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Aberrant resting-state functional connectivity associated with childhood trauma among juvenile offenders

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ABSTRACT

Individuals with history of childhood trauma are characterized by aberrant resting-state limbic and paralimbic functional network connectivity. However, it is unclear whether specific subtypes of trauma (i.e., experienced vs observed or community) showcase differential effects. This study examined whether subtypes of childhood trauma (assessed via the Trauma Checklist [TCL] 2.0) were associated with aberrant intra-network amplitude of fluctuations and connectivity (i.e., functional coherence within a network), and inter-network connectivity across resting-state networks among incarcerated juvenile males ($n = 179$). Subtypes of trauma were established via principal component analysis of the TCL 2.0 and resting-state networks were identified by applying group independent component analysis to resting-state fMRI scans. We tested the association of subtypes of childhood trauma (i.e., TCL Factor 1 measuring experienced trauma and TCL Factor 2 assessing community trauma), and TCL Total scores to the aforementioned functional connectivity measures. TCL Factor 2 scores were associated with increased high-frequency fluctuations and increased intra-network connectivity in cognitive control, auditory, and sensorimotor networks, occurring primarily in paralimbic regions. TCL Total scores exhibited similar neurobiological patterns to TCL Factor 2 scores (with the addition of aberrant intra-network connectivity in visual networks), and no significant associations were found for TCL Factor 1. Consistent with previous analyses of community samples, our results suggest that childhood trauma among incarcerated juvenile males is associated with aberrant intra-network amplitude of fluctuations and connectivity across multiple networks including predominately paralimbic regions. Our results highlight the importance of accounting for traumatic loss, observed trauma, and community trauma in assessing neurobiological aberrances associated with adverse experiences in childhood, as well as the value of trained-rater trauma assessments compared to self-report.

1. Introduction

Nearly all incarcerated youth have experienced some form of trauma prior to their incarceration (Abram et al., 2004; Abram et al., 2007). Incarcerated juvenile males are nearly-three times more likely to have been victims of assaultive violence and are two to 15 times more likely to have witnessed violence than comparable juvenile community samples (Abram et al., 2004; Abram et al., 2007; Kilpatrick et al., 2003). Accordingly, the rate of PTSD in incarcerated juvenile males is estimated to be up to eight times the rate present in non-incarcerated youth (Abram et al., 2004; Ford et al., 2007). Emerging research suggests that these types of childhood traumas and resulting psychopathologies have an undue effect on the neurobiology of the individual (see Cassiers et al., 2018 for a review on the subject). While the descriptive prevalence of trauma exposure and the resulting psychopathologies in incarcerated juvenile populations is well-established in the literature (e.g., Abram

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et al., 2004; Abram et al., 2007; Ford et al., 2007; Kilpatrick et al., 2003), the exact effects of childhood trauma on neural abnormalities are less clear.

Broadly, research suggests that childhood trauma is related to abnormal intra- and inter-network activational profiles during resting-state functional magnetic resonance imaging (rsfMRI) scans. These functional aberrances have been reported to primarily occur in limbic and paralimbic regions within the salience network (e.g., anterior cingulate cortex, insulae, temporal poles, ventral striatum, and amygdalae), though have also been observed in non-limbic/paralimbic networks as well (e.g., the default mode network including the precuneus and medial prefrontal cortex; Cassiers et al., 2018; Cisler, 2017; Fan et al., 2023; Fareri et al., 2017; Herringa et al., 2013; Krause et al., 2016; Rakesh et al., 2021a; Reda et al., 2021; Teicher et al., 2015; van der Werff et al., 2013; Wang et al., 2014; Zhao et al., 2021). On a more global, inter-network level, childhood maltreatment also relates to aberrant connectivity between the default mode, dorsal attention, and frontoparietal networks (Rakesh et al., 2021b). While many of the analyses constituting this field have assessed trauma more generally (i.e., total scores on trauma measures), studies have not investigated whether subtypes of trauma (e.g., physical abuse vs traumatic loss) relate to particular resting-state functional connectivity measures. Specifically, previous studies have failed to measure instances of observed trauma or control for this subtype of trauma in their analyses with other subtypes of trauma (e.g., experienced trauma). Likewise, the relationship of trauma to alternative resting-state activational measures, including amplitude of fluctuations (AFs), has been left unexplored in the literature. AFs may be particularly important to investigate, as they have been linked to psychiatric disorders, behavioral characteristics, and are thought to underlie functional connectivity more generally (Allen et al., 2022; Eggart et al., 2019; Gazula et al., 2022; Guo et al., 2013; Weightman et al., 2019; Wielaard et al., 2018; Yue et al., 2015; Zamani Esfahlani et al., 2020), By assessing aberrant global (inter-network) and local (intra-network and AFs) measures of trauma-related connectivity, a more thorough picture of the effects of trauma on the brain can be offered.

As different types of childhood trauma are associated with alternative psychopathologies and divergent tendencies towards antisocial outcomes (e.g., relapse and rearrest), it is imperative to understand the neurobiological correlates that may be promoting these patterns (Curran et al., 2018; Dalsklev et al., 2019; Hyman et al., 2008). Likewise, being able to establish the relationship between specific childhood traumas and regional abnormal brain activity may have additional translational value in region-specific non-invasive brain stimulation interventions meant to ease the symptoms related to trauma-induced psychopathologies (Blades et al., 2020; Hu et al., 2021). Here we report the use of the Trauma Checklist (TCL) 2.0—an assessment scored using multiple data sources (including institutional files, self-report and clinical assessments, and clinical videotaped interviews)—and principal component analysis (PCA) to test the effects of summed childhood trauma (in the case of novel cumulative effects of trauma) and specific subtypes of childhood trauma exposure (including types of community and observed trauma) on resting-state functional connectivity in a sample of 179 incarcerated juvenile males. We hypothesized that childhood trauma would be associated with aberrant functional connectivity (FC) in paralimbic regions spanning multiple cognitive domains, and that subtypes of trauma would exhibit differential patterns within these domains.

