Archival Report

Biological Psychiatry: GOS

Transdiagnostic Symptom Domains Have Distinct Patterns of Association With Head Motion During Multimodal Imaging in Children

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ABSTRACT

BACKGROUND: It is unclear how transdiagnostic symptoms including attention, disruptive behavior, and internalizing problems are linked to in-scanner motion in children across structural and functional magnetic resonance imaging (fMRI). In the current study, we examined whether transdiagnostic symptoms of attention, disruptive behavior, and internalizing problems were associated with scanner motion in children during multimodal imaging.

METHODS: In 9045 children ages 9 to 10 years in the ABCD (Adolescent Brain Cognitive Development) Study, logistic regression and linear mixed-effects models were used to examine associations between motion and behavior. Motion was indexed using ABCD Study quality control (QC) metrics and mean framewise displacement for T1- and T2-weighted structural, resting-state, and diffusion MRI; stop-signal task; monetary incentive delay task; and emotional n-back task. The Child Behavior Checklist was used as a continuous measure of symptom severity.

RESULTS: Greater severity of attention and disruptive behavior problems was associated with a lower likelihood of passing motion QC across imaging modalities, while increased internalizing severity was associated with a higher likelihood of passing. There was also an interaction between sex and attention-related problems in passing QC for T2-weighted and diffusion MRI scans. Increased attention and disruptive behavior problems were associated with increased mean motion, whereas increased internalizing problems were associated with decreased mean motion. Greater severity of attention problems was associated with worse performance across the fMRI tasks.

CONCLUSIONS: These findings have implications for advancing the development of computational and behavioral approaches for mitigating motion effects in youths, enhancing accessibility of imaging protocols and representativeness influences across child psychiatric disorders, and identifying brain-based biomarkers.

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In cognitive developmental neuroscience research, head motion during scanning is a challenge that can have complex effects on the neural signal depending on features such as the duration, timing, and trajectory of motion (1–4). For example, head motion can affect accurate estimation of the blood oxygen level–dependent signal, potentially obscuring or impacting neural correlates of structure and function (1,5–8). Effects of motion also have the potential to obscure true effects or inflate between-group differences in functional connectivity, particularly between groups that include clinical versus unaffected samples (1,6,7,9–12). For instance, low-motion clinical groups may be more phenotypically similar to unaffected, typically developing control participants than to excluded high-motion participants, thereby reducing potential between-group differences (13). Regarding developmental effects, between-group differences in cognitive processes and neural markers attributed to age may also be exaggerated due to differences in head motion between youths of different ages (4,6,11,14–16). Despite postacquisition approaches for addressing motion—including motion correction via movement parameters entered as covariates in the general linear model (8), global signal regression (17,18), censoring or scrubbing approaches (1), and denoising (3,5,19–21)—motion-related confounds remain a concern. These confounds reduce data retention and impact the accessibility and representativeness of functional magnetic resonance imaging (fMRI) research for pediatric populations, thus hindering the development of robust and reliable brain-based biomarkers (7,15,22). Notably, most previous work on in-scanner motion in youths has focused on neuroimaging modalities including resting-state (7,11,13,23–25) and/or task-based (14,16,26–28) fMRI, with no studies to our knowledge having simultaneously examined multimodal imaging including functional and structural MRI (e.g., T1- and T2-weighted structural and diffusion MRI). Given the importance of functional as well as structural MRI for identifying brain-based biomarkers in child mental health (29–31), it is

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important to understand the impact of motion across imaging modalities in youths.

Clinical subgroups in pediatric populations may be more prone to motion during scanning and data exclusion due to co-occurring symptoms that can make all neuroimaging challenging, particularly attention, disruptive behavior, and internalizing problems. The few existing studies have shown lower scan success rates and greater motion in clinical samples that include children with autism spectrum disorder (ASD), attention-deficit/hyperactivity disorder (ADHD), and epilepsy than unaffected control participants (13,25,28,32,33) as well as effects of demographic variables such as age on motion (13,16,27,33). Studies have also shown associations between greater motion and attention-related ADHD symptoms in youths (25,28,33). However, no studies have focused on head motion linked to transdiagnostic symptom domains that commonly co-occur in child mental health conditions (i.e., attention, disruptive behavior, and internalizing problems), particularly in a large, diverse, and heterogeneous sample. It is also unclear how the distinct relationship between motion and each of the symptom severities is impacted by multimodal neuroimaging spanning functional and structural MRI. Additionally, no studies to date have simultaneously modeled transdiagnostic symptom domains to identify distinct associations with motion, particularly disruptive behavior (e.g., aggression, anger, and/or noncompliance) and internalizing (e.g., anxiety/depression) problems. It is important to note that disruptive behavior and internalizing disorders are the most prevalent psychiatric conditions for youths worldwide (34). Therefore, a priority of developmental neuroimaging is to elucidate distinct and shared neural etiologies related to these transdiagnostic symptoms (35,36).

Evaluating Associations Between In-Scanner Motion and Transdiagnostic Symptom Domains

In the current study, we examined distinct associations between commonly co-occurring transdiagnostic symptom domains of attention, disruptive behavior, and internalizing problems in youths and head motion during functional and structural MRI in the ABCD (Adolescent Brain Cognitive Development) Study (37,38). First, we tested whether transdiagnostic symptom domains were associated with passing scan quality control (QC) across imaging modalities (T1- and T2-weighted structural MRI, resting-state fMRI, task-based fMRI, and diffusion MRI) (38). The task-based fMRI scans included the stop signal task (SST), which measures inhibitory control; the monetary incentive delay (MID) task, which measures reward-based learning; and the emotional n-back (EN-back) task, which measures working memory and emotion perception (37,38). Together, these tasks engage processes and circuitry related to cognitive control (37,39–43). Associations between in-scanner motion and symptom severities were examined separately for each task. We reasoned that leveraging all available fMRI tasks in analyses would provide a nuanced understanding of distinct associations between transdiagnostic symptom domains that have commonly been linked to cognitive control dysfunction in youths and to in-scanner motion. Second, we asked whether transdiagnostic symptom domains were associated with mean head motion modeled as a continuous variable for each modality in the sample of participants who passed motion QC. To expand on previous work that has examined main effects of sex on motion (12,23,25,44), we directly tested for interactions between sex and each of the behavior domains on motion to fully understand distinct patterns of associations that may be different for girls and boys with elevated symptom severities. Given the co-occurrence and diagnostic overlap between attention, disruptive behavior, and internalizing problems in youths (45–49), we included all symptoms in a single analytical step to account for this covariance and to identify potentially distinct relationships between the behaviors and mean motion as well as passing QC.

Based on previous research investigating in-scanner motion and related symptoms of attention and disruptive behavior problems (e.g., ADHD) (12–14,23,28,32) as well as studies that have implicated these behavioral domains in difficulties with cognitive control processes engaged during ABCD Study tasks (37,50,51), we predicted that increased severity of attention-related and disruptive behavior problems would be associated with increased in-scanner motion and a decreased likelihood of passing motion QC for task and nontask sequences. To the best of our knowledge, no prior work has directly examined associations between internalizing severity and head motion; therefore, we did not have a priori directional hypotheses for this symptom domain related to task and nontask sequences. As an additional follow-up, we tested whether specific imaging modalities were differentially affected by motion.

Although previous work has examined domains of cognitive control linked to task performance in the ABCD Study (43), it remains unclear how performance is differentially associated with transdiagnostic symptom domains during each of the ABCD fMRI tasks. Therefore, as a follow-up to task-based analyses, we also tested the association between task performance and severity for each transdiagnostic symptom domain. Based on previous work that has implicated attention, disruptive behavior, and internalizing problems with broader impairments during cognitive control tasks in youths—including processes that are engaged during the SST (51–53) and the EN-back task (50,51,53,54)—we expected symptom severity across domains to be linked to reduced performance across each of these tasks, with the exception of internalizing symptoms, where the directionality of results with respect to inhibitory control was unclear (55).

METHODS AND MATERIALS

Participants

We analyzed a subset of participants from the ABCD Study (Data Release 4.0) (37), which is a multisite longitudinal study with over 11,876 children ages 9 to 10 years at baseline. The final sample included 9045 children (4408 females) with complete behavioral and imaging data available for analysis. All 9045 children were included in analyses of the effect of transdiagnostic symptom domains on passing neuroimaging QC. Only participants who passed inclusion QC were included in our subsequent analyses of the effect of transdiagnostic symptom domains on in-scanner motion (Figure 1). Participant characteristics are shown in Table 1.

