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Associations of Observed Performance Monitoring During Preschool With Obsessive-Compulsive Disorder and Anterior Cingulate Cortex Volume Over 12 Years

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IMPORTANCE Monitoring one's performance is necessary for learning and adaptive behavior; however, heightened performance monitoring is a purported endophenotype of obsessive-compulsive disorder (OCD). The anterior cingulate cortex (ACC), a brain region implicated in the pathogenesis of OCD, is associated with performance monitoring. Whether performance monitoring early in development is an identifiable risk factor for OCD and whether early childhood performance monitoring is associated with later alterations in ACC volume are unknown.

OBJECTIVE To determine whether an observed indicator of heightened performance monitoring during the preschool age is associated with later onset of OCD and altered dorsal ACC (dACC) volume through adolescence.

DESIGN, SETTING, AND PARTICIPANTS This longitudinal observational cohort study was performed at an academic medical center as part of the Preschool Depression Study. A sample of 292 children oversampled for depression from September 22, 2003, through May 12, 2005, completed a performance-based observational task during which they received persistent negative evaluation. Blind raters behaviorally coded child performance monitoring. During the next 12 years, children completed annual diagnostic assessments; 133 completed the final behavioral follow-up and 152 contributed 1 to 3 magnetic resonance imaging scans. Follow-up was completed on August 14, 2017.

MAIN OUTCOMES AND MEASURES Onset of *DSM-5* diagnosis of OCD from baseline to the final behavioral assessment and whole-brain–adjusted dACC volume at the 3 waves of scanning.

RESULTS Among the 292 preschool children who completed the baseline evaluation (51.4% boys; mean [SD] age, 4.5 [0.8] years), when controlling for demographic and clinical indicators, those who exhibited observed heightened performance monitoring were 2 times more likely to develop OCD (n = 35) during the next 12 years (odds ratio, 2.00; 95% CI, 1.06-3.78; $P = .03$). Multilevel modeling of dACC volume across the 3 scan waves (n = 152) demonstrated that heightened performance monitoring was associated with smaller right dACC volume (intercept estimate, −0.14; SE, 0.07; $t = -2.17$; $P = .03$).

CONCLUSIONS AND RELEVANCE An ecologically valid indicator of performance monitoring in early childhood was associated with onset of OCD and smaller dACC volumes in later childhood and adolescence. Early childhood observed performance monitoring is a readily observed risk factor of OCD that can be identified in preschool-aged children.

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Supplemental content

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Monitoring one's performance is vital for detecting and learning from errors, leading to behavioral adaptation and flexibility. However, heightened monitoring of performance may contribute to compulsive behaviors in an attempt to correct and avoid future errors, as evidenced in obsessive-compulsive disorder (OCD).[1,2] Heightened performance monitoring has repeatedly been demonstrated to be a cognitive process characteristic of OCD, leading to it being posited to be a core dysfunction or endophenotype of the disorder.[1,3,4] Despite these associations, no evidence indicates that heightened performance monitoring exhibited before symptom expression is directly associated with onset of OCD. Successfully identifying elevated performance monitoring in early childhood before and in association with later disorder onset would provide evidence that heightened performance monitoring is an early emerging risk factor for OCD. This evidence could inform identification of children at high risk for developing OCD and lead to targeted preventive intervention before such tendencies become stable and less modifiable. This latter point is of critical importance because little is understood about prevention of OCD.[5] Given that OCD is a psychiatric disorder associated with high levels of impairment and treatment resistance,[6,7] identifying early markers of OCD before disorder onset has critical public health implications.

Heightened performance monitoring is often assessed using behavioral indicators (eg, reaction time and number of behavioral errors) and adjustments after an error (ie, post-error slowing) during cognitive tasks. Heightened performance monitoring also is indexed by a neural marker, specifically, the error-related negativity, a negative component in an electroencephalogram that occurs after a behavioral error. Heightened performance monitoring is consistently elevated in patients with OCD,[1,3] first-degree relatives of individuals with OCD,[4,8] and healthy children and adults exhibiting obsessive-compulsive tendencies.[9,10] Moreover, treatment for OCD that effectively decreases obsessive-compulsive symptoms has proved ineffective at reducing performance monitoring.[11-13]

Neurobiological models of OCD implicate the anterior cingulate cortex (ACC), a region of the cortico-striato-thalamo-cortical circuit, in the etiology of the disorder.[14] The ACC is purportedly associated with elevated performance and error monitoring, detection of cognitive conflict, and persistence.[15-17] When electrically stimulated, the ACC induces compulsive goal-directed behaviors and perseverance.[18,19] The ACC can be divided functionally into the dorsal ACC (dACC), thought to be activated by conflict and errors in cognitive tasks, and the rostral ACC, purportedly implicated in emotionally salient tasks and error responding.[20] Although the rostral ACC[21-23] and dACC[14] have been implicated in the pathophysiology of OCD, a greater supporting literature demonstrates the aforementioned error-related negativity, an electroencephalographic marker of performance monitoring, to be localized in the dACC.[24,25] As such, patients with OCD demonstrate hyperactivation in the dACC to errors and cognitive conflict,[26] and this hyperactivation is speculated to be associated with overactive monitoring that contributes to OCD symptoms.[2,26] Indeed, dACC hyperactivation has been correlated with OCD symptom severity,[27,28] whereas lesioning the dACC (via dorsal anterior cingulotomy) appears to reduce OCD symptoms in patients with treatment-refractory OCD.[29,30] Adults with OCD also demonstrate volumetric and thickness differences in the dACC. Specifically, adults with OCD exhibit dACC cortical thinning that is correlated with self-reported obsessions.[31] In addition, patients with OCD have repeatedly demonstrated a reduced volume of the dACC in meta-analyses[32] and mega-analyses.[33]

Key Points

Question Is observed performance monitoring in preschool associated with onset of obsessive-compulsive disorder and anterior cingulate cortex volume across child development?

Findings In this observational cohort study of 292 preschool children oversampled for depression, performance monitoring was observationally coded during an ecologically valid task. Heightened performance monitoring was significantly associated with onset of obsessive-compulsive disorder during the next 12 years and smaller right dorsal anterior cingulate cortex volume across 3 neuroimaging scans.

Meaning An observational indicator of heightened performance monitoring is evident before symptom onset and is an identifiable risk factor for obsessive-compulsive disorder in preschool years.

Although performance monitoring has consistently been purported to play a key role in the pathogenesis of OCD and is associated with neurobiological aberrations in the dACC, whether elevated performance monitoring evident early in development is present before and is directly associated with later onset of OCD is unknown. Moreover, whether an early childhood indicator of heightened performance monitoring is associated with neurobiological structural differences in the dACC is also unknown. The focus of the present study was to assess performance monitoring in preschool-aged children studied longitudinally and assessed for later psychiatric disorder and volumetric brain change. Because performance monitoring in very young children may be most readily measured using an observational measure rather than cognitive tasks or neural signatures, we developed an observed indicator of performance monitoring.

In the present prospective longitudinal study, we measured heightened performance monitoring in preschoolers using an observational task designed to elicit performance monitoring. We hypothesized that baseline observed heightened performance monitoring would be associated with onset of OCD during the course of the 12-year study. In addition, given that reduced dACC volume is evident in patients with OCD,[33] we also hypothesized that the indicator of performance monitoring would be associated with smaller dACC volumes across 3 waves of magnetic resonance imaging scans.

Methods

Participants

Participants included 292 children from the Preschool Depression Study[34] who had usable baseline observational data. The Preschool Depression Study is an ongoing longitudinal investigation conducted at Washington University School of Medicine, St Louis, Missouri, that uses multiple methods and informants to evaluate mental health and brain outcomes from preschool through

Table 1. Characteristics of the Study Sample and Associations With Heightened Performance Monitoring

Characteristic	Time of Assessment[a]					Baseline Performance Monitoring, Mean (SD)	Baseline Association With Performance Monitoring	*P* Value
	Baseline (n = 292)	Scan 1 (n = 138)	Scan 2 (n = 124)	Scan 3 (n = 110)	Final Behavioral Follow-up (n = 133)			
Sex, No. (%)								
Male	150 (51.4)	72 (52.2)	64 (51.6)	56 (50.9)	66 (49.6)	2.29 (0.74)	$t_{285.71} = -0.98$	.37
Female	142 (48.6)	66 (47.8)	60 (48.4)	54 (49.1)	67 (50.4)	2.36 (0.61)		
Race, No. (%)								
White	157 (53.8)	77 (55.8)	62 (50.0)	50 (45.5)	72 (54.1)	2.43 (0.67)	$t_{290} = 2.95$	.003
African American or other minority	135 (46.2)	61 (44.2)	62 (50.0)	60 (54.5)	61 (45.9)	2.19 (0.69)		
Age, mean (SD), y	4.5 (0.8)	10.3 (1.3)	11.9 (1.2)	13.1 (1.1)	16.4 (1.0)	NA	$r = 0.40$	<.001
Income-to-needs ratio, mean (SD)[b]	2.08 (1.17)	1.68 (0.99)	1.65 (0.98)	1.58 (0.99)	1.90 (0.78)	NA	$r = 0.13$	.03
Psychotropic medication ever used, No. (%)								
Yes	24 (8.3)	29 (21.0)	33 (26.6)	35 (31.8)	48 (36.1)	2.30 (0.68)	$t_{288} = -1.04$	.30
No	266 (91.7)	109 (79.0)	91 (73.4)	75 (68.2)	85 (63.9)	2.46 (0.61)		
Current depression diagnosis, No. (%)								
Depression	99 (33.9)	25 (18.2)	9 (7.3)	10 (9.1)	17 (12.8)	2.31 (0.67)	$t_{290} = 0.20$	.84
No depression	193 (66.1)	112 (81.8)	115 (92.7)	100 (90.9)	116 (87.2)	2.33 (0.69)		
Compulsions severity symptom score, mean (SD)[c]	0.18 (0.85)	NA	NA	NA	NA	NA	$r = 0.14$	.02
Externalizing severity symptom score, mean (SD)[d,e]	7.27 (7.07)	5.16 (5.97)	4.04 (4.75)	3.24 (5.26)	NA	NA	$r = -0.01$	.81
Anxiety severity symptom score, mean (SD)[d,f]	2.20 (2.74)	2.39 (2.53)	1.66 (1.85)	1.29 (1.45)	NA	NA	$r = 0.04$	.50

Abbreviation: NA, not applicable.

[a] Owing to missing data, numbers may not total column heads.

[b] Calculated by dividing the total family income by the federal poverty level based on family size for the year of data collection.

[c] Full diagnoses were assigned after the baseline assessment, and sum scores were not quantified. Scores range from 0 to 7, with higher scores indicating higher compulsions severity.

[d] Calculated from baseline to point but not at the final behavioral follow-up session because the Kiddie Schedule for Affective Disorders and Schizophrenia was used as a diagnostic interview rather than the Child and Adolescent Psychiatric Assessment (CAPA) due to age limits for the CAPA, and thus identical items could not be summed to create a severity score.

[e] Scores range from 0 to 32, with higher scores indicating more externalizing symptoms.

[f] Scores range from 0 to 13, with higher scores indicating more anxiety symptoms.

adolescence. From September 22, 2003, to May 12, 2005, children aged 3 to 5 years and their primary caregivers were recruited from primary care centