the findings were influenced by symptoms of comorbid disorders.

This study is the first to show that female and male adolescents with CD exhibit common alterations in WM microstructure within the body of the corpus callosum and the anterior thalamic radiation. For the corpus callosum, consistent with the results of previous studies on CD with male only,13,21 female only11 or mixed-sex samples,12,14 we observed higher AD values (lower diffusivity) within this tract across sexes. The corpus callosum, which connects homologous regions across the hemispheres, is the largest WM tract and commissural pathway in the brain, and is thus central to interhemispheric communication.45 Disrupted interhemispheric communication has been associated with anger and aggression;46 behaviors that are characteristic of CD individuals. Importantly, the corpus callosum is structurally and functionally heterogeneous across its three sub-divisions: the genu, body, and splenium.47 The observed group difference was located centrally in the posterior part of the body of the corpus callosum, which connects precentral regions (premotor area, supplementary motor area), as well as the insular, mid-posterior cingulate and somatosensory cortices.47 As such, that sub-division connects regions involved in response inhibition and socioemotional processing,46,48 consistent with the observed association between corpus callosum AD and commission errors to emotional faces in the CD group. Interestingly, our exploratory analysis revealed that higher AD within the corpus callosum partially mediated the relationship between callous traits and the number of commission errors to emotional ‘no-go’ stimuli, implicating corpus callosum alterations in the association between callous traits and impulsive responses to emotional faces in youths with CD. We note, however, that previous research using this task has identified commission errors to emotional no-go stimuli as an index of emotion (dys)regulation.33

Youths with CD also exhibited lower RD (lower diffusivity) bilaterally within the anterior thalamic radiation, a result consistent with just one study using a mixed-sex sample where greater CD severity was associated with increased FA (lower diffusivity) within this tract.14 The anterior thalamic radiation forms part of the limbic system and connects the mediodorsal and anterior thalamic nuclei with the dorsolateral, ventrolateral, orbitofrontal and anterior cingulate cortices.49 These prefrontal regions are implicated in working memory, affective decision-making, and empathy; notably, youths with CD also show impairments in these domains.2 Given our results and the prominent role of the thalamus as a ‘relay station’ and ‘gatekeeper’ of sensory information between subcortical and cortical regions,50 future studies should clarify to what extent impairments observed in CD and structural/functional alterations within those prefrontal regions might reflect ‘downward consequences’ of WM differences within the anterior thalamic radiation.

The observed sex-by-diagnosis interactions were restricted to association (uncinate fasciculus) and projection pathways (posterior limb of the internal capsule, the fornix, and the posterior thalamic radiation) in the left hemisphere. The MD effect in the left uncinate fasciculus is consistent with those observed in previous studies that reported increased FA in males with CD9,10,13 and one study on a mixed-sex sample.12 Taken together, these results reinforce the view that the orbitofrontal cortex–amygdala circuitry might be central to the pathophysiology of CD and to some of its associated emotional and decision-making impairments, as suggested by a neurocognitive model of CD.2 Most previous studies of CD have not observed group differences in the projection tracts we identified (although see 11,14,19). The internal capsule contains both ascending (from thalamus to cortex) and descending fibers (from fronto-parietal cortex to basal ganglia and corticospinal tract) and is considered a ‘neuroanatomical backbone’ supporting perceptual, motor and higher-order cognitive functions.45 The fornix forms part of the limbic system and connects the medial temporal lobe and hippocampus to the mammillary bodies and hypothalamus, thereby playing a central role in memory formation and retrieval.45 Finally, the posterior thalamic radiation, which connects the posterior parts of the thalamus with the occipital and the parietal cortices, is a critical component of the visual system. Our results, along with those of two previous studies,12,20 provide novel evidence that the relationship between CD and WM microstructure partly differs by sex, but given the novelty of these findings, future studies should seek to replicate them and investigate their origins and functional significance.

Building on, and extending, previous behavioral and neuroimaging studies,2 we demonstrated that amongst youths with CD, the unique variance associated with CD symptoms and callous traits exhibited opposing associations with corpus callosum WM microstructure, with callous traits identified as the unique clinical feature predicting the group differences in AD observed within the corpus callosum and in RD in the bilateral anterior thalamic radiation. From a theoretical stance, these results: (i) identify novel WM correlates of CD, supporting the view that youths with CD constitute a heterogeneous group with different neurocognitive profiles,25,26, and, (ii) could help explain some of the inconsistent results reported in previous DTI studies.5 Finally, our finding that callous traits were the strongest predictor of the group differences is consistent with two fMRI studies examining neural responses to others’ pain in youths with conduct problems. The first showed that callous traits predicted lower anterior insula and anterior cingulate cortex responses,26 while the second reported that callous traits predicted reduced functional connectivity of the amygdala and insula with the anterior cingulate cortex.27 These results, together with recent psychometric, experimental, behavioral, genetic, and meta-analytic evidence demonstrating that the ICU subscales are each associated with distinct phenotypic and etiological characteristics as well as external correlates51-53, highlight the importance of considering the distinct dimensions underlying the CU traits construct as operationalized by the ICU.36 This line of research may inform future research and clinical work. Future studies should also examine how different clinical presentations of CD (e.g., aggressive versus non-aggressive) might relate to WM differences.

**Neurodevelopmental considerations**

Despite the fact that CD is considered a neurodevelopmental disorder,54 and the hypothesis that the relationship between CD and WM microstructure may differ with age,5,9,20 no age- or puberty-related interactions were observed. This tentatively suggests that the magnitude of differences between groups that we report here reflects similar developmental trajectories across the age range (9-18 years) for both CD and TD youths. Thus, it is possible that any neurodevelopmental changes might have already occurred by age 9. In any case, this developmental trend is different from the deviant and age-related trajectories reported for autism spectrum disorders,55 another neurodevelopmental disorder. However, cross-sectional or correlational designs preclude drawing any valid inferences regarding (neuro)developmental processes,56 highlighting the pressing need for prospective longitudinal studies of CD. Second, our results and those of previous studies suggest that CD might be characterized by a unique pattern of lower diffusivity (higher AD, lower RD and MD as reported here) compared to other neurodevelopmental disorders such as ADHD (lower FA with TBSS28) and autism spectrum disorders (lower FA, higher MD57) where meta-analyses have identified higher WM diffusivity.28,58 DTI studies in youths with depression,29 generalized anxiety disorder,30 and substance misuse31 have also consistently reported higher diffusivity (lower FA) in those clinical groups across a range of WM tracts that includes the uncinate fasciculus and corpus callosum. The fact that these results are in the opposite direction to those reported here may explain why the unique pattern of findings in CD youths were not influenced by symptoms of comorbid disorders. Finally, the adult condition of antisocial personality disorder, for which a diagnosis of CD by age 15 is required,1 has also been associated with WM differences in the same tracts that we identified. However, in contrast to our findings, there is a consistent pattern of higher diffusivity (e.g. lower AD59) in in adults with antisocial personality disorder,5,59 and those with psychopathy.5 Interestingly, a recent study in adults with antisocial personality disorder found a negative correlation between AD in the corpus callosum and self-reported impulsivity.60 Taken together, these data highlight the need for prospective longitudinal studies to clarify the association between WM microstructure and the developmental course of severe antisocial behavior and associated personality traits.

Despite the strengths of our study, which include the use of a much larger sample than has been included in previous DTI studies of CD, groups matched on pubertal status, and a systematic examination of the influence of of age, puberty, IQ, and clinical variables on the findings, some limitations should be noted. As with all previous DTI studies of CD, the cross-sectional design prevents us from inferring whether WM differences are a cause or a consequence of the disorder.56 Relatedly, until replicated, the results of our exploratory mediation analysis should be interpreted as preliminary given that the observed effect was small and mediation analyses are more suited to longitudinal data.61 We also note that, because faces are the targets in the Go/No-Go task used here,33 this paradigm might conflate emotional processing (known to be impaired in CD2) with impulsivity. However, because corpus callosum AD values did not correlate with any performance indices (accuracy or reaction time) on the Emotion Hexagon task62 in which participants have to identify emotional facial expressions (see Supplement 4), we believe that our interpretation of the association between AD values and commission errors is consistent with an impulsivity account, albeit when target stimuli are emotional faces. The ROI analysis approach of using atlas-derived probability maps to extract tract means from the voxel-wise skeleton, whilst common (e.g.11), is not optimal due to the use of an atlas-inferred rather than individually-calculated trajectory to define the tracts. Furthermore, the results of our ROI analysis should be interpreted cautiously, as the correction for multiple comparisons was applied to each DTI-index separately, rather than across all four indices simultaneously. Indeed, when we tested for group differences/interactions within all ROIs (n=16) across all four DTI-indices (i.e. 16\*4 = 64 tests), the reported ROI results did not survive this highly conservative multiple comparison procedure. However, when the findings were corrected for multiple comparisons within each DTI-index (i.e. for FA, AD, RD and MD only; 16 tests) then all reported ROI results were significant. Finally, diffusivity measures can be influenced by factors such as partial volume, fiber crossing effects, fiber alignment, myelination density of the tract, tract coherence, or a combination of any/all of these factors, which are unrelated to ‘WM integrity’.63 In this context, the interpretability of any observed group differences is challenging. Thus, we have been careful to describe our results as differences in specific DTI metrics and the nature of diffusivity without specific reference to WM ‘integrity’.63

In summary, female and male youths with CD exhibit common increases in AD in the corpus callosum and common reductions in RD and MD in the anterior thalamic radiation, relative to TD youths. However, sex-specific effects of CD on WM microstructure were observed within the left uncinate fasciculus and projection pathways in the left hemisphere. Importantly, while the results were not influenced by symptoms of comorbid disorders, unique variance associated with CD symptoms and callous traits exhibited opposing influences on corpus callosum AD, with callous traits identified as the unique clinical feature predicting higher AD and lower RD within the corpus callosum and anterior thalamic radiation, respectively. Finally, AD in the corpus callosum partially mediated the association between callous traits and impulsive responses to emotional faces in youths with CD. These data suggest that there are sex differences in the neurobiological basis of CD, and provide further evidence that callous traits may delineate a distinct subtype of CD.

**References**

1. American Psychiatric Association. *Diagnostic and statistical manual of mental disorders.* 5th ed. Washington, DC: Author; 2013.

2. Blair R, Veroude K, Buitelaar JK. Neuro-cognitive system dysfunction and symptom sets: A review of fMRI studies in youth with conduct problems*.* *Neuroscience & Biobehavioral Reviews*. 2016; 91(10).

3. Alegria A, Radua J, Rubia K. Meta-Analysis of fMRI Studies of Disruptive Behavior Disorders. *Am J Psychiatry.* 2016;173(11):1119-1130.

4. Rogers JC, De Brito SA. Cortical and subcortical gray matter volume in youths with conduct problems: A meta-analysis. *JAMA Psychiatry.* 2016;73(1):64-72.

5. Waller R, Dotterer HL, Murray L, Maxwell AM, Hyde LW. White-matter tract abnormalities and antisocial behavior: A systematic review of diffusion tensor imaging studies across development. *NeuroImage: Clinical.* 2017.

6. Smith SM, Johansen-Berg H, Jenkinson M, et al. Acquisition and voxelwise analysis of multi-subject diffusion data with tract-based spatial statistics. *Nat Protoc.* 2007;2(3):499.

7. Alexander AL, Lee JE, Lazar M, Field AS. Diffusion Tensor Imaging of the Brain. *Neurotherapeutics.* 2007;4(3):316-329.

8. Elman JA, Panizzon MS, Hagler DJ, et al. Genetic and environmental influences on cortical mean diffusivity. *NeuroImage.* 2017;146:90-99.

9. Passamonti L, Fairchild G, Fornito A, et al. Abnormal Anatomical Connectivity between the Amygdala and Orbitofrontal Cortex in Conduct Disorder. *PLoS ONE.* 2012;7(11).

10. Sarkar S, Craig MC, Catani M, et al. Frontotemporal white-matter microstructural abnormalities in adolescents with conduct disorder: A diffusion tensor imaging study. *Psychological Medicine.* 2013;43(2):401-411.

11. Menks WM, Furger R, Lenz C, Fehlbaum LV, Stadler C, Raschle NM. Microstructural White Matter Alterations in the Corpus Callosum of Girls With Conduct Disorder. *J Am Acad Child Adolesc Psychiatry.* 2017;56(3):258-265. e251.

12. Zhang J, Gao J, Shi H, et al. Sex differences of uncinate fasciculus structural connectivity in individuals with conduct disorder. *BioMed Research International.* 2014;2014.

13. Zhang J, Zhu X, Wang X, et al. Increased structural connectivity in corpus callosum in adolescent males with conduct disorder. *J Am Acad Child Adolesc Psychiatry.* 2014;53(4):466-475.e461.

14. Haney-Caron E, Caprihan A, Stevens MC. DTI-measured white matter abnormalities in adolescents with Conduct Disorder. *Journal of Psychiatric Research.* 2014;48(1):111-120.

15. Wang Y, Horst KK, Kronenberger WG, et al. White matter abnormalities associated with disruptive behavior disorder in adolescents with and without attention-deficit/hyperactivity disorder. *Psychiatry Research: Neuroimaging.* 2012;202(3):245-251.

16. Tiet QQ, Wasserman GA, Loeber R, McReynolds LS, Miller LS. Developmental and Sex Differences in Types of Conduct Problems. *Journal of Child and Family Studies.* 2001;10(2):181-197.

17. Meier MH, Slutske WS, Heath AC, Martin NG. Sex differences in the genetic and environmental influences on childhood conduct disorder and adult antisocial behavior. *J Abnorm Psychol.* 2011;120(2):377.

18. Giedd JN, Raznahan A, Mills KL, Lenroot RK. magnetic resonance imaging of male/female differences in human adolescent brain anatomy. *Biol Sex Differ.* 2012;3(1):19.

19. Sarkar S, Dell’Acqua F, Froudist Walsh S, et al. A Whole-Brain Investigation of White Matter Microstructure in Adolescents with Conduct Disorder. *PLoS One.* 2016;11(6):e0155475.

20. Decety J, Yoder KJ, Lahey BB. Sex differences in abnormal white matter development associated with conduct disorder in children. *Psychiatry Research: Neuroimaging.* 2015;233(2):269-277.

21. Puzzo I, Seunarine K, Sully K, et al. Altered White-Matter Microstructure in Conduct Disorder Is Specifically Associated with Elevated Callous-Unemotional Traits. *J Abnorm Child Psychol.* 2018, 46(7), 1451-466.

22. Sethi A, Sarkar S, Dell’Acqua F, et al. Anatomy of the dorsal default-mode network in conduct disorder: Association with callous-unemotional traits. *Dev Cogn Neurosci.* 2018;30:87-92.

23. Cohn M, Popma A, Van Den Brink W, et al. Fear conditioning, persistence of disruptive behavior and psychopathic traits: an fMRI study. *Translational psychiatry.* 2013;3(10):e319.

24. Cohn MD, Viding E, McCrory E, et al. Regional grey matter volume and concentration in at-risk adolescents: Untangling associations with callous-unemotional traits and conduct disorder symptoms. *Psychiatry Research: Neuroimaging.* 2016;254:180-187.

25. Sebastian CL, McCrory EJ, Cecil CA, et al. Neural responses to affective and cognitive theory of mind in children with conduct problems and varying levels of callous-unemotional traits. *Arch Gen Psychiatry.* 2012;69(8):814-822.

26. Lockwood PL, Sebastian CL, McCrory EJ, et al. Association of callous traits with reduced neural response to others' pain in children with conduct problems. *Current Biology.* 2013;23(10):901-905.

27. Yoder KJ, Lahey BB, Decety J. Callous traits in children with and without conduct problems predict reduced connectivity when viewing harm to others. *Scientific Reports.* 2016;6:20216.

28. Aoki Y, Cortese S, Castellanos FX. Diffusion tensor imaging studies of attention-deficit/hyperactivity disorder: meta-analyses and reflections on head motion. *J Child Psychol Psychiatry.* 2017.

29. Cullen KR, Klimes-Dougan B, Muetzel R, et al. Altered White Matter Microstructure in Adolescents with Major Depression: A Preliminary Study. *J Am Acad Child Adolesc Psychiatry.* 2010;49(2):173-183.e171.

30. Liao M, Yang F, Zhang Y, He Z, Su L, Li L. White matter abnormalities in adolescents with generalized anxiety disorder: a diffusion tensor imaging study. *BMC Psychiatry.* 2014;14:41-41.

31. Jacobus J, Thayer RE, Trim RS, Bava S, Frank LR, Tapert SF. White Matter Integrity, Substance Use, and Risk Taking in Adolescence. *Psychol Addict Behav.* 2013;27(2):431-442.

32. Asato M, Terwilliger R, Woo J, Luna B. White matter development in adolescence: a DTI study. *Cereb Cortex.* 2010;20(9):2122-2131.

33. Hare TA, Tottenham N, Davidson MC, Glover GH, Casey BJ. Contributions of amygdala and striatal activity in emotion regulation. *Biol Psychiatry.* 2005;57(6):624-632.

34. Kaufman J, Birmaher B, Brent D, et al. Schedule for affective disorders and schizophrenia for school-age children-present and lifetime version (K-SADS-PL): Initial reliability and validity data. *J Am Acad Child Adolesc Psychiatry.* 1997;36(7):980-988.

35. American Psychiatric Association. *Diagnostic and statistical manual of mental disorders. Fourth Edition, Text Revision (DSM-IV-TR).* Vol Fourth Edition, Text Revision (DSM-IV-TR). Washington D.C.: American Psychiatric Association; 2000.

36. Essau CA, Sasagawa S, Frick PJ. Callous-unemotional traits in a community sample of adolescents. *Assessment.* 2006;13(4):454-469.

37. Wechsler D. WASI manual. *San Antonio: Psychological Corporation.* 1999.

38. Wechsler D. Wechsler intelligence test for children (WISC-IV). *San Antonio, TX: Psychological Corporation.* 2003.

39. Petersen AC, Crockett L, Richards M, Boxer A. A self-report measure of pubertal status: Reliability, validity, and initial norms. *J Youth Adolesc.* 1988;17(2):117-133.

40. Jenkinson M, Beckmann CF, Behrens TEJ, Woolrich MW, Smith SM. FSL. *Neuroimage.* 2012;62(2):782-790.

41. Mori S, Oishi K, Jiang H, et al. Stereotaxic white matter atlas based on diffusion tensor imaging in an ICBM template. *Neuroimage.* 2008;40(2):570-582.

42. Eickhoff SB, Stephan KE, Mohlberg H, et al. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. *Neuroimage.* 2005;25(4):1325-1335.

43. Lozier LM, Cardinale EM, Van Meter JW, Marsh AA. Mediation of the relationship between callous-unemotional traits and proactive aggression by amygdala response to fear among children with conduct problems. *JAMA Psychiatry.* 2014;71(6):627-636.

44. F Hayes A. *Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach.* 2013.

45. Catani M, Thiebaut de Schotten M. A diffusion tensor imaging tractography atlas for virtual in vivo dissections. *Cortex.* 2008;44(8):1105-1132.

46. Schutter DJLG, Harmon-Jones E. The corpus callosum: A commissural road to anger and aggression. *Neurosci Biobehav Rev.* 2013;37(10):2481-2488.

47. van der Knaap LJ, van der Ham IJ. How does the corpus callosum mediate interhemispheric transfer? A review. *Behav Brain Res.* 2011;223(1):211-221.

48. Aron AR. From Reactive to Proactive and Selective Control: Developing a Richer Model for Stopping Inappropriate Responses. *Biol Psychiatry.* 2011;69(12):e55-e68.

49. Jang SH, Yeo SS. Thalamocortical Connections between the Mediodorsal Nucleus of the Thalamus and Prefrontal Cortex in the Human Brain: A Diffusion Tensor Tractographic Study. *Yonsei Med J.* 2014;55(3):709-714.

50. Moustafa A, McMullan R, Rostron B, DH. H, Haladjian H. The thalamus as a relay station and gatekeeper: relevance to brain disorders. In. *Reviews in the Neurosciences.* Vol 282017:203.

51. Henry J, Pingault JB, Boivin M, Rijsdijk F, Viding E. Genetic and environmental aetiology of the dimensions of Callous-Unemotional traits. *Psychol Med.* 2016;46(2):405-414.

52. Cardinale EM, Marsh AA. The Reliability and Validity of the Inventory of Callous Unemotional Traits: A Meta-Analytic Review. *Assessment.* 2017;0(0): 1073191117747392.

53. Kimonis ER, Branch J, Hagman B, Graham N, Miller C. The psychometric properties of the Inventory of Callous–Unemotional Traits in an undergraduate sample. *Psychol Assess.* 2013;25(1):84-93.

54. Blair RJJ. The neurobiology of psychopathic traits in youths. *Nat Rev Neurosci.* 2013;14(11):786.

55. Travers BG, Tromp DPM, Adluru N, et al. Atypical development of white matter microstructure of the corpus callosum in males with autism: a longitudinal investigation. *Mol Autism.* 2015;6(1):15.

56. Kraemer HC, Yesavage JA, Taylor JL, Kupfer D. How Can We Learn About Developmental Processes From Cross-Sectional Studies, or Can We? *Am J Psychiatry.* 2000;157(2):163-171.

57. Travers B, Adluru N, Ennis C, et al. Diffusion Tensor Imaging in Autism Spectrum Disorder: A Review*.* *Autism research : official journal of the International Society for Autism Research*. 2012. 5. 289-313.

58. Aoki Y, Yoncheva YN, Chen B, et al. Association of white matter structure with autism spectrum disorder and attention-deficit/hyperactivity disorder. *JAMA Psychiatry*. 2017. 74(11):1120–1128.

59. Lindner P, Savic I, Sitnikov R, et al. Conduct disorder in females is associated with reduced corpus callosum structural integrity independent of comorbid disorders and exposure to maltreatment. *Translational psychiatry.* 2016;6(1):e714.

60. Jiang W, Shi F, Liu H, et al. Reduced White Matter Integrity in Antisocial Personality Disorder: A Diffusion Tensor Imaging Study. *Sci Rep.* 2017;7:43002.

61. Maxwell SE, Cole DA. Bias in cross-sectional analyses of longitudinal mediation. *Psychol Methods.* 2007;12(1):23-44.

62. Calder AJ. Facial Emotion Recognition after Bilateral Amygdala Damage: Differentially Severe Impairment of Fear. *Cogn Neuropsychol.* 1996;13(5):699-745.

63. Jones DK, Knösche TR, Turner R. White matter integrity, fiber count, and other fallacies: the do's and don'ts of diffusion MRI. *Neuroimage.* 2013;73:239-254.

**TABLE 1** Demographic and Clinical Characteristics of Youths with Conduct Disorder (CD) and Typically-Developing (TD) Participants.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | | | | | | | | | | Statistical analysis | | | | | | | |
| Characteristic/  Variable | 1. Female  CD  (n=59) | | 2.Female  TD  (n=103) | | 3. Male  CD  (n=65) | | | 4.Male  TD  (n=71) | | | Group (CD/TD)  effects | | | Sex  (M/F)  effects | | | Group X Sex interactions | |
|  | Mean | SD | Mean | SD | | Mean | SD | Mean | SD | F | | p | F | | p | F | | p |
| Age (years) | 15.1 | 1.9 | 14.1 | 2.6 | | 14.7 | 2.2 | 14.5 | 2.4 | 3.5 | | 0.07 | <1 | | 0.94 | 1.4 | | 0.24 |
| Full-scale IQ | 97.6 | 13.1 | 102.5ᵃ | 11.0 | | 93.4ᵇ | 11.8 | 102.5ᵃ | 10.6 | 26.4 | | 0.001 | 2.3 | | 0.13 | 2.3 | | 0.13 |
| SES | -0.4ᵃ | 0.8 | 0.09 | 0.9 | | -0.17 | 0.6 | 0.24ᵇ | 0.7 | 13.5 | | 0.001 | 2.37 | | 0.13 | 0.1 | | 0.7 |
| Lifetime CD symptoms | 5.5ᵃ | 2.5 | 0.2ᵇ | 0.4 | | 6.2ᵃ | 2.5 | 0.3ᵇ | 0.6 | 814.5 | | 0.001 | 4.3 | | 0.04 | 2.2 | | 0.14 |
| Lifetime ODD symptoms | 6.1ᵃ | 2.7 | 0.2ᵇ | 0.6 | | 5.8ᵃ | 2.8 | 0.1ᵇ | 0.4 | 742.7 | | 0.001 | <1 | | 0.6 | <1 | | 0.7 |
| Lifetime ADHD symptoms | 6.1ᵇ | 6.3 | 0.1ͨ | 0.3 | | 9.4ᵃ | 6.4 | 0.1ͨ | 0.2 | 241.9 | | 0.001 | 12.1 | | 0.001 | 12.0 | | 0.001 |
| Lifetime GAD symptoms | 1.3ᵃ | 1.7 | 0.1ͨ | 0.4 | | 0.8ᵇ | 1.4 | 0.04c | 0.2 | 63.1 | | 0.001 | 7.3 | | 0.007 | 4.4 | | 0.04 |
| Lifetime MDD symptoms | 8.8ᵃ | 7.9 | 0.4ͨ | 1.9 | | 5.0ᵇ | 6.4 | 0.2c | 1.0 | 135.6 | | 0.001 | 12.4 | | 0.001 | 10.6 | | 0.001 |
| Total ICU | 32.5ᵇ | 12.6 | 16.4ͨ | 8.0 | | 37.5ᵃ | 12.7 | 19.3ͨ | 7.8 | 202.3 | | 0.001 | 10.8 | | 0.01 | <1 | | 0.4 |
| *Callous subscale of ICU* | 11.3ᵇ | 6.2 | 4.2ͨ | 3.4 | | 13.7ᵃ | 6.5 | 4.7ͨ | 2.5 | 202.6 | | 0.001 | 6.9 | | 0.01 | 2.8 | | 0.1 |
| *Uncaring subscale of ICU* | 14.1ᵃ | 5.0 | 7.9ᵇ | 4.3 | | 15.8ᵃ | 5.0 | 8.9ᵇ | 4.3 | 140.9 | | 0.001 | 6.1 | | 0.01 | <1 | | 0.5 |
| *Unemotional subscale of ICU* | 7.2ᵃ | 3.9 | 4.2ᵇ | 2.5 | | 8.0ᵃ | 3.2 | 5.6ᵇ | 2.9 | 52.5 | | 0.001 | 9.6 | | 0.01 | <1 | | 0.5 |
| *Current*  *DSM-IV diagnoses* | N | % | N | % | | N | % | N | % | χ2 | | p | χ2 | | p | χ2 | | P |
| ODD | 41 | 70 | 0 | 0 | | 48 | 74 | 0 | 0 | 178.1 | | 0.001 | 3.5 | | 0.06 | <1 | | 0.6 |
| ADHD | 26ᵇ | 44 | 0 | 0 | | 39ᵃ | 60 | 0 | 0 | 123.6 | | 0.001 | 11.1 | | 0.01 | 5.3 | | 0.02 |
| GAD | 12ᵃ | 20 | 0 | 0 | | 4ᵇ | 6 | 0 | 0 | 23.7 | | 0.001 | 2.9 | | 0.09 | 5.5 | | 0.02 |
| MDD | 22 | 37 | 0 | 0 | | 18 | 28 | 0 | 0 | 64.8 | | 0.001 | <1 | | 0.9 | 1.3 | | 0.3 |
| Alcohol abuse | 2 | 3 | 0 | 0 | | 1 | 2 | 0 | 0 | 4.3 | | 0.05 | <1 | | 0.7 | 5.3 | | 0.2 |
| Drug abuse  (cannabis) | 3 | 5 | 0 | 0 | | 4 | 6 | 0 | 0 | 10.1 | | 0.01 | <1 | | 0.5 | <1 | | 0.8 |
| Medication | 17 | 29 | 0 | 0 | | 13 | 20 | 0 | 0 | 43.3 | | 0.001 | <1 | | 0.7 | 1.3 | | 0.3 |
| *PDS* | N | % | N | % | | N | % | N | % | χ2 | | p | χ2 | | p | χ2 | | p |
| Pre/Early (stages I & II) | 3 | 5 | 7 | 7 | | 12 | 18 | 17 | 24 | 6.5 | | 0.2 | 31.2 | | 0.001 | 3.0 | | 0.6 |
| Mid/Late/Post (stages III – V) | 56ᵇ | 95 | 96ᵃ | 93 | | 53ᵇ | 82 | 54ᵇ | 76 |  | |  |  | |  |  | |  |
| *Age of onset[[1]](#footnote-1)* |  |  |  |  | |  |  |  |  |  | |  |  | |  |  | |  |
| Childhood | 17 | 33 | 0 | 0 | | 34 | 54 | 0 | 0 |  | |  | 2.7 | | 0.1 |  | |  |
| Adolescent | 27 | 53 | 0 | 0 | | 28 | 44 | 0 | 0 |  | |  |  | |  |  | |  |
| Missing | 7 | 14 | 0 | 0 | | 1 | 2 | 0 | 0 |  | |  |  | |  |  | |  |
| *Handedness* |  |  |  |  | |  |  |  |  |  | |  |  | |  |  | |  |
| Right | 49 | 83 | 91 | 88 | | 51 | 78 | 66 | 93 | 4.9 | | 0.08 | <1 | | 0.9 | 3.9 | | 0.1 |
| Left | 4 | 7 | 11 | 11 | | 11 | 17 | 3 | 4 |  | |  |  | |  |  | |  |
| Ambidextrous | 3 | 5 | 0 | 0 | | 1 | 1.5 | 1 | 1 |  | |  |  | |  |  | |  |
| Missing | 3 | 5 | 1 | 0.9 | | 2 | 3 | 1 | 1 |  | |  |  | |  |  | |  |

Note: Where appropriate, group (CD/TD) and sex (male/female) differences, sex-by-diagnosis interactions and subsequent post-hoc tests were computed using ANOVAs and Chi square tests. Means with different superscripts (a, b and c) denote significant differences (pairwise comparisons with Bonferroni adjusted p-values are shown, p < .05). In addition to the commonly comorbid disorders currently listed in Table 1 which were present in our sample, the following disorders were also screened for as part of the K-SADS assessment: Psychosis, mania, schizophrenia, autism spectrum disorder, bipolar disorder, panic disorder, separation anxiety disorder, phobia (simple/social/agoraphobia), obsessive compulsive disorder, post-traumatic stress disorder, enuresis, encopresis. Further information regarding the presence of those disorders in our sample is available upon request.

ADHD = attention-deficit/hyperactivity disorder; CD = conduct disorder; GAD = Generalized anxiety disorder; ICU = Inventory of Callous-Unemotional traits; IQ = intelligence quotient; MDD = Major depressive disorder ODD = Oppositional defiant disorder; PDS = Pubertal Development Scale; SD = standard deviation; SES = Socio-economic Status; TD = typically developing. Diagnoses of CD and comorbid disorders were made using the Kiddie-Schedule for Affective Disorders and Schizophrenia-Present and Lifetime version.

**Legends to Figures**

**FIGURE 1** **White Matter Microstructure in Corpus Callosum: Youths with Conduct Disorder (CD) compared with Typically-Developing (TD) Youths. (A)** Voxels within the body of the corpus callosum (coordinates, *x=*7, *y=*-27, *z=*24; p=.02; *k=*41; *d*=.59) where axial diffusivity (AD) differed between groups (CD>TD). All voxels (shown in red-yellow) are thresholded at p<.05, TFCE; FWE-corrected for multiple comparisons. Findings overlaid onto mean fractional anisotropy (FA) skeleton (green) in MNI-space (x, y, z). Corpus callosum shown in blue overlaid on to a 3D MNI152\_T1\_1mm template. For viewing purposes, statistical images were “thickened”. **(B)** Partial regression plots showing unique associations between CD symptoms and mean AD in the corpus callosum (*left*) and ICU callous subscale scores and mean AD in the corpus callosum (*right*) in CD youths only (n=124). *P* and *β* values reflect the level of statistical significance and the standardized regression coefficients, respectively. Shaded error bars reflect 95% confidence intervals.