2. Methods

2.1. Participants

Participants included juvenile male offenders recruited from a maximum-security juvenile correctional facility—the Youth Diagnostic and Development Center of Albuquerque, New Mexico—who previously participated as part of NIH-funded research studies (R01 MH071896 and R01 HD092331). While all offenders within the correctional facility were offered the opportunity to participate in the current study, the final sample consisted of participants who completed the trauma assessment, met inclusion criteria, and had acceptable resting-state functional MRI scans (final $n = 179$). Inclusion criteria consisted of fluency in English at or above a fourth-grade reading level; estimated IQ over 60 (Ryan & Ward, 1999; Wechsler, 2003); no history of psychotic disorder; and minimal motion, as assessed by an average spatial cross-correlation >0.75 of each participant's most superior five mask slices during the resting-state fMRI scan with the *EPI* template (resulting in the removal of two participants from the original sample) (see Du et al., 2023 for similar methods).

Participants were between the ages of 14 and 20 (average age = 17.61 years, SD = 1.14 years) at the time of their rsfMRI scan and approximately 11 % were left-handed. Based on National Institutes of Health racial and ethnic classification, 58.7 % of the sample self-identified as white, 4.0 % as black/African American, 11.7 % as American Indian or Alaskan Native, 26.6 % as mixed/other, and, ethnically, 76.5 % as Hispanic or Latino. Participants provided written informed consent in protocols approved by the University of New Mexico Health Sciences Center Institutional Review Board via Independent Review (E&I) Services for the Mind Research Network and were paid at a rate commensurate with institution compensation for work assignments at their facility.

2.2. Trauma scoring

History of trauma was assessed using the TCL 2.0 [henceforth, TCL],[1] a modified version of a previous trauma assessment developed by our research group (for more detailed information on this trauma assessment, see Dargis et al., 2019). While both scoring methods investigated the same seven categories of trauma—i.e., instances of physical abuse, emotional abuse, sexual abuse, and neglect/poverty, and also instances of trauma occurring in the environment they were raised in, such as observing trauma happening to others, instances of community violence, and experiencing traumatic loss—expansions to our trauma assessment included more detailed definitions and examples under each trauma category as well as raters using additional collateral information to score the TCL (e.g., the Upsetting Events Scale [UES], the Childhood Trauma Questionnaire, and the My Worst Experience Scale: Kohr, 1996; Kubany et al., 2000). Consistent with Dargis and colleagues (2019), the scoring criteria is as follows: 0 (not present/no evidence of trauma), 1 (few/minor instances of trauma), or 2 (many/serious/prolonged instances of trauma), with TCL Total scores potentially ranging from 0 to 14. Consistent with our previous study, we utilized principal component analysis to explore subtypes of trauma across the seven trauma categories (Dargis et al., 2019).

2.3. Substance use severity

To control for the potential influence of substance use severity on resting-state functional connectivity measures, participants' total summed years of regular alcohol/substance use (as assessed via a modified version of the Addiction Severity Index [ASI]) was calculated across the following categories: alcohol, cannabis, stimulants, sedatives, cocaine, opioids, PCP, hallucinogens, solvents, and other (McLellan et al., 1992). Regular substance use was defined as three or more times per week for a minimum period of one month. Total years of substance use were then divided by the participant's age (to control for opportunity to use), multiplied by 100, and a square root transformation was applied to correct for skewness. This operational definition of substance use severity has been incorporated in previous studies by our research group (Ermer et al., 2012).

[1] See supplemental materials for full details of the TCL 2.0 protocol.

2.4. Diagnoses of psychiatric disorders

Similar to our previous report (Dargis et al., 2019), we utilized the Kiddie Schedule for Affective Disorders and Schizophrenia (KSADS; Kaufman et al., 1997) to assess whether or not participants met criteria for various forms of psychopathology, including anxiety disorders, mood disorders, post-traumatic stress disorder (PTSD), and attention-deficit/hyperactivity disorder (ADHD). Potential anxiety disorders included generalized anxiety disorder, obsessive compulsive disorder, acute stress disorder, panic disorder (with and without agoraphobia), separation anxiety, phobias (i.e., social phobia and/or specific phobias), agoraphobia, or an anxiety disorder not otherwise specified (NOS). Potential mood disorders included major depressive disorder (with and without psychotic features), dysthymia, melancholic depression, adjustment disorder with depressed mood, depressive disorder NOS, schizoaffective disorder (depressed and manic types), mania, hypomania, cyclothymia, or bipolar disorder NOS. Based on this criteria, and out of the 173 participants that were administered the KSADS, $n = 5$ participants met criteria for any anxiety disorder, $n = 29$ participants met criteria for any mood disorder,[2] and $n = 9$ participants met criteria for ADHD and PTSD, respectively (see Table 1).

2.5. Imaging parameters

Resting-state functional magnetic resonance images were collected on the grounds of the correctional facility where participants were scanned using the Mind Research Network's mobile Siemens 1.5 T Avanto with advanced SQ gradients (max slew rate 200 T/m/s, 346 T/m/s vector summation, rise time 200 us) equipped with a 12-element head coil. The *EPI* gradient echo pulse sequence (TR = 2000 ms, TE = 39 ms, flip angle = 75, FOV = 24 × 24 cm, 64 × 64 matrix, 3.75 × 3.75 mm in-plane resolution, 4 mm slice thickness, 1 mm gap, 27 slices) effectively covered the entire brain (150 mm) in 2.0 s. Head motion was minimized using padding and restraint. The participants were asked to lay still, look at the fixation cross and keep eyes open during the five-minute rsfMRI scanning. Compliance with instructions was monitored by eye-tracking.

Table 1
Clinical Descriptive Information.

Clinical variable	Endorsed (%)
Trauma Checklist Total score	99.4
Physical abuse	59.2
Emotional abuse	31.8
Sexual abuse	19.6
Neglect/Poverty	67.0
Community violence	93.3
Traumatic loss	90.5
Observed trauma	90.5
Mood	16.8
Anxiety	2.9
PTSD	5.2
ADHD	5.2

Note. Endorsement (%) of Trauma Checklist Total score entails the participant scoring above zero on the TCL for any item. Endorsement of psychiatric disorder reflects a participant meeting past or present criteria for *any* mood or anxiety disorder, and PTSD/ADHD singularly, out of $n = 173$.