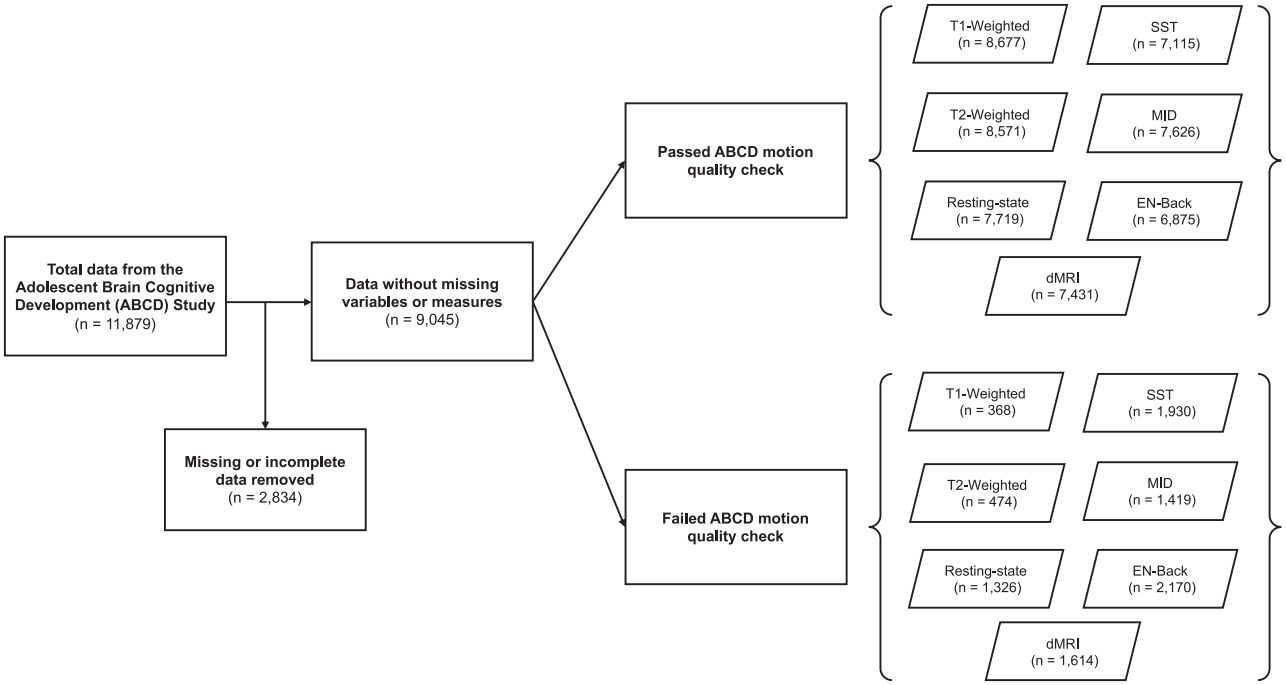

Figure 1. Flowchart illustrating data structure and participants from the ABCD (Adolescent Brain Cognitive Development) Study dataset. Analyses were conducted for each of the imaging modalities: T1- and T2-weighted structural magnetic resonance imaging (MRI), resting-state functional MRI, diffusion MRI (dMRI), stop signal task (SST), monetary incentive delay (MID) task, and the emotional version of the n-back task (EN-back).

Behavioral Measures

We used a broadband continuous measure of symptoms related to child mental health, the parent-rated Child Behavior Checklist (CBCL) subscales of Attention, Externalizing, and Internalizing Problems (56), which were selected to allow comparison with previous imaging studies that used the ABCD dataset (39,57–60). Participants completed cognitive assessments including the NIH Toolbox Cognition Battery (61), and the age-corrected total composite score was used in analyses. Additional details for behavioral measures are provided in Supplemental Methods.

ABCD Study: Imaging Data and Processing

The design and imaging protocol of the ABCD Study has been described in previous work (37,38) and in Supplemental Methods. Details of ABCD Study recruitment (62), neurocognitive batteries (63), and imaging protocols (38) are also available elsewhere. The released imaging data (T1- and T2-weighted structural MRI, diffusion MRI, and resting-state and task-based fMRI) were processed through ABCD's Data Analysis, Informatics and Resource Center (DAIRC) image processing pipeline (38). Mean framewise displacement (FD) (1), a commonly used metric of head motion, was used for linear mixed-effects analyses to predict motion as a continuous variable. Additional details are provided in Supplemental Methods for study inclusion flags and QC criteria by imaging modality as well as in Table S1.

Statistical Analysis

Details on assumption testing, handling of missing data, and assessment of multicollinearity (64) (Figure 2) are provided in Supplemental Methods.

Logistic Regression Models. The total sample (N = 9045) was partitioned into 2 subgroups of participants who passed and failed QC for each imaging modality (see Table 1 and Figure 1 for subgroup sample sizes). Then, we applied logistic regression models in R (via glmer) to test whether transdiagnostic symptom domains (CBCL Attention, Externalizing, and Internalizing Problems subscales) were associated with passing versus failing scan QC, modeled as a binary dependent variable (1 = pass, 0 = fail) based on ABCD DAIRC inclusion variables for each imaging modality (Figure 1). We fitted logistic regression models for each of the 7 imaging modalities: T1- and T2-weighted structural MRI, resting-state MRI, diffusion MRI, and task fMRI (SST and MID and EN-back tasks). All models included the following independent variables: age, sex assigned at birth, race/ethnicity, cognitive performance, and symptom domains (CBCL Attention, Externalizing, and Internalizing Problems scores). Random intercepts were included for study site, scanner manufacturer (using the variable mri_info_manufacturers), and family (i.e., having a sibling in the study) nested within the site. Thus, the logistic regression analyses used the following model:

Table 1. Participant Demographics and Characteristics

Variable	Total, N = 9045	T1-Weighted MRI			T2-Weighted MRI			Resting-State fMRI			Diffusion MRI			SST			MID Task			EN-Back Task		
		Pass QC, n = 8677	Fail QC, n = 368	p[a]	Pass QC, n = 8571	Fail QC, n = 474	p[a]	Pass QC, n = 7719	Fail QC, n = 1326	p[a]	Pass QC, n = 7431	Fail QC, n = 1614	p[a]	Pass QC, n = 7115	Fail QC, n = 1930	p[a]	Pass QC, n = 7626	Fail QC, n = 1419	p[a]	Pass QC, n = 6875	Fail QC, n = 2170	p[a]
Age, Years	9.9 (7.5)	9.9 (7.5)	9.8 (7.3)	.001	9.93 (7.5)	9.81 (7.3)	3.87×10^{-5}	9.9 (7.5)	9.8 (7.2)	1.27×10^{-13}	9.9 (7.5)	9.9 (7.4)	.043	9.9 (7.5)	9.9 (7.4)	1.57×10^{-8}	9.9 (7.5)	9.9 (7.4)	.0654	10.0 (7.5)	9.8 (7.3)	4.18×10^{-23}
Sex, Male	51.3%	51.1%	54.6%	.207	51.1%	54.4%	.171	49.6%	61.1%	1.21×10^{-14}	50.9%	52.9%	.168	50.8%	53.1%	.0802	50.2%	56.8%	6.37×10^{-6}	51.3%	51.1%	.884
Race/Ethnicity																						
Asian	2.1%	2.1%	3.0%	.312	20.3%	18.8%	.452	2.0%	2.6%	.179	1.9%	2.9%	.018	2.2%	1.9	.0177	2.0%	2.6%	.189	2.2%	1.8%	.362
Black	13.1%	13.0%	16.6%	.055	12.8%	18.8%	2.46×10^{-4}	12.5%	16.6%	6.6×10^{-5}	13.6%	11.2%	.011	11.6%	18.8	.0105	12.4%	16.8%	8.14×10^{-6}	10.7%	20.7%	3.99×10^{-33}
Hispanic	20.2%	20.3%	19.8%	.899	10.2%	13.7%	.0167	20.2%	20.4%	.869	20.1%	20.7%	.635	20.0%	21.2%	.635	20.6%	18.1%	.0332	19.2%	23.5%	1.57×10^{-5}
Other	10.4%	10.2%	14.1%	.019	2.1%	3.2%	.140	10.2%	11.4%	.195	10.4%	10.2%	.82	9.8%	12.3	.82	10.1%	11.7%	.0766	10.1%	11.2%	.126
White	54.2%	54.5%	46.5%	.003	54.7%	45.6%	1.36×10^{-4}	55.1%	48.9%	4×10^{-5}	54.0%	55.1%	.436	56.4%	45.8	.436	54.8%	50.7%	.0051	57.8%	42.7%	8.16×10^{-35}
Cognition[b]	101.4 (17.5)	101.5 (17.5)	98.5 (17.7)	.001	101.6 (17.5)	97.5 (17.5)	0	102.1 (17.5)	97.6 (17.6)	3.55×10^{-17}	101.3 (17.4)	102.0 (18.3)	.146	102.7 (17.3)	96.6 (17.6)	1.96×10^{-40}	101.8 (17.4)	99.2 (18.4)	5.18×10^{-7}	103.8 (16.9)	93.8 (17.5)	1.12×10^{-112}
CBCL Attention	2.8 (3.4)	2.8 (3.4)	3.4 (3.6)	.003	2.8 (3.4)	3.4 (3.6)	0	2.7 (3.3)	3.5 (3.7)	3.19×10^{-14}	2.8 (3.4)	2.8 (3.3)	.541	2.7 (3.3)	3.5 (3.8)	1.13×10^{-16}	2.8 (3.4)	3.2 (3.5)	.0001	2.7 (3.3)	3.4 (3.7)	7.38×10^{-17}
CBCL Externalizing	4.3 (5.7)	4.3 (5.7)	4.3 (5.5)	.947	4.3 (5.7)	4.5 (5.7)	.36	4.1 (5.5)	5.0 (6.5)	3.25×10^{-6}	4.3 (5.7)	4.0 (5.3)	.038	4.0 (5.4)	5.1 (6.5)	2.48×10^{-10}	4.2 (5.6)	4.6 (6.1)	.009	4.0 (5.4)	5.0 (6.4)	3.63×10^{-11}
CBCL Internalizing	5.0 (5.5)	5.0 (5.5)	4.8 (5.5)	.526	4.9 (5.5)	4.9 (5.6)	.65	4.9 (5.4)	5.3 (5.8)	.0285	5.0 (5.5)	4.7 (5.3)	.027	4.9 (5.4)	5.2 (5.8)	.0619	4.9 (5.4)	5.1 (5.6)	.292	4.9 (5.3)	5.2 (5.9)	.0498
FD, mm	–	–	–	–	–	–	–	0.3 (0.24)	0.9 (0.79)	2.57×10^{-133}	1.3 (0.48)	1.6 (0.88)	1×10^{-44}	0.4 (0.40)	0.7 (0.95)	3.92×10^{-42}	0.4 (0.36)	0.6 (0.82)	2.08×10^{-20}	0.4 (0.4)	0.8 (0.95)	3.58×10^{-53}