**FIGURE 2** **White Matter Microstructure in Anterior Thalamic Radiation: Youths with Conduct Disorder (CD) compared with Typically-Developing (TD) Youths. (A)** Voxels within the anterior thalamic radiation (left anterior thalamic radiation: *x=-*8, *y=*-28, *z=*15; p<.01; *k=*140; *d*=.41: right anterior thalamic radiation: *x=*13, *y=*-28, *z=*15; p=.01; *k=*80; *d*=.27) where radial diffusivity (RD) differed between groups (CD < TD). Partial regression plots show unique associations between ICU callous subscale scores and mean RD within the left (*left* graph) and right (*right* graph) anterior thalamic radiation in CD youths only (n=124). *P* and *β* values reflect the level of statistical significance and the standardized regression coefficients, respectively. Shaded error bars reflect 95% confidence intervals.  **(B)** Voxels within the left anterior thalamic radiation (*x=-*6 *y=*-20, *z=*16; p=.03; *k=*52; *d*=.31) where mean diffusivity (MD) differed between groups (CD < TD). All voxels (shown in red-yellow (*top*) and blue-light-blue (*bottom*)) are thresholded at P < .05, TFCE; FWE-corrected for multiple comparisons. Findings are overlaid onto the mean fractional anisotropy (FA) skeleton (green).

**FIGURE 3** **Sex-by-Diagnosis Interaction in Posterior Limb of Internal Capsule.(A)** Voxels within the left internal capsule (*x=-*20, *y=*-12, *z=*5; p=.04; *k=*8; *d*=1.35) revealing a sex-by-diagnosis interaction in radial diffusivity (RD). All voxels (shown in red-yellow) are thresholded at P < .05, TFCE; FWE-corrected for multiple comparisons. Findings are overlaid onto the mean fractional anisotropy (FA) skeleton (green). The internal capsule (bilateral) is shown in blue and the corticospinal tract (bilateral) is shown in yellow overlaid on to a 3D MNI152\_T1\_1mm template. Bar-graph shows white-matter differences in the left internal capsule cluster for females (t=3.26, df=160, p = .005) and males (t=-2.71, df=134, p=.04) with CD compared to TD controls. \*\* =p<.01, \* =p<.05 (Bonferroni-corrected; p<.05); SE = std. error. **(B)** Inset (dashed line) partial regression plot shows unique associations between CD symptoms for females and males with CD and mean RD within the left internal capsule cluster. P and β values reflect the level of statistical significance and the standardized regression coefficients, respectively. Shaded error bars reflect 95% confidence intervals.

**FIGURE 4 Region of Interest Analysis: Youths with Conduct Disorder (CD) compared to Typically-Developing (TD) Youths. (A)** Voxels within the left fornix (x=-1, y=-13, z=18; p=.02; k=6; d=1.15) revealing a sex-by-diagnosis interaction in axial diffusivity (AD). Bar-graph shows white matter differences for females (t = 3.27, df = 160, p < .01) and males (t = 2.1, df = 134, p = .22). **(B)** Voxels within the left posterior thalamic radiation (x=-34, y=-61, z=7; p=.03; k=7; d=1.5) revealing a sex-by-diagnosis interaction in AD. Bar-graph shows white matter differences for females (t = 2.35, df = 160, p = .04) and males (t = 3.41, df = 134, p < .01). **(C)** Voxels within the left uncinate fasciculus (x=-33, y=-11, z=7; p=.01; k=9; d=0.81) revealing a sex-by-diagnosis interaction in mean diffusivity. Bar-graph shows white matter differences for females (t = 1.97, df = 160, p = .03) and males (t = 1.98, df = 134, p < .01). All voxels (shown in red-yellow (A-B) and blue-light-blue (C)) are thresholded at p < .05, TFCE; FWE-corrected for multiple comparisons. Findings are overlaid onto the mean fractional anisotropy (FA) skeleton (green).

PTR = posterior thalamic radiation; SE = std. error. UF = uncinate fasciculus.

n/s = non-significant; \* = p <.05; \*\* = p <.01.

1. Not including the 10 participants with ODD plus CD symptoms [↑](#footnote-ref-1)