2.6. EPI preprocessing

Data were preprocessed using statistical parametric mapping (SPM12) (Friston et al., 1994) (https://www.fil.ion.ucl.ac.uk/spm) including image reorientation, realignment (motion estimation using INRIAlign: Freire & Mangin, 2001), and spatial normalization to the Montreal Neurological Institute standard space at a resolution of a 3 × 3 × 3 mm^3. A full-width half maximum Gaussian kernel of 6 mm was then used for spatial smoothing. Framewise displacement (FWD), a measure of motion, as calculated utilizing the INRIAlign derived realignment parameters (utilizing the translation and rotation parameters as the mean of the sums of the absolute translation and rotation frame displacement), was investigated. As reported in our Supplementary Materials, Section 9.6, results reported in our main manuscript were nearly identical when including FWD as a covariate in analyses performed.

2.7. Independent component analysis

We applied group Independent Component Analysis (gICA) on the preprocessed rsfMRI data using the GIFT toolbox (https://trendscenter.org/software/gift) (Calhoun et al., 2001). The rsfMRI data was compressed using two stages of PCA (Rachakonda et al., 2016). For the first data reduction step, we retained 100 principal components (PCs), and 50 independent components (ICs) for group data reduction, consistent with previously published studies (Elseoud et al., 2011; Allen et al., 2011a; Allen et al., 2022; Erhardt et al., 2011; Kiviniemi et al., 2009; Smith et al., 2009; Ystad et al., 2010). Individual specific spatial maps and their time-courses were obtained using gICA. Out of the 50 ICs that were estimated, 28 components were identified as components of resting-state networks (RSNs) by evaluating whether peak activation occurred in gray matter, whether the peak spectral amplitude of fluctuations (AFs) occurred in the low-frequency power portion of the spectra of components, and whether the networks showcased reliability (Allen et al., 2011b; Meda et al., 2008; Robinson et al., 2009). The reliability and stability of these extracted networks were evaluated by ICASSO (Du et al., 2014; Himberg & Hyvärinen, 2003), a process that runs multiple component estimations with alternatively bootstrapped datasets. This analysis suggested high stability across the 28 components (*mean stability index* = 0.94), well above the threshold of 0.80 established in the literature (Iraji et al., 2022; Ma et al., 2011). Within GIFT, the time-courses of the RSNs underwent despiking and bandpass by filtering with [0.01–0.15] Hz cutoffs.

2.8. Functional connectivity measures

In order to assess various types of resting-state functional connectivity measures, we calculated the static functional network connectivity (sFNC) between the selected 28 RSNs as pairwise correlations between the RSNs time-courses for each individual (inter-network connectivity or functional network connectivity; FNC, resulting in 378 values), pairwise correlations between individual voxels within the RNSs to the overall RSN's time-course (intra-network connectivity, reflecting local functional connectivity, and values dependent on the number of voxels within a component), and the AFs within each RSN (divided into 127 spectral bins).

2.9. Statistical analyses

We performed regression analyses using two separate factor scores of childhood trauma (see the Trauma Principal Component Analysis section below for extended details), as well as a total trauma score based on Dargis and colleagues' primary focus in their establishing of the original TCL (2019), to identify associations between individual FNC values, intra-network connectivity, and AFs with these trauma measures: TCL Factor 1, Factor 2, and TCL Total scores. The models were corrected for

[2] In order to assess depressive symptomology, we utilized the Reynolds Adolescent Depression Scale (RADS; Score, 2004), in order to explore the relationship between trauma assessments with depressive symptomology in a portion of the current sample (n =109).

"nuisance" covariates (age, IQ, and substance use severity),[3] and were also covaried with the other TCL Factor within models (i.e., TCL Factor 2 was controlled for while testing regressions of TCL Factor 1, and vice-versa). The significance of the univariate trauma results for each factor was determined using a false discovery rate (FDR) (Genovese et al., 2002) threshold at $p < 0.05$. Finally, in a subset of the sample ($n = 78$), we assessed whether scores from a self-report measure of trauma (i.e., the Upsetting Events Survey [UES]; Akin et al., 2021; Kubany et al., 2000) were associated with similar neurobiological effects as the trainer-rated TCL.

3. Results

3.1. Trauma measures

Scoring of the TCL was conducted by two independent raters who categorized and rated trauma experiences for each participant and then met to come to consensus on the final TCL scores to ensure reliability and accuracy of scoring. Pre-consensus ICCs suggested interrater reliability was moderate to high across all categories including Total score (α = 0.82), and subscale scores: physical abuse (α = 0.86), emotional abuse (α = 0.73), sexual abuse (α = 0.81), neglect/poverty (α = 0.64), observed trauma (α = 0.70), community violence (α = 0.75), and traumatic loss (α = 0.75). See Table 1 for group-wide endorsement of TCL items.

3.2. Trauma principal component analysis

PCA with a varimax rotation of the TCL yielded a two-factor[4] solution, accounting for 47 % of the variance in the total scale.[5] The two-factor solution was chosen based on multiple criteria: an Eigenvalue threshold of >1 (replicating methods used in our previous solution: Dargis et al., 2019), declining variance accounted for by higher factor solutions, and avoidance of single item factors solutions. As outlined in Table 2, the Physical, Emotional, Sexual Abuse, and Neglect/Poverty items loaded onto one factor (i.e., Factor 1) and the Community Trauma, Observed Trauma, and Traumatic Loss items loaded on to a second factor (i.e., Factor 2). Generally, these factors correspond to trauma enacted on the individual (Factor 1: Experienced Trauma) and trauma observed by the individual (Factor 2: Community Trauma) (see Table 3 for average TCL scores across factors, and sample demographics). Factors 1 and 2 demonstrated good ICCs of α = 0.85 and α = 0.78, respectively.[6]

Table 2
Principal component factor loadings.

Type of trauma	Factor 1	Factor 2
Physical abuse	**0.776**	0.101
Emotional abuse	**0.654**	−0.064
Sexual abuse	**0.515**	−0.285
Neglect/Poverty	**0.580**	0.192
Community violence	0.010	**0.789**
Traumatic loss	−0.037	**0.555**
Observed trauma	0.521	**0.559**

Note. $n = 179$. Bolded numbers identify subscales that load onto each factor. Eigenvalues for the two-factor solution and subsequent factors: Factor 1 = 2.03; Factor 2 = 1.26; Factor 3 = 0.94; Factor 4 = 0.86; Factor 5 = 0.77; Factor 6 = 0.61; Factor 7 = 0.53. Percent variance explained for the two-factor solution and subsequent factors: Factor 1 = 28.95; Factor 2 = 17.92; Factor 3 = 13.45; Factor 4 = 12.32; Factor 5 = 8.69; Factor 6 = 0.61; Factor 7 = 7.63. While Observed trauma loads onto both extracted factors, it was chosen to be included in Factor 2 due to a higher loading coefficient.

3.3. Group independent component analysis

Fig. 1 shows the spatial maps of the 28 selected RSNs. The 28 RSNs listed in Table 4 were grouped into six domains: auditory (AU), cerebellar (CB), cognitive control (CC), default mode (DM), sensorimotor (SM), and visual (VI) based on based on their peak coordinate, functional properties, the automatic labeling tool in GIFT (Salman et al., 2022), and confirmed by visual inspection (see Fig. 2 for the estimated inter-network functional connectivities between domains and RSNs). As expected, strong within domain inter-network connectivities are present.

3.4. Time course power spectra

3.4.1. TCL factor 1 scores: Experienced trauma

There were no significant associations between TCL Factor 1 scores and AFs that survived FDR correction while controlling for age, substance use severity, IQ, and TCL Factor 2 scores.

3.4.2. TCL factor 2 scores: Community trauma

TCL Factor 2 scores were associated with increased AF at high-frequency spectra bands (0.15 Hz−0.25 Hz) in the superior temporal gyri (Component 6, AU), insulae (Component 7, CC), and temporal poles (Component 9, CC) (see Figs. 3 and 4, Table 5), while controlling for age, substance use severity, IQ, and TCL Factor 1 scores.

3.4.3. TCL total scores

TCL Total scores were associated with increased AF at high-frequency spectra bands (0.20 Hz−0.25 Hz) in the temporal poles (Component 9, CC) (see Fig. 5 and Table 5), while controlling for aforementioned covariates.

Table 3
Participant Demographics and assessment scores.

	Mean	*SD*	Min.	Max.
Age (years)	17.61	1.14	14.50	20.43
IQ	92.68	12.10	63	140
Substance use severity (yrs.)	8.85	6.63	0	38.00
TCL total scores	7.82	2.65	0	14
Factor 1 scores	2.79	2.07	0	8
Factor 2 scores	5.03	1.27	0	6
RADS	66.96	11.67	37.00	94.00
UES	7.62	5.30	0	25.00

Note. Substance use severity is presented without transformations for ease of interpretation. For RADS and UES total score, results reflect subsamples of $n = 109$ and $n = 78$, respectively.

[3] In the case of missing covariates, mean values were imputed; $n = 17$ participants were missing IQ and $n = 2$ were missing substance use severity.

[4] The term "factor" was chosen over "component" for the present descriptions to be consistent our previous study (Dargis et al., 2019) and to make it easier for readers to differentiate and interpret correctly usages of "component" while discussing the effects of trauma components/factors on resting-state independent components.

[5] Data was deemed appropriate for a PCA based on Kaiser-Meyer-Olkin Measure of Sampling Adequacy = .67 and a Bartlett's test of sphericity result of $p < .001$.

[6] No TCL measures (i.e., TCL Factor 1, Factor 2, and Total) were significantly associated with time served under the participant's current sentence, suggesting measures and observed effects are simply not measuring length of time incarcerated.

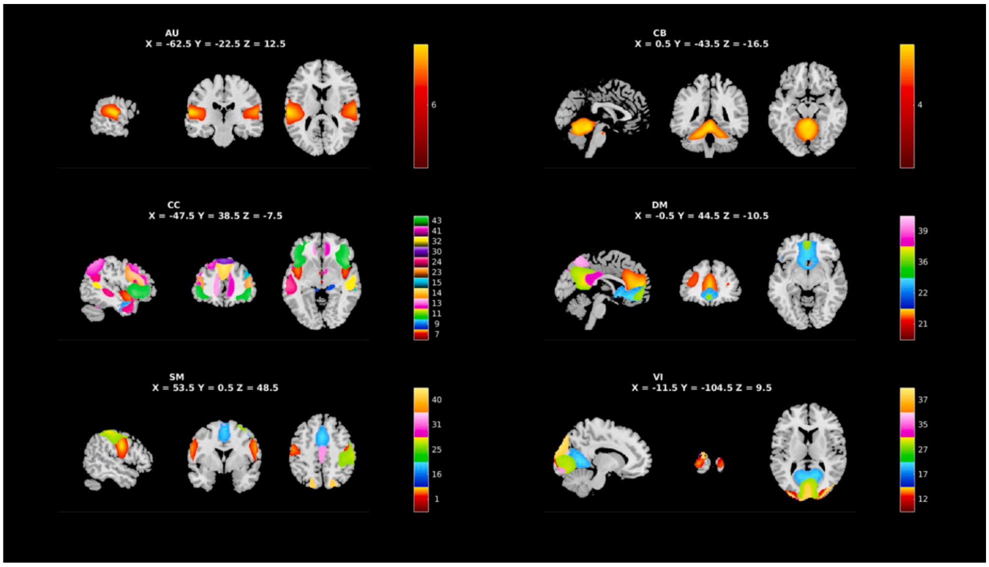

Fig. 1. Spatial maps of the 28 independent components identified as RSNs categorized by domain [auditory (AU), cerebellar (CB), cognitive control (CC), default mode (DM), sensorimotor (SM), and visual (VI)] and component number.

Table 4
Resting-state networks (RSNs) domain names, IC numbers, and MNI peak coordinates.

RSNs and domain names	IC Number	MNI Peak
Auditory (AU)		
Left superior temporal gyrus	6	(-62, −20, 10)
Cerebellar (CB)		
Anterior lobe	4	(0, −44, −15)
Cognitive Control (CC)		
Left insula	7	(-38, 10, −20)
Left temporal pole	9	(−32, 12, −35)
Posterior cingulate cortex	11	(0, −28, 10)
Left dorsolateral prefrontal cortex	13	(-48, 44, 10)
Left frontal eye field	14	(0, 44, 50)
Right angular gyrus	15	(48, −58, 55)
Left Broca operculum	23	(-52, 18, 30)
Left dorsolateral prefrontal cortex	24	(-50, 20, −5)
Supplementary motor area	30	(2, 20, 65)
Right fusiform gyrus	32	(62, −50, 10)
Left visuomotor cortex	41	(-42, −64, 55)
Right insula	43	(50, 18, −5)
Default Mode (DM)		
Anterior prefrontal cortex	21	(0, 54, 10)
Left orbitofrontal cortex	22	(-2, 36, −15)
Posterior cingulate cortex	36	(0, −50, 20)
Right angular gyrus	39	(48, −76, 30)
Sensorimotor (SM)		
Primary motor cortex	1	(58, −6, 30)
Supplementary motor area	16	(2, 14, 45)
Primary sensory cortex	25	(50, −28, 60)
Supplementary motor area	31	(0, −24, 75)
Left precuneus	40	(-6, −58, 70)
Visual (VI)		
Right secondary visual cortex	12	(24, −100, −10)
Left ventral posterior cingulate cortex	17	(-12, −58, 5)
Secondary visual cortex	27	(0, −82, −5)
Left fusiform gyrus	35	(-48, −38, −20)
Secondary visual cortex	37	(0, −94, 25)

Note. RSN network names and domains were determined by peak MNI coordinates and GIFT's component labeling function.

3.5. *Intra-network connectivity*

3.5.1. *TCL factor 1 scores: Experienced trauma*

There were no significant associations between TCL Factor 1 scores and intra-network connectivity that survived FDR correction while controlling for age, substance use severity, IQ, and TCL Factor 2 scores, measuring community trauma.

3.5.2. *TCL factor 2 scores: Community trauma*

TCL Factor 2 scores were associated with increased functional connectivity within the precuneus (Component 40, SM) (see Fig. 6 and Table 6), while controlling for age, substance use severity, IQ, and TCL Factor 1 scores.

3.5.3. *TCL total scores*

TCL Total scores were associated with functional connectivity within Component 27 (VI), the secondary visual cortex, such that higher TCL Total scores were associated with both decreased and increased intra-network functional connectivity in the cuneus and fusiform gyrus, respectively (see Fig. 7 and Table 6).

3.6. *Functional network connectivity*

There were no significant associations between TCL factor/total scores and sFNC that survived FDR correction while controlling for age, substance use severity, and IQ, and the alternative subtype of trauma.

3.7. *Comparison of Trained-Rater TCL to Self-Report trauma measure (UES)*

To assess the ability of trained-rater trauma scales compared to self-reported trauma scales to account for variability in resting-state functional connectivity, we directly compared behavioral and neurobiological results associated with the TCL to the self-report UES, an adaptation of the Traumatic Life Events Questionnaire (Akin et al., 2021; Kubany et al., 2000), in a subsample of participants with available scores in the present sample ($n = 78$). The UES is a self-report scale that includes 17 questions assessing different instances of childhood trauma, taking into account repeated instances of trauma. A Total UES score is calculated by summing across all 17 types of traumatic events.

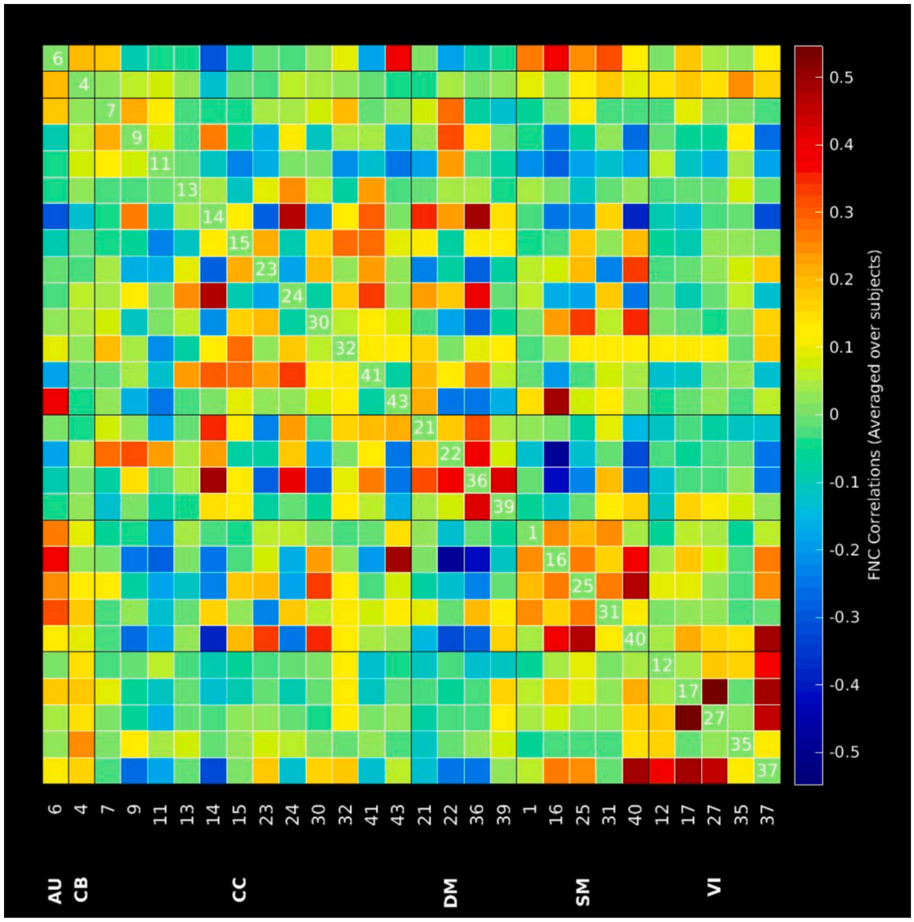

Fig. 2. Functional network connectivity matrix of the 28 RSNs.

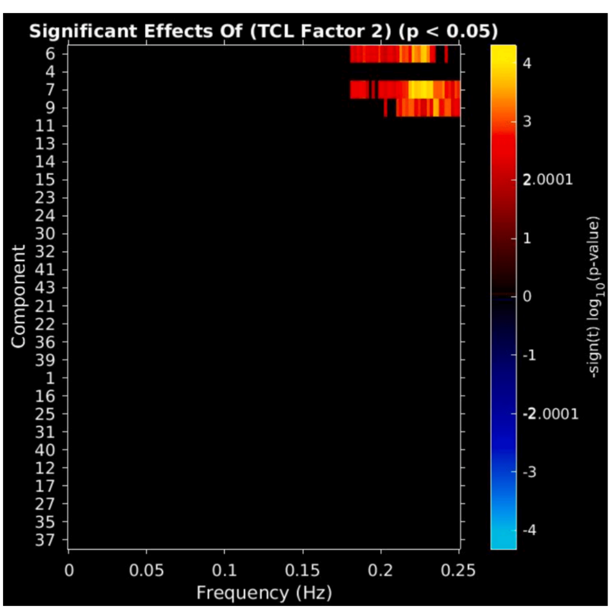

Fig. 3. Univariate associations between TCL Factor 2 scores and power spectra of significant components. Panel depicts the significance and direction of TCL Factor 2 scores as a function of frequency for each significant component, displayed as - sign(t)log10(p), FDR corrected $p < 0.05$.

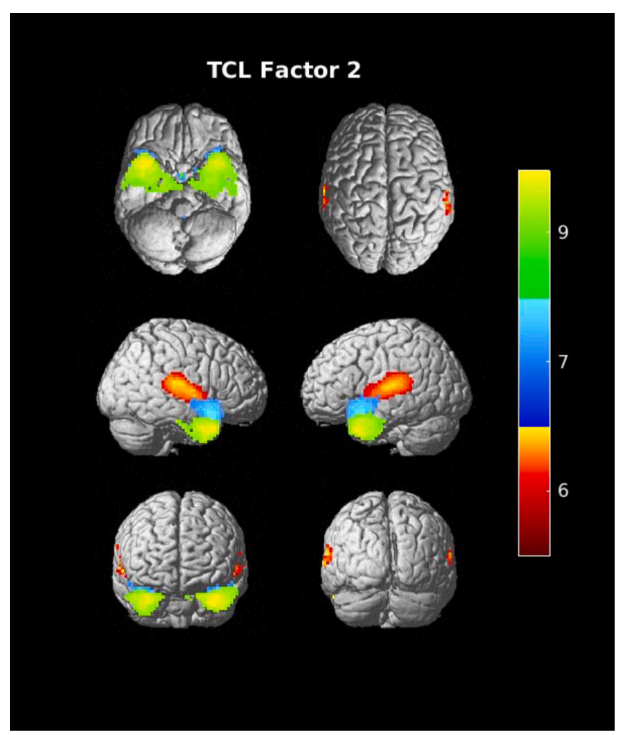

Fig. 4. Resting-state networks (ICs 6, 7, and 9) featuring aberrant AFs related to TCL Factor 2 trauma (and Total Trauma while considering IC9).

Table 5
Effects of childhood trauma on AFs, FDR corrected.

Measure	RSN	IC, domain	Beta Range
TCL Factor 2			
	Superior temporal gyri	6, AU	0.121–0.185
	Insulae	7, CC	0.119–0.209
	Temporal poles	9, CC	0.117–0.156
TCL Total			
	Temporal poles	9, CC	0.058–0.076

Note. Table shows all AF effects that survive FDR correction at $p < 0.05$ level and range of Beta Values per effect.

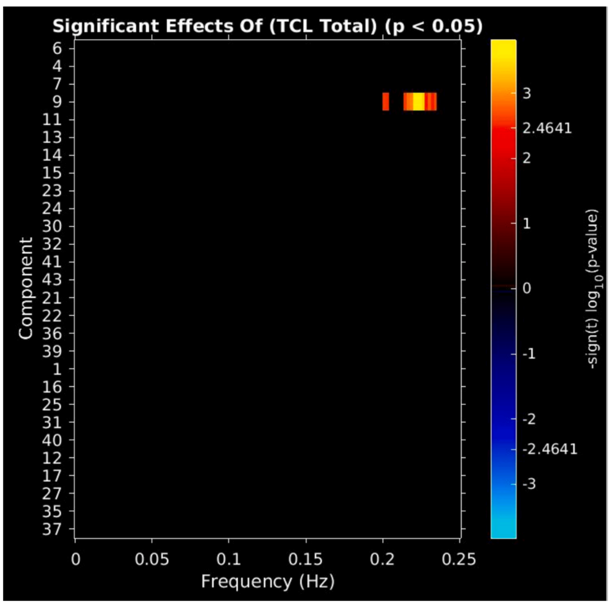

Fig. 5. Univariate associations between TCL Total score and power spectra of significant components. Panel depicts the significance and direction of TCL Total scores as a function of frequency for each significant component, displayed as - sign(t)log10(p), FDR corrected $p < 0.05$.

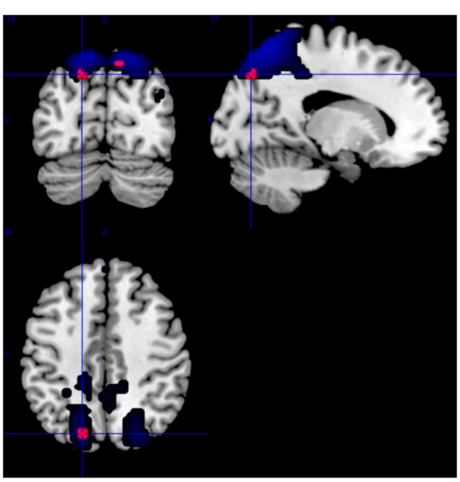

Fig. 6. Association between TCL Factor 2 score and increased intra-network connectivity within the precuneus, FDR corrected $p < 0.05$. Blue mapping corresponds to Component 40′s spatial map, and red reflects regions of increased intra-network connectivity.

3.7.1. *Relationship between trained-rater and self-report trauma scales*

As expected, there was a one-tailed positive correlation between TCL Factor 1, TCL Factor 2, and TCL Total scores ($M = 7.62$, $SD = 5.30$) with

Table 6
Effects of childhood trauma on intra-network connectivity, FDR corrected.

Measure	RSN	IC, domain	Average Beta
TCL Factor 2			
	Precuneus	40, SM	0.515
TCL Total			
	Secondary visual cortex: Fusiform gyrus and cuneus	27, VI	−0.223 & 0.305

Note. Table shows all clusters that survive FDR correction at $p < 0.05$ level and average Beta effect size. Because of positive and negative beta-values associated with TCL Total Score, averages of both are displayed in the table.

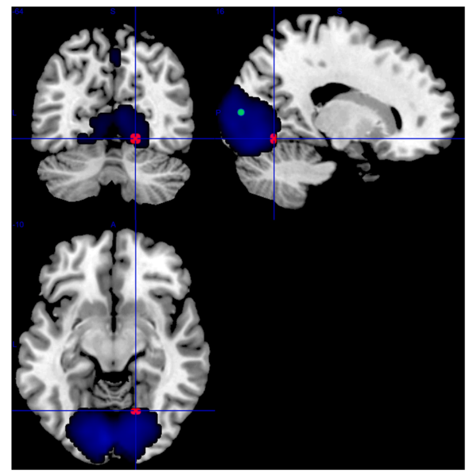

Fig. 7. Association between TCL Total score and intra-network connectivity within the fusiform gyrus and cuneus, FDR corrected $p < 0.05$. Blue mapping corresponds to Component 27′s spatial map, red reflects regions of increased intra-network connectivity, and green reflects regions of decreased intra-network connectivity.

Total UES scores of r (76) = 0.219, p = 0.027, r (76) = 0.352, p = 0.001, and r (76) = 0.347, p = 0.001, respectively (see Table 7).

3.7.2. *Relationship between Trained-Rater and Self-Report trauma scales with neurobiological measures*

To assess whether the neurobiological effects associated with the TCL extend to self-report trauma measures, we extracted average high-frequency spectra bands (0.17–0.25 Hz) from each component that showed corrected effects associated with TCL scores (i.e., components 6, 7, and 9). As expected, TCL Factor 2 and TCL Total Scores are associated with high-frequency bands of all three components (all $r (177) > 0.191$, $p < 0.05$), whereas UES Total scores are not significantly associated (p's > 0.50: see Table 7).

4. Discussion

Here, we report that a specific subtype of childhood trauma (assessed via the TCL by trained-raters) was associated with aberrant functional connectivity measures during a resting-state fMRI experimental paradigm in a sample of incarcerated juvenile males. Consistent with our hypotheses and previous research (Cassiers et al., 2018; Cisler, 2017; Fan et al., 2023; Fareri et al., 2017; Herringa et al., 2013; Krause et al., 2016; Rakesh et al., 2021a; Reda et al., 2021; Teicher et al., 2015; van der Werff et al., 2013; Wang et al., 2014; Zhao et al., 2021), measures of childhood trauma—primarily those measuring community trauma, observed trauma, and traumatic loss—were associated with aberrant functional connectivity across multiple domains, yet primarily occurred within limbic and paralimbic regions.

Table 7
Correlation matrix.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Age	–													
2. IQ	0.068	–												
3. Substance Use	−0.036	0.116	–											
4. TCL Factor 1	−0.10	0.204**	0.145	–										
5. TCL Factor 2	−0.055	0.031	0.183*	0.219**	–									
6. TCL Total	−0.034	0.144	0.200**	0.885***	0.649***	–								
7. UES Total	−0.123	0.028	0.379**	−0.219†	0.352**	0.347**	–							
8. IC6 High Freq.	0.086	0.100	0.147*	0.083	0.247**	0.183*	0.056	–						
9. IC7 High Freq.	0.043	0.156	0.151*	0.059	0.277***	0.179*	0.024	0.646***	–					
10. IC9 High Freq.	0.104	0.119	0.099	0.144	0.191*	0.204**	−0.077	0.523***	0.713***	–				
11. RADS Total	−0.036	0.121	0.048	0.132	0.129	0.160†	0.133	0.011	0.013	0.150	–			
12. Anxiety	−0.053	−0.007	0.006	0.019	−0.120	−0.042	−0.034	−0.043	−0.018	−0.035	0.107	–		
13. Mood	0.021	0.208**	0.36	0.171*	−0.124	0.074	−0.127	−0.031	−0.034	0.026	0.247*	0.107	–	
14. PTSD	−0.158*	−0.039	0.067	0.077	0.029	0.074	0.059	−0.104	−0.110	−.143	0.147	−0.041	0.104	–
15. ADHD	−0.002	0.166*	0.084	0.102	−0.075	0.044	0.142	−0.101	−0.126	−0.076	0.173†	−0.040	0.313***	0.180*

Note: Results of bivariate Pearson's correlations. Reported values for UES and RADS total are reflective of sub-samples ($n = 78$ and $n = 109$, respectively; overlap $n = 29$). Likewise, reported values for KSADS assessments (presence of any anxiety or mood disorder, PTSD, and ADHD) reflect a sub-sample of $n = 173$, with a complete overlap with age, IQ, substance use, TCL values, and neurobiological values, and an overlap of $n = 77$ and $n = 106$ with the UES and RADS, respectively. All other relationships are for the entire sample ($n = 179$). IC6, IC7, and IC9 High Frequency Band values are the binned spectral values spanning from 0.17 to 0.25 Hz of components 6, 7, and 9, respectively. † $p < 0.05$ (one-tailed), *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

Instances of trauma assessed via Factor 2 of the TCL (i.e., community violence, observed trauma, and traumatic loss) were associated with increased AFs in high-frequency bands within the paralimbic system, including the superior temporal gyrus (IC6), insulae (IC7), and temporal poles (IC9), with Total TCL scores also showcasing similar temporal pole effects (see Table 5 and Fig. 5). Notably, these paralimbic regions contribute to multiple cognitive processes, including social cognition, theory of mind, and interoceptive representation, and previous research has demonstrated disrupted network connectivity stemming from these regions to be associated with childhood maltreatment (Craig, 2009; Ross & Olson, 2010; Teicher et al., 2015). More generally, a shift towards high-frequency AFs in rsfMRI is commonly associated with the natural aging process (Allen et al., 2011a; Yang et al., 2018; Zhong & Chen, 2020). Childhood trauma has been previously associated with higher brain-age gaps (Keding et al., 2021; Rakesh et al., 2021c), representing a more rapid maturing of the brain for those that experienced trauma (e.g., cortical thinning). Furthermore, research suggests that increased high-frequency AFs in the temporal and frontal lobes may serve as biomarkers for late onset depression, a form of psychopathology commonly associated with childhood trauma, and subsequently, poor interoception and social cognition (Eggart et al., 2019; Guo et al., 2013; Weightman et al., 2019; Wielaard et al., 2018; Yue et al., 2015). Thus, the observed increase in high-frequency paralimbic AFs may relate to previously noted trauma-induced brain-age gaps, as well as literature establishing biomarkers for the development of late-onset depression.[7]

We also observed that individuals with a history of more severe Community Trauma exhibited increased intra-network connectivity within the precuneus (IC40). More generally, those who scored high across all items on the TCL exhibited both increased and decreased intra-network connectivity within the fusiform gyrus and precuneus, respectively (IC27: see Fig. 7). These regions are commonly implicated in self-referential thinking and stimuli processing during social interaction (i.e., face processing) (Cavanna & Trimble, 2006; Schultz et al., 2003). Altered connectivity stemming from the precuneus, more specifically, has previously been linked to childhood maltreatment, substance use relapse, and depressive episodes in individuals with recurrent depression (Liu et al., 2017; Fan et al., 2023; Teicher et al., 2015; Wang et al., 2020). Likewise, consistent with our findings of aberrant intra-network fusiform gyrus connectivity, additional research on the effect of childhood maltreatment suggests altered BOLD activity while viewing novel faces in the fusiform gyrus, an effect interpreted to denote trauma-induced heightened sensitivity to potential threats (Edmiston & Blackford, 2013). Thus, our observed effects may relate to literature noting trauma-induced vulnerability to neural alterations relevant to altered social interaction, antisocial actions, and depression (Farina et al., 2018).