Values are presented and mean (SD) or %. QC is based on the ABCD (Adolescent Brain Cognitive Development) Study protocol procedures (37,38).

CBCL, Child Behavior Checklist; EN-back, emotional n-back; FD, framewise displacement; fMRI, functional magnetic resonance imaging; MID, monetary incentive delay; QC, quality control; SST, stop signal task.

[a]Significant group differences at $p < .05$ using χ^2 tests for categorical variables or independent samples t test for continuous variables.

[b]General cognition measured by the NIH Toolbox (61).

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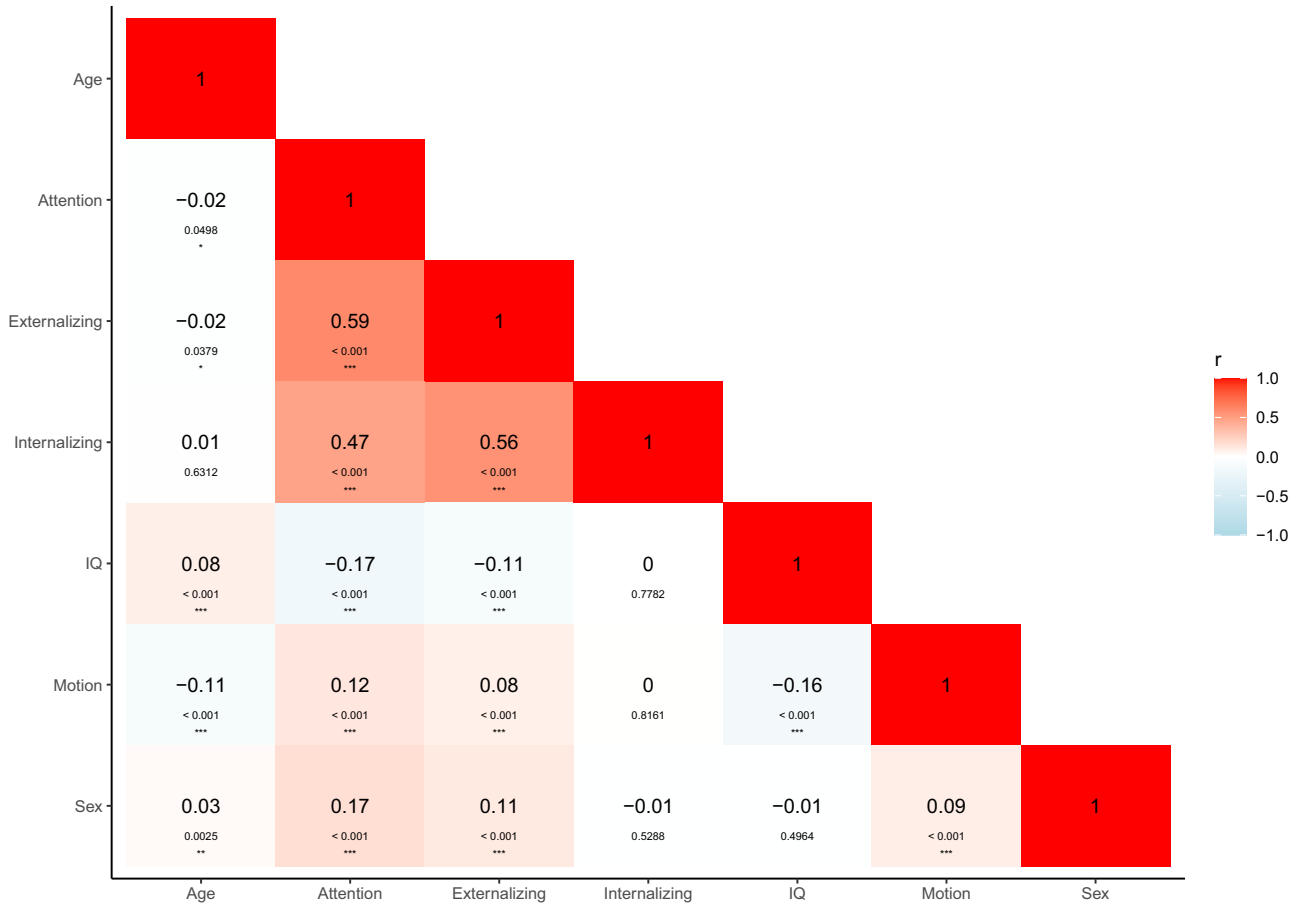

Figure 2. Correlations among study variables. Pearson correlations and significance values are shown for age, Child Behavior Checklist scales (Attention, Externalizing, and Internalizing Problems subscale scores), cognition (IQ), motion indexed by mean framewise displacement (mm), and sex assigned at birth. The matrix values indicate the correlation coefficient (top) and the corresponding *p* values (bottom). The strength and direction of the correlations are color coded, with red representing positive correlations and blue representing negative correlations. Statistically significant correlations are denoted by asterisks: **p* < .05, ***p* < .01, ****p* < .001.

$$\begin{aligned} y \sim\ & \text{age} + \text{sex} + \text{race/ethnicity} + \text{cognition} \\ & + \text{CBCL Attention Problems} \\ & + \text{CBCL Externalizing Problems} \\ & + \text{CBCL Internalizing Problems, random} \\ & = 1 \mid \text{site/scanner} + 1 \mid \text{family} \end{aligned} \quad (1)$$

As follow-up supplemental analyses, logistic regression models were repeated with an interaction term for sex with each behavioral domain (i.e., sex × CBCL Attention Problems, sex × CBCL Externalizing Problems, and sex × CBCL Internalizing Problems). All results and final *p* values were then false discovery rate (FDR) corrected across all tests. To facilitate interpretation of results and effect sizes, odds ratios were calculated for each variable across each scanning series or imaging modality.

Linear Mixed-Effects Models. In the sample of participants who passed ABCD QC (*n* = 7300), we then applied linear mixed-effects models in R (via lmer) to test the association between transdiagnostic domains of behavior and motion modeled as a continuous variable using mean FD as the dependent variable. We fitted linear mixed-effects models for each of the 5 relevant imaging modalities with mean FD: resting-state, diffusion MRI, and task fMRI (SST and MID and EN-back tasks). All models included the same independent variables for fixed and random effects described in the Logistic Regression Models section. Thus, the linear mixed-effects model analyses used the following model:

$$\begin{aligned} y \sim\ & \text{age} + \text{sex} + \text{race/ethnicity} + \text{cognition} \\ & + \text{CBCL Attention Problems} \\ & + \text{CBCL Externalizing Problems} \\ & + \text{CBCL Internalizing Problems, random} \\ & = 1 \mid \text{site/scanner} + 1 \mid \text{family} \end{aligned} \quad (2)$$

As follow-up supplemental analyses, linear mixed-effects models were repeated as above with an interaction term for sex with each behavioral domain. All results and final *p* values

were FDR corrected across all tests. To facilitate the interpretation of results and effect sizes, we calculated semipartial R^2 for the linear mixed-effects models using the partR2 package in R (65). This metric quantifies the unique proportion of variance explained by each fixed-effect predictor, thereby providing an intuitive measure of effect size (66–69).

Supplemental Analyses of Task Performance. Detailed descriptions of fMRI tasks can be found in the Supplemental Methods. For comparison with previous ABCD studies, we used the stop signal reaction time as a performance measure for SST, the average amount earned across task runs for the MID task (43), and participants' average accuracy for each of the 2 memory load conditions: 0- and 2-back for the EN-back tasks (43,51,70). For consistency with linear mixed-effects models, we included children who passed ABCD QC (n = 7114 for SST, n = 7602 for MID, and n = 6872 for EN-back tasks). The identical linear mixed-effects models from primary analyses with independent variables and random intercepts were used (see Linear Mixed-Effects Models) to test the association between symptom domains and performance for each task as well as interactions between sex and behavior. Full details for the task performance analyses are provided in the Supplemental Methods.

RESULTS

Transdiagnostic Domains of Behavior and Imaging QC

Increased severity of attention problems was linked to a decrease in odds or lower likelihood of passing motion quality checks for the T1-weighted scan (25.7% decrease, p_{FDR} = .0002), T2-weighted scan (23.7% decrease, $p_{FDR} = 1.86 \times 10^{-4}$), resting-state (20.2% decrease, $p_{FDR} = 5.47 \times 10^{-7}$), diffusion MRI (19.6% decrease, $p = 8.27 \times 10^{-4}$), and SST (15.4% decrease, $p_{FDR} = 2.13 \times 10^{-5}$) (Table 2). Effects for the MID and EN-back tasks were less pronounced, with 9.1% (p_{FDR} = .0462) and 9.7% (p_{FDR} = .012) decreases in odds, respectively. Increased internalizing problem severity was linked to a 10% increase (p = .019) in the likelihood of passing motion QC during SST, while increased disruptive behavior problem severity was linked to a 9.5% decrease (p_{FDR} = .018) in the likelihood of passing motion QC during the EN-back task. Details regarding the associations between motion and demographic variables (Table 2) are provided in the Supplemental Results: Associations with Demographic Variables.

Interactions with Sex and Symptom Domains. Significant sex interaction effects were observed for T2-weighted and diffusion MRI wherein males with attention problems had 28.1% (p_{FDR} = .0494) and 28.7% (p_{FDR} = .023) lower odds of passing the motion quality check than girls with attention problems, respectively (Table S2).

Transdiagnostic Domains of Behavior and In-Scanner Motion

Regarding attention-related problems, greater severity of attention problems was significantly associated with increased motion across all imaging modalities (all $ps < .01$) (Table 3 and Figure 3). Regarding disruptive behavior and internalizing symptoms, increased severity of disruptive behavior problems was significantly associated with increased motion during resting-state (p_{FDR} = .004) and the EN-back task (p_{FDR} = .022), while increased internalizing problem severity was associated with decreased motion during resting-state ($p = 5.01 \times 10^{-5}$) and the EN-back task (p_{FDR} = .004) (Table 3 and Figure 3). Additional details regarding unit increases of motion associated with symptom domains are provided in the Supplemental Results. Details regarding the association between motion and demographic variables (Table 3) are provided in the Supplemental Results: Associations with Demographic Variables.

Interactions with Sex and Symptom Domains. There were no significant sex × behavior interactions across imaging modalities (Table S3, Figure S1).

Follow-Up Supplemental Analyses for Scanner and Session

Analyses Restricted to Siemens and GE Scanners. We also conducted follow-up analyses to assess whether motion-related image degradation for structural MRI scans was impacted by Siemens and GE scanners that implement prospective motion correction. Restricting analyses to Siemens and GE scanners revealed a highly similar pattern of results as the primary models (Tables 2 and 3). These findings are provided in the Supplemental Results and Tables S4 and S5.

Siemens As a Proxy for FIRMM. We restricted analyses to Siemens scanners as an approximation for FIRMM implementation (37,38). Participants who completed the sessions in Siemens scanners were more likely to pass motion QC than participants who completed the sessions in non-Siemens scanners. These findings are provided in the Supplemental Results and Table S7.

Number of Scanning Sessions. The association between the number of scanning sessions and mean motion was also explored. Linear mixed-effects models showed that having 2 scanning sessions versus 1 was associated with lower mean motion for all tasks (all $ps < .04$). No significant effects of scan sessions were observed for other sequences. These results are provided in the Supplemental Results and Table S6.

Follow-Up Supplemental Analyses of QC and In-Scanner Motion Across Imaging Modalities

There were significant differences in QC pass rates across the imaging modalities ($p < 2 \times 10^{-16}$): T1 > T2 > resting-state = MID > diffusion MRI > SST > EN-back (Figure S3 and Supplemental Results). There were also significant differences in mean FD across the imaging modalities ($p < 2 \times 10^{-16}$): diffusion MRI > SST > EN-back > MID > resting-state (Figure S4 and Supplemental Results).

Supplemental Analyses of Task Performance. Greater severity of attention problems was significantly associated with worse performance indexed by slower reaction time on

Table 2. Results of Logistic Regression Models Predicting Scan Quality Control and Domains of Transdiagnostic Symptoms

Variables	Estimate	Standard Error	*z*	*p*	p_{FDR}	OR	95% CI	
							2.5%	97.5%
T1-Weighted MRI								
Intercept	1.65	0.942	1.75	.0805	.159	5.19	0.819	32.8
Age	0.012	0.00725	1.7	.0899	.173	1.01	0.998	1.03
Sex	−0.098	0.11	−0.894	.371	.501	0.907	0.731	1.12
Race/Ethnicity								
Asian	0.073	0.163	0.449	.653	.709	1.08	0.782	1.48
Black	−0.223	0.171	−1.3	.193	.309	0.8	0.572	1.12
Hispanic	−0.098	0.169	−0.578	.563	.667	0.907	0.65	1.26
Other	−0.376	0.332	−1.13	.257	.396	0.687	0.358	1.32
Cognition	0.007	0.00338	1.99	.0463	.108	1.01	1	1.01
CBCL Attention	−0.297	0.0725	−4.1	4.19×10^{-5}	.000233	0.743	0.645	0.856
CBCL Externalizing	0.136	0.0717	1.89	.0584	.125	1.15	0.995	1.32
CBCL Internalizing	0.112	0.067	1.68	.0934	.175	1.12	0.981	1.28
T2-Weighted MRI								
Intercept	0.292	0.842	0.348	.728	.768	1.34	0.257	6.97
Age	0.018	0.0065	2.74	.00622	.0199	1.02	1.01	1.03
Sex	−0.089	0.0976	−0.91	.363	.501	0.915	0.756	1.11
Race/Ethnicity								
Asian	0.023	0.148	0.154	.878	.889	1.02	0.765	1.37
Black	−0.288	0.149	−1.94	.0528	.116	0.75	0.561	1
Hispanic	−0.155	0.153	−1.01	.311	.46	0.856	0.635	1.16
Other	−0.577	0.289	−1.99	.0461	.108	0.562	0.318	0.99
Cognition	0.01	0.00305	3.13	.00172	.00699	1.01	1	1.02
CBCL Attention	−0.271	0.0645	−4.2	2.66×10^{-5}	.000186	0.763	0.672	0.865
CBCL Externalizing	0.089	0.064	1.38	.166	.273	1.09	0.964	1.24
CBCL Internalizing	0.12	0.0594	2.01	.0442	.108	1.13	1	1.27
Resting-State fMRI								
Intercept	−2.24	0.546	−4.09	4.24×10^{-5}	.000233	0.107	0.0367	0.312
Age	0.027	0.00426	6.34	2.28×10^{-10}	2.93×10^{-9}	1.03	1.02	1.04
Sex	−0.449	0.0645	−6.96	3.45×10^{-12}	5.32×10^{-11}	0.638	0.563	0.725
Race/Ethnicity								
Asian	−0.079	0.0955	−0.83	.406	.527	0.924	0.766	1.11
Black	−0.068	0.101	−0.678	.498	.615	0.934	0.767	1.14
Hispanic	−0.08	0.105	−0.764	.445	.561	0.923	0.751	1.13
Other	−0.433	0.206	−2.1	.0357	.0949	0.649	0.433	0.972
Cognition	0.012	0.00201	6	1.92×10^{-9}	2.11×10^{-8}	1.01	1.01	1.02
CBCL Attention	−0.226	0.0416	−5.43	5.68×10^{-8}	5.47×10^{-7}	0.798	0.736	0.866
CBCL Externalizing	0.013	0.042	0.309	.757	.786	1.01	0.933	1.1
CBCL Internalizing	0.025	0.0388	0.645	.519	.624	1.02	0.95	1.11
Diffusion MRI								
Intercept	0.016	1.04	0.0152	.988	.988	1.02	0.132	7.84
Age	0.009	0.00588	1.55	.12	.215	1.01	0.998	1.02
Sex	−0.123	0.0891	−1.39	.166	.273	0.884	0.742	1.05
Race/Ethnicity								
Asian	0.145	0.131	1.1	.27	.407	1.16	0.894	1.5
Black	−0.054	0.144	−0.376	.707	.756	0.947	0.715	1.26
Hispanic	−0.068	0.136	−0.496	.62	.697	0.934	0.716	1.22
Other	−0.238	0.27	−0.882	.378	.501	0.788	0.464	1.34
Cognition	0.004	0.00271	1.44	.151	.258	1	0.999	1.01
CBCL Attention	−0.218	0.0583	−3.74	.000183	.000827	0.804	0.717	0.901
CBCL Externalizing	0.069	0.0585	1.17	.241	.379	1.07	0.955	1.2
CBCL Internalizing	0.045	0.0546	0.823	.41	.527	1.05	0.94	1.16

Table 2. Continued

Variables	Estimate	Standard Error	*z*	*p*	p_{FDR}	OR	95% CI 2.5%	95% CI 97.5%
SST								
Intercept	−1.85	0.463	−3.99	6.47×10^{-5}	.000332	0.157	0.0633	0.389
Age	0.014	0.00362	3.9	9.77×10^{-5}	.00047	1.01	1.01	1.02
Sex	−0.036	0.0544	−0.67	.503	.615	0.965	0.867	1.07
Race/Ethnicity								
Asian	−0.039	0.0806	−0.482	.63	.697	0.962	0.821	1.13
Black	−0.244	0.0849	−2.88	.004	.0147	0.783	0.663	0.925
Hispanic	−0.217	0.0886	−2.45	.0141	.0435	0.805	0.676	0.957
Other	−0.098	0.196	−0.5	.617	.697	0.907	0.618	1.33
Cognition	0.016	0.00175	9.21	3.19×10^{-20}	8.18×10^{-19}	1.02	1.01	1.02
CBCL Attention	−0.167	0.0354	−4.71	2.48×10^{-6}	2.13×10^{-5}	0.846	0.79	0.907
CBCL Externalizing	−0.077	0.0363	−2.11	.0347	.0949	0.926	0.863	0.994
CBCL Internalizing	0.092	0.0334	2.77	.00561	.0188	1.1	1.03	1.17
MID Task								
Intercept	0.752	0.511	1.47	.141	.247	2.12	0.779	5.77
Age	0.004	0.004	0.909	.364	.501	1	0.996	1.01
Sex	−0.25	0.0608	−4.12	3.87×10^{-5}	.000233	0.779	0.691	0.877
Race/Ethnicity								
Asian	0.187	0.0922	2.03	.0428	.108	1.21	1.01	1.44
Black	−0.17	0.0955	−1.78	.0748	.155	0.844	0.699	1.02
Hispanic	−0.056	0.0991	−0.565	.572	.667	0.946	0.779	1.15
Other	−0.316	0.197	−1.6	.11	.201	0.729	0.495	1.07
Cognition	0.007	0.00188	3.66	.000256	.0011	1.01	1	1.01
CBCL Attention	−0.095	0.0392	−2.42	.0156	.0462	0.909	0.842	0.982
CBCL Externalizing	−0.012	0.0402	−0.298	.766	.786	0.988	0.913	1.07
CBCL Internalizing	0.018	0.0371	0.477	.633	.697	1.02	0.946	1.09
EN-Back Task								
Intercept	−5.18	0.467	−11.1	1.2×10^{-28}	4.64×10^{-27}	0.006	0.00225	0.014
Age	0.028	0.00359	7.72	1.19×10^{-14}	2.28×10^{-13}	1.03	1.02	1.04
Sex	0.048	0.0533	0.902	.367	.501	1.05	0.945	1.16
Race/Ethnicty								
Asian	−0.168	0.0777	−2.16	.031	.0884	0.845	0.726	0.985
Black	−0.358	0.0825	−4.34	1.46×10^{-5}	.000112	0.699	0.595	0.822
Hispanic	−0.157	0.0889	−1.77	.0767	.155	0.855	0.718	1.02
Other	−0.192	0.194	−0.988	.323	.469	0.825	0.564	1.21
Cognition	0.032	0.00184	17.2	3.24×10^{-66}	2.5×10^{-64}	1.03	1.03	1.04
CBCL Attention	−0.102	0.0346	−2.96	.00305	.0117	0.903	0.843	0.966
CBCL Externalizing	−0.1	0.0357	−2.8	.00506	.0177	0.905	0.844	0.97
CBCL Internalizing	0.064	0.0327	1.95	.0506	.115	1.07	1	1.14

General cognition was measured by the NIH Toolbox age corrected scores (61). ORs are reported relative to the reference group in the case of categorical variables. ORs > 1 indicate increased likelihood of passing quality control among the nonreference group relative to the reference group (i.e., lower likelihood of passing quality control in the reference group), while ORs < 1 indicate decreased likelihood of passing quality control. For continuous measures, the ORs represent the change in odds per unit change in the measure.

CBCL, Child Behavior Checklist; EN-back, emotional n-back; FDR, false discovery rate; fMRI, functional magnetic resonance imaging; MID, monetary incentive delay; OR, odds ratio; SST, stop signal task.

SST (all $p_{FDR} < .001$), less average earnings for the MID task (all $p_{FDR} < .05$), and lower percentage correct for the 0-back ($p_{FDR} < .05$) and 2-back ($p_{FDR} < .001$) blocks of the EN-back task (Table 4 and Figure 4). For internalizing problems, greater symptom severity was significantly associated with better performance on SST ($p_{FDR} < .05$). No significant associations were observed between disruptive behavior problems and task performance (all $ps > .1$). There was also a significant sex × CBCL Attention Problems interaction for the MID task ($p_{FDR} < .05$) wherein females with increased attention-related

Table 3. Results of Linear Mixed-Effects Models Predicting Motion and Domains of Transdiagnostic Symptoms

Variables	Estimate	Standard Error	Semipartial R^2	t	p	p_{FDR}	95% CI	
							2.5%	97.5%
Resting-State fMRI								
Intercept	0.824	0.0462	–	17.8	1.22×10^{-68}	6.69×10^{-67}	0.733	0.914
Age	−0.00335	0.000359	0.0111	−9.35	1.09×10^{-20}	9.99×10^{-20}	−0.00406	−0.00265
Sex	0.0279	0.00544	0.00307	5.13	2.9×10^{-7}	7.6×10^{-7}	0.0173	0.0386
Race/Ethnicity								
Asian	0.029	0.0197	0.00975	1.47	.142	.163	−0.00971	0.0677
Black	0.0505	0.00933		5.41	6.58×10^{-8}	1.9×10^{-7}	0.0322	0.0688
Hispanic	0.0514	0.00821		6.26	4.03×10^{-10}	1.39×10^{-9}	0.0353	0.0675
Other	0.0215	0.00932		2.3	.0213	.0285	0.00321	0.0398
Cognition	−0.00131	0.000168	0.00745	−7.82	6.05×10^{-15}	2.77×10^{-14}	−0.00164	−0.000985
CBCL Attention	0.0167	0.0035	0.00297	4.78	1.79×10^{-6}	3.94×10^{-6}	0.00985	0.0236
CBCL Externalizing	0.0113	0.00366	0.00115	3.08	.0021	.00369	0.00408	0.0184
CBCL Internalizing	−0.0143	0.00338	0.002	−4.22	2.46×10^{-5}	5.01×10^{-5}	−0.0209	−0.00765
Diffusion MRI								
Intercept	1.71	0.106	–	16.2	1.66×10^{-20}	1.31×10^{-19}	1.51	1.92
Age	−0.00191	0.000699	0.000773	−2.73	.00628	.00934	−0.00328	−0.00054
Sex	0.00764	0.0106	4.15×10^{-5}	0.719	.472	.490	−0.0132	0.0285
Race/Ethnicity								
Asian	0.0616	0.0396	0.00227	1.56	.12	.143	−0.016	0.139
Black	0.0605	0.0179		3.37	.000749	.00137	0.0253	0.0956
Hispanic	0.0455	0.0161		2.82	.00476	.00727	0.0139	0.0771
Other	0.0291	0.0182		1.6	.109	.135	−0.0065	0.0647
Cognition	−0.0018	0.000331	0.00278	−5.44	5.6×10^{-8}	1.71×10^{-7}	−0.00245	−0.00115
CBCL Attention	0.0182	0.00678	0.000729	2.68	.00732	.0106	0.0049	0.0315
CBCL Externalizing	0.00227	0.0071	1.04×10^{-5}	0.32	.749	.763	−0.0116	0.0162
CBCL Internalizing	−0.00998	0.00657	0.000198	−1.52	.129	.15	−0.0229	0.00289
SST								
Intercept	1.1	0.0794	–	13.8	2.5×10^{-42}	3.43×10^{-41}	0.94	1.25
Age	−0.00401	0.000619	0.00582	−6.48	9.54×10^{-11}	3.5×10^{-10}	−0.00523	−0.0028
Sex	0.054	0.00941	0.0043	5.73	1.03×10^{-8}	3.33×10^{-8}	0.0355	0.0724
Race/Ethnicity								
Asian	0.00728	0.033	0.00427	0.221	.825	.825	−0.0573	0.0719
Black	0.0489	0.0165		2.96	.00306	.0048	0.0165	0.0812
Hispanic	0.0557	0.0142		3.91	9.29×10^{-5}	.000176	0.0278	0.0835
Other	0.039	0.0164		2.38	.0173	.0238	0.00688	0.071
Cognition	−0.0024	0.000291	0.00901	−8.22	2.46×10^{-16}	1.23×10^{-15}	−0.00297	−0.00182
CBCL Attention	0.0183	0.00599	0.00129	3.06	.00221	.00369	0.0066	0.0301
CBCL Externalizing	0.0107	0.00627	0.000412	1.7	.0889	.114	−0.00162	0.023
CBCL Internalizing	−0.00678	0.00582	0.000129	−1.16	.244	.264	−0.0182	0.00463
MID Task								
Intercept	1.16	0.0693	–	16.7	3.99×10^{-61}	1.1×10^{-59}	1.02	1.3
Age	−0.0047	0.000543	0.00961	−8.66	5.94×10^{-18}	3.63×10^{-17}	−0.00576	−0.00363
Sex	0.07	0.00824	0.00856	8.5	2.34×10^{-17}	1.28×10^{-16}	0.0538	0.0861
Race/Ethnicity								
Asian	−0.0217	0.0298	0.00719	−0.727	.467	.490	−0.0802	0.0368
Black	0.0677	0.0142		4.78	1.77×10^{-6}	3.94×10^{-6}	0.04	0.0955
Hispanic	0.0606	0.0123		4.92	8.81×10^{-7}	2.11×10^{-6}	0.0365	0.0847
Other	0.0247	0.0141		1.75	.0808	.106	−0.00302	0.0524
Cognition	−0.00252	0.000256	0.012	−9.86	8.91×10^{-23}	9.8×10^{-22}	−0.00302	−0.00202
CBCL Attention	0.0282	0.00528	0.00367	5.35	9.21×10^{-8}	2.53×10^{-7}	0.0179	0.0386
CBCL Externalizing	0.00789	0.0055	0.000264	1.43	.151	.170	−0.00289	0.0187
CBCL Internalizing	−0.00814	0.0051	0.000236	−1.6	.11	.135	−0.0181	0.00186

Table 3. Continued

Variables	Estimate	Standard Error	Semipartial R^2	t	p	p_{FDR}	95% CI 2.5%	95% CI 97.5%
EN-Back Task								
Intercept	1.19	0.081	–	14.7	8.1×10^{-48}	1.48×10^{-46}	1.03	1.35
Age	−0.00451	0.000629	0.00715	−7.17	8.41×10^{-13}	3.3×10^{-12}	−0.00574	−0.00327
Sex	0.0745	0.00966	0.00809	7.71	1.47×10^{-14}	6.24×10^{-14}	0.0555	0.0934
Race/Ethnicity								
Asian	0.0457	0.0336	0.00727	1.36	.174	.191	−0.0202	0.112
Black	0.0695	0.0172		4.03	5.64×10^{-5}	.000111	0.0357	0.103
Hispanic	0.0737	0.0147		5.02	5.3×10^{-7}	1.33×10^{-6}	0.0449	0.102
Other	0.05	0.0166		3	.00267	.00432	0.0174	0.0826
Cognition	−0.00267	0.000301	0.0106	−8.87	9.07×10^{-19}	6.23×10^{-18}	−0.00326	−0.00208
CBCL Attention	0.0286	0.00613	0.00305	4.67	3.06×10^{-6}	6.47×10^{-6}	0.0166	0.0407
CBCL Externalizing	0.0155	0.00642	0.000798	2.42	.0156	.022	0.00295	0.0281
CBCL Internalizing	−0.0183	0.00596	0.00106	−3.07	.00217	.00369	−0.0299	−0.0066

General cognition was measured by the NIH Toolbox age corrected scores (61). The intercept does not have a semipartial R^2 value because it represents the baseline level of the dependent variable when all fixed-effect predictors are set to 0. Unlike predictors, the intercept does not contribute to explaining variance in the outcome.

CBCL, Child Behavior Checklist; EN-back, emotional n-back; FDR, false discovery rate; fMRI, functional magnetic resonance imaging; MID, monetary incentive delay; SST, stop signal task.

problems showed better performance (i.e., mean amount of earnings) than males with increased attention-related problems (Supplemental Results; Table S10 and Figure S5).

DISCUSSION

In the current study, we examined the relationships between transdiagnostic symptom domains and head motion during multimodal neuroimaging in children. Four main findings emerged. First, greater attentional and disruptive behavior problems in youths were linked to greater in-scanner motion and reduced likelihood of passing motion QC. Second, greater internalizing problems were associated with reduced in-scanner motion and greater likelihood of passing motion QC across imaging modalities. Third, severity of transdiagnostic symptoms was differentially related to behavioral performance across the fMRI tasks. Fourth, we observed a sex × attention problems interaction in QC for diffusion MRI. To address limitations of previous research, in the current study, we leveraged a diverse sample from the ABCD Study, a relatively young school-age group, and to our knowledge the largest sample to understand distinct effects of prevalent and commonly co-occurring transdiagnostic domains on motion-behavior associations and the moderating role of sex during multimodal neuroimaging in youths. For the first time, in this study, we also examined the relationship between transdiagnostic symptoms and behavioral performance for each fMRI task. Overall, findings suggest that severity of transdiagnostic symptom domains are distinctly linked to motion in youths.

Transdiagnostic Symptom Domains and Imaging QC

Distinct associations were observed between transdiagnostic symptom domains and passing motion QC. Children with increased attention-related difficulties had a significantly lower likelihood of passing motion QC across all neuroimaging modalities. Additionally, increased severity of disruptive behavior problems was associated with a decrease (9.4%) in the likelihood of passing motion QC during the EN-back task. These findings are consistent with previous results that have indicated that increased attention- and externalizing-related problems may impact scanning for youths with a greater likelihood of motion and artifact, thereby impacting data retention (28). These findings are also consistent with work suggesting that youths with elevated attention and disruptive problems are more prone to scanner movement than unaffected control youths (23,71,72). Similar findings of motion-behavior associations have also been reported in studies that have compared children with neurodevelopmental conditions, including children with ASD and ADHD, with neurotypical control children (10,44). Previous work suggests that head motion tends to be lower when youths are actively engaged in cognitive and/or language tasks (16,23), while other studies have reported greater motion during demanding cognitive control tasks (14,25,44). Exploratory analyses also indicated differences in odds ratios for passing QC across nontask and task neuroimaging modalities, which may suggest an impact of task engagement on in-scanner motion susceptibility during initial QC assessments (Supplemental Results: Differences in Odds Ratios for Quality Control and Attention-Related Problem Severity). In terms of sex interactions with motion-behavior associations, male youths with increased attention problems showed a decreased likelihood of passing motion QC for T2-weighted and diffusion MRI versus females with increased attention problems, which extends previous findings of main effects of sex on motion (10,12,16,23,44) (see Supplemental Discussion).

We also observed that increased internalizing problem severity was linked to an increase (10%) in the likelihood of passing motion QC during SST. Related to this, supplemental