Because incarcerated juveniles are at heightened risk of childhood trauma and resulting psychopathologies, and have already demonstrated subsequent antisocial actions, our investigation of the impact of childhood trauma on brain-wide connectivity measures serves as an important and relevant contribution to the literature. More specifically, by demonstrating not only the regions affected by childhood trauma, but also in what way they are affected (e.g., increased high-frequency activations), our research provides support to previous literature in establishing and validating potential correlates for trauma-induced psychopathology and pinpointing possible regions for intervention (e.g., non-invasive brain stimulation) meant to curb the negative downstream effects of trauma (Blades et al., 2020; Colich et al., 2020; Gonda et al., 2022; Guo et al., 2013; Hu et al., 2021; Wielaard et al., 2018; Yue et al., 2015; Zhang et al., 2021).

[7] While the observed effects may be associated with late-onset depression, correlational analyses in a portion of the present sample ($n = 109$) suggest no significant relationship between observed neurobiological effects and self-reported depression (see Table 7).

Likewise, our analyses showcase the importance of trained-rater childhood trauma assessments as compared to self-reported trauma measures in identifying these types of neurobiological effects (see Section 3.7.2, for a direct comparison between the TCL and the UES, as they relate behaviorally and neurobiologically). While we found a modest association between the TCL and UES, it is possible that additional variance is accounted for by the TCL trained-rater assessment compared to the self-report UES for multiple reasons: 1) scoring of the TCL relies on multiple potential sources of information (institutional files, self-report, and clinical interviews) rather than solely self-report, 2) the self-report UES was only available for a subset of the present sample ($n = 78$), 3) the trauma categories included in the TCL (e.g., observed and community violence) may be more applicable to the sample tested (New Mexican youth) than questions included in the UES (e.g., weather disasters, etc.), and 4) while participants may experience traumatic experiences, they may not categorize such experiences as traumatic themselves (an issue that is avoided by the trained-rater TCL). The additional variance (and relationships with neurobiological measures) accounted for by the trained-rater TCL may suggest that more comprehensive trained-rater measures are more sensitive in identifying neural correlates of trauma that similar self-report measures.

4.1. Study limitations

The results of this study are presented alongside a number of limitations. While we report effects of Community Trauma (Factor 2) on aberrant functional connectivity, effects of Experienced Trauma (Factor 1) are null. One explanation of this (lack of) result, is that comparatively, Factor 1 had a much lower base rate compared to Factor 2 (see Table 3), leaving analyses potentially underpowered for detecting effects related to this specific subtype of trauma. Likewise, because our present sample is comprised of 179 juvenile males, it is unknown whether our results would generalize to females nor to individuals with childhood trauma that is less proximate (i.e., older adults, incarcerated or not, with childhood trauma).

An additional limitation of the present study is the fMRI paradigm utilized: a five-minute resting-state scan. While some research suggests that five-minutes is adequate time to ensure high stability RSNs (Allen et al., 2011a; Duda et al., 2022; Espinoza et al., 2018; Espinoza et al., 2019), others suggest longer scans are necessary (Birn et al., 2013). Likewise, though results garnered through resting-state analyses are informative in establishing correlates and potential targets for intervention, future research should consider the use of task-based scans to explore the relationship more granularly between childhood trauma, neurobiological correlates, and functional deficits. Thus, more work is needed to probe the relationships between various inter- and intra-network connectivity measures as they relate to childhood trauma (specifically, that of enacted trauma such as physical, sexual, and emotional abuse, and neglect) and perhaps longer resting-state and task-based measures in large samples of both juvenile and adult men and women.

4.2. Conclusion

This study contributes to the current literature by examining the relationships of subtypes of childhood traumas with whole brain inter- and intra- network connectivity and AFs across RSNs. We showed that childhood trauma (specifically, Community Trauma) is associated with increased high-frequency AFs, and both increased and decreased intra-network connectivity across four brain domains (AU, CC, VI, SM), associated with decision-making, self-referential thinking, and social interaction. Similar to previous research, our results suggest that childhood trauma is primarily associated with aberrant functional profiles in paralimbic regions (e.g., temporal poles and insulae), yet effects also extend to sensory domains (i.e., auditory, visual, and sensorimotor). Our results showcase childhood trauma related aberrant functional connectivities at a local (i.e., intra-network connectivity and AFs) rather than a global (i.e., inter-network connectivity) level, suggesting the benefit of alternative approaches to investigating the neurobiological correlates that may undergird trauma induced psychopathologies. To our knowledge, this represents the largest study to date on the relationships of childhood trauma and functional connectivity aberrances in incarcerated juveniles.

CRediT authorship contribution statement

Corey H. Allen: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Jenna Shold:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **J. Michael Maurer:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **Brooke L. Reynolds:** Data curation, Writing – review & editing. **Nathaniel E. Anderson:** Data curation, Methodology, Writing – review & editing. **Carla L. Harenski:** Data curation, Methodology, Writing – review & editing. **Keith A. Harenski:** Data curation, Methodology, Writing – review & editing. **Vince D. Calhoun:** Methodology, Writing – review & editing. **Kent A. Kiehl:** Data curation, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Data Availability Statement

The data presented in this article are not readily available because of the potential for personal re-identification of participants in the present sensitive population (incarcerated juveniles). Interested parties should contact Dr. Kent Kiehl (kkiehl@mrn.org) for the data used in this report which may be shared under a data use agreement.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nicl.2023.103343.

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