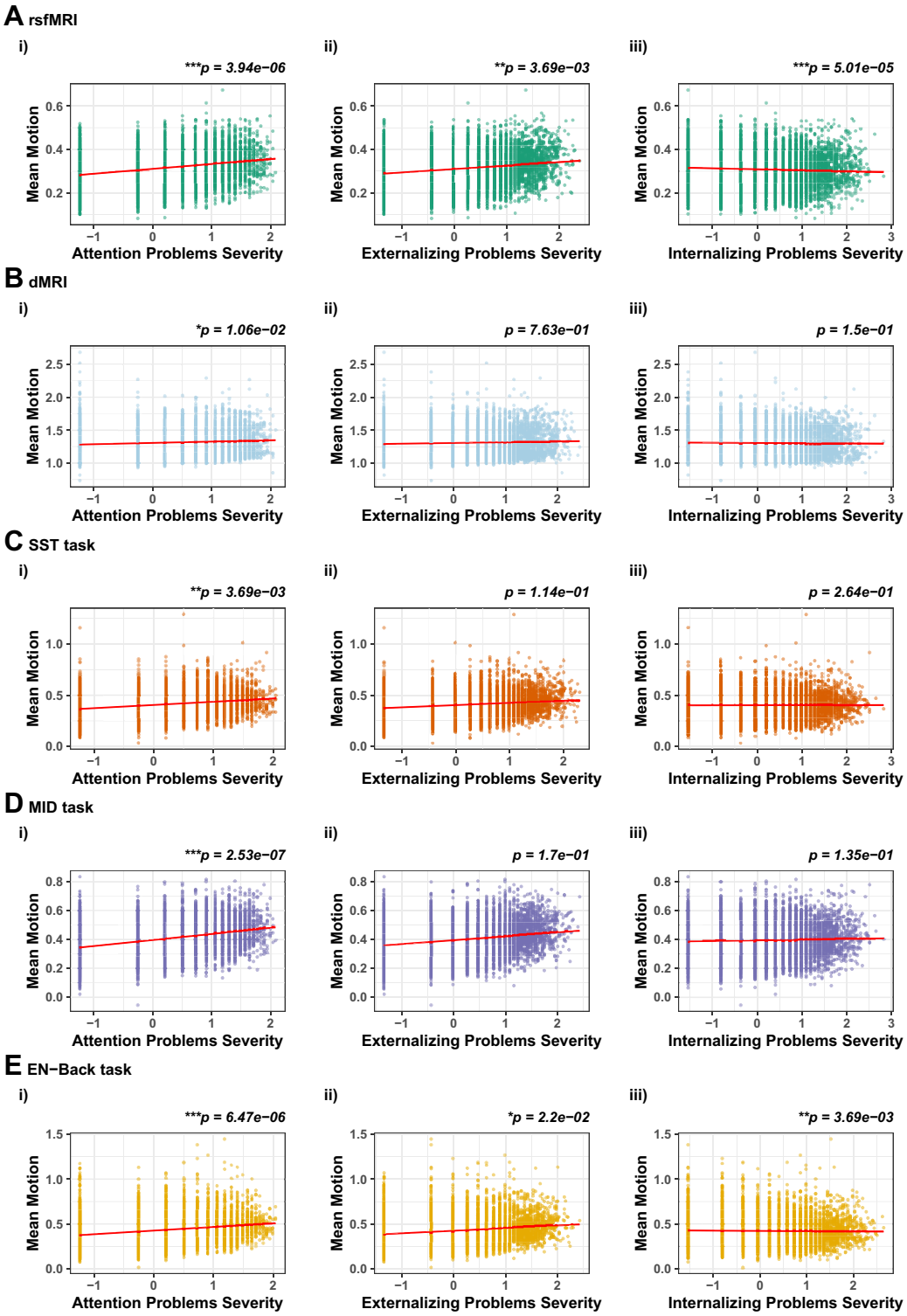

Figure 3. Severity of transdiagnostic symptom domains in youths are associated with motion during functional and structural imaging, accounting for the effect of scanner manufacturer. Scatterplots depict results of linear mixed-effects models (see Table 3) for Child Behavior Checklist Attention, Externalizing, and Internalizing Problems scores for resting-state functional magnetic resonance imaging (rsfMRI) **(A)**, diffusion MRI (dMRI) **(B)**, the stop signal task (SST) **(C)**, the monetary incentive delay (MID) task **(D)**, and the emotional version of the n-back task (EN-back) **(E)**. The red trendline represents the regression line based on the linear mixed-effects models fit. Statistical significance is denoted by asterisks: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Table 4. Results of Linear Mixed-Effects Models Predicting Task Performance and Domains of Transdiagnostic Symptoms

Variables	Estimate	Standard Error	Semipartial R^2	t	p	p_{FDR}	95% CI	
							2.5%	97.5%
SST								
Intercept	513	13.3	–	38.5	<.001	<.001	487	539
Age	−1.28	0.1	0.01976	−12.8	7.53×10^{-37}	4.14×10^{-36}	−1.47	−1.08
Sex	0.62	1.53	0.00003	0.406	.685	.717	−2.37	3.61
Race/Ethnicity								
Asian	−3.26	5.37	0.00548	−0.607	.544	.63	−13.8	7.26
Black	−18.2	2.69		−6.77	1.38×10^{-11}	4.98×10^{-11}	−23.5	−12.9
Hispanic	−6.31	2.33		−2.7	.00688	.0132	−10.9	−1.73
Other	−6.31	2.67		−2.37	.018	.0305	−11.5	−1.08
Cognition	−0.523	0.0473	0.01493	−11.1	3.27×10^{-28}	1.44×10^{-27}	−0.616	−0.431
CBCL Attention	3.61	0.969	0.00165	3.73	.000192	.000444	1.72	5.51
CBCL Externalizing	−0.949	1.02	0.00010	−0.934	.35	.44	−2.94	1.04
CBCL Internalizing	−2.13	0.943	0.00048	−2.26	.0239	.0375	−3.98	−0.282
MID Task								
Intercept	−3.37	1.3	–	−2.6	.00926	.017	−5.91	−0.834
Age	0.0693	0.0102	0.0058	6.76	1.47×10^{-11}	4.98×10^{-11}	0.0492	0.0894
Sex	0.913	0.157	0.00435	5.83	5.93×10^{-9}	1.74×10^{-8}	0.606	1.22
Race/Ethnicity								
Asian	−0.267	0.566	0.00164	−0.473	.637	.691	−1.38	0.842
Black	−0.457	0.269		−1.7	.0897	.123	−0.985	0.0707
Hispanic	−0.32	0.232		−1.38	.168	.223	−0.774	0.134
Other	−0.696	0.27		−2.58	.01	.0177	−1.23	−0.166
Cognition	0.05	0.00486	0.0136	10.3	1.21×10^{-24}	4.83×10^{-24}	0.0405	0.0595
CBCL Attention	−0.295	0.0999	0.00117	−2.96	.00313	.00655	−0.491	−0.0995
CBCL Externalizing	0.0799	0.104	0.00007	0.766	.444	.543	−0.125	0.284
CBCL Internalizing	−0.0697	0.0968	0.00009	−0.72	.471	.56	−0.259	0.12
EN-Back 0								
Intercept	0.475	0.0177	–	26.9	<.001	<.001	0.44	0.51
Age	0.00174	0.000138	0.0196	12.6	7.90×10^{-36}	3.86×10^{-35}	0.00147	0.00201
Sex	0.00437	0.00211	0.00056	2.07	.0384	.0563	0.000235	0.00851
Race/Ethnicity								
Asian	−0.00107	0.0073	0.00576	−0.147	.883	.883	−0.0154	0.0132
Black	−0.0188	0.00373		−5.04	4.72×10^{-7}	1.22×10^{-6}	−0.0261	−0.0115
Hispanic	−0.00873	0.00314		−2.78	.00542	.0108	−0.0149	−0.00258
Other	−0.00782	0.00359		−2.18	.0296	.0449	−0.0149	−0.000776
Cognition	0.00175	6.58×10^{-5}	0.0880	26.7	<.001	<.001	0.00162	0.00188
CBCL Attention	−0.00429	0.00135	0.00139	−3.18	.00146	.0032	−0.00693	−0.00165
CBCL Externalizing	−0.00248	0.00141	0.00039	−1.76	.0782	.111	−0.00524	0.00028
CBCL Internalizing	−0.000701	0.00131	0.00007	−0.537	.591	.667	−0.00326	0.00186
EN-Back 2								
Intercept	0.368	0.0157	–	23.5	<.001	<.001	0.337	0.398
Age	0.00186	0.000122	0.0262	15.3	7.73×10^{-52}	5.67×10^{-51}	0.00162	0.0021
Sex	0.0259	0.00186	0.0216	13.9	2.79×10^{-43}	1.75×10^{-42}	0.0222	0.0295
Race/Ethnicity								
Asian	−0.00298	0.00645	0.0101	−0.462	.644	.691	−0.0156	0.00967
Black	−0.0201	0.0033		−6.1	1.10×10^{-9}	3.47×10^{-9}	−0.0266	−0.0137
Hispanic	−0.0148	0.0028		−5.29	1.25×10^{-7}	3.44×10^{-7}	−0.0203	−0.00933
Other	−0.00727	0.00317		−2.29	.022	.0358	−0.0135	−0.00105
Cognition	0.00187	5.80×10^{-5}	0.1164	32.3	<.001	<.001	0.00176	0.00199
CBCL Attention	−0.00477	0.00119	0.0020	−4.02	5.93×10^{-5}	.000145	−0.00709	−0.00244

Table 4. Continued

Variables	Estimate	Standard Error	Semipartial R^2	t	p	p_{FDR}	95% CI 2.5%	95% CI 97.5%
CBCL Externalizing	−0.0015	0.00124	0.00017	−1.21	.225	.292	−0.00394	0.000928
CBCL Internalizing	−0.000438	0.00115	0.00004	−0.381	.703	.72	−0.00269	0.00182

General cognition was measured by the NIH Toolbox age-corrected scores (61). The intercept does not have a semipartial R^2 value because it represents the baseline level of the dependent variable when all fixed-effect predictors are set to 0. Unlike predictors, the intercept does not contribute to explaining variance in the outcome.

CBCL, Child Behavior Checklist; EN-back, emotional n-back; FDR, false discovery rate; MID, monetary incentive delay; SST, stop signal task.

analyses indicated that greater internalizing symptoms were associated with better performance during SST, which provides a measure of the speed of inhibitory processes (37). Here, increased internalizing symptoms may reflect anxiety-related symptoms, such as fearing negative evaluation, which may impact fMRI task compliance (73). Alternately, decreased likelihood of passing QC checks associated with attention and disruptive behavior problem severity during ABCD Study fMRI tasks may reflect difficulties in broader cognitive control processes (e.g., inhibitory control, cognitive flexibility), which may not necessarily emerge as areas of cognitive difficulty for youths with internalizing problems (74).

Transdiagnostic Symptom Domains and In-Scanner Motion

Distinct associations were observed between transdiagnostic symptom domains and in-scanner head motion (indexed using mean FD) across functional and structural neuroimaging. Related to attention problems, children with increased attention-related behavioral challenges showed increased motion across all neuroimaging modalities, which is consistent with results for imaging QC. Our findings are also consistent with previous work that suggests an association between attention-related symptoms and increased mean motion in youths despite motion scrubbing or censoring approaches (11,28), as well as in clinical samples of children with ADHD (13,23). While main effects of sex were found for resting-state, diffusion MRI, and task fMRI whereby males showed greater movement than females, we did not observe significant interactions between sex and behavior domains across neuroimaging modalities (see Supplemental Discussion). Supplemental analyses indicated a relationship between greater severity of attention problems and reduced task performance across fMRI tasks (see Figure 4), which is consistent with previous work that has leveraged the ABCD Study dataset whereby ADHD symptoms were associated with worse performance on the EN-back task and SST (51). Tasks such as the SST or variations thereof tap into cognitive control processes during a moderately- or fast-paced paradigm with a requirement for frequent responses and attending (11,37). While it is suggested that head motion may be lower when participants are actively engaged in a cognitive task, other studies have reported null or opposite effects in which associations between certain task conditions may show comparable motion depending on the required cognitive and/or language demands (16,23,27). Regardless of task or nontask sequences, we observed that attention problems were consistently implicated in higher mean movement as well as higher likelihood of exclusion based on initial QC checks. Our findings also suggest that motion could represent differences in participant groups (e.g., clinical groups vs. unaffected controls) and the cognitive processes recruited during tasks (12,75). In support of this, attention-related problems were associated with worse performance for each of the fMRI tasks, which recruit cognitive control processes (37,38,43) and may be more challenging for children with attention-related difficulties. Thus, future work may consider accounting for differences in task performance linked to attention symptom domains.

Our results also show that increased severity of disruptive behavior problems is associated with increased head motion during resting-state and the EN-back task, but the opposite pattern was observed for internalizing problems. That is, increased severity of internalizing symptoms was associated with decreased head motion during resting-state and the EN-back task. A similar pattern was observed for QC findings. While these symptom domains were positively correlated based on Pearson correlations (Figure 2), distinct associations with motion consistently emerged across regression models. Given the diagnostic overlap of attention, disruptive behavior, and internalizing problems (45–49), we modeled symptom domains simultaneously in regression models to account for the shared covariance and to identify distinct associations with motion. Interestingly, no significant associations between task performance and motion were observed for the EN-back task for disruptive behavior or internalizing problems (Figure 4). Overall, our findings for disruptive behavior and internalizing problems are consistent with studies indicating associations between in-scanner motion, modeled as a continuous variable, and behavior domains in youths (13,44) including externalizing- and internalizing-related symptoms during resting-state (7,25). We also provide considerations for developmental neuroimaging that could help accelerate future work aimed at mitigating in-scanner motion for youths (see Supplemental Discussion: Considerations and Future Directions for Translational Developmental Neuroimaging).

Limitations

There are limitations of the current study to acknowledge. First, we did not investigate the influence of movement or data scrubbing on image quality, brain activation, or functional connectivity, which was beyond the scope of the current study. Second, ABCD Study participants primarily consisted of a community-based sample of children with varying levels of externalizing and internalizing symptoms. This may limit the generalizability of our findings to clinical groups or youths with more severe symptomatology. Thus, future work that tests

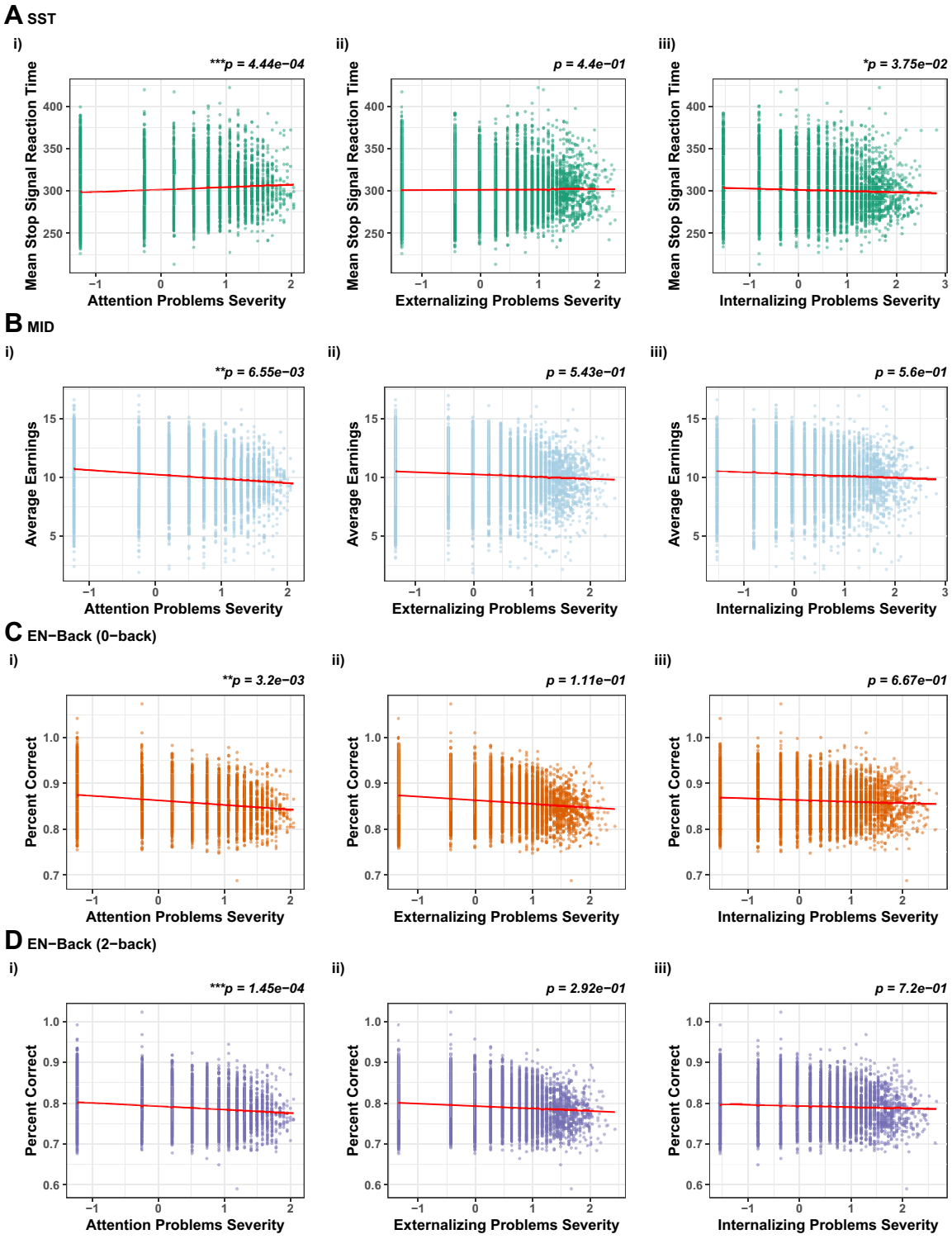

Figure 4. Attention problems were associated with behavioral performance on the stop signal task (SST), monetary incentive delay (MID) task, and the emotional version of the n-back (EN-back) task in youths. Scatterplots depict results of linear mixed-effects models (see Table 4) for Child Behavior Checklist Attention, Externalizing, and Internalizing Problem scores for task-based functional magnetic resonance imaging: SST **(A)**, MID task **(B)**, and the EN-back task for the 0-back **(C)** and 2-back **(D)** rounds, respectively. The trendline represents the regression line based on the linear mixed-effects model fit. Statistical significance is denoted by asterisks: $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

replication of findings in clinical groups will be important. Nonetheless, the ABCD Study sample provides heterogeneity and diversity both demographically and across a range of clinical phenotypes. Third, the variability in fMRI tasks, behavioral measures, and acquisition protocols across different research groups beyond ABCD Study sites may limit the generalizability of our findings to other research and/or clinical settings. Additionally, although examining timing effects linked to motion-behavior associations during scanning sessions as well as motion differences in task versus nontask sequences would be informative (Supplemental Discussion), it is beyond the scope of the current study and compounded by several confounds such as a subsample of children who completed scans in multiple sessions, repeated scan acquisitions due to motion, and randomized order of tasks. Here, we implemented best-practice recommendations for analysis of ABCD Study data, which include random effects for family and site (76). Exploratory follow-up tests also indicate that transdiagnostic symptom domains are an important predictor of motion, even after site effects are accounted for (Supplemental Results and Table S8). However, it is important to emphasize that the ABCD Study protocol was designed to optimize harmonization of sequence acquisition protocols across the 21 sites and uses well-established measures of child psychopathology (i.e., the CBCL) (37,38). Lastly, the age range of participants was narrow (9–10 years in the first wave), and future longitudinal work will be needed to understand the stability of motion across development, particularly given the potential heritable contributions of motion stability throughout development (11). However, we opted to use a narrow age range to limit the developmental heterogeneity of the sample as a potential confound in analyses.

Conclusions

The results of the current study suggest that the transdiagnostic symptom domains of attention and disruptive behavior problems are associated with increased motion while the internalizing symptoms domain is associated with decreased motion in youths. Enhancing the accessibility of neuroimaging protocols in pediatric populations by accommodating a range of symptom severities and behavioral challenges in children will have implications for the development of robust, reliable, and generalizable brain biomarkers for child mental health.

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A portion of the data used in the preparation of this article was obtained from the ABCD Study (https://abcdstudy.org), which is held in the NIMH Data Archive (NDA). This is a multisite longitudinal study that was designed to recruit more than 10,000 children ages 9 to 10 and follow them over 10 years into early adulthood. A listing of participating sites and a complete listing of the study investigators can be found at https://abcdstudy.org/consortium_members/. The ABCD data repository grows and changes over time. The ABCD data used in this report came from NDA 4.0 release (https://doi.org/10.15154/z563-zd24). Data from the ABCD Study are shared in the NDA https://nda.nih.gov/. To promote transparency, all code used for analyses is available on GitHub (https://github.com/EmotionNeuroscienceLab).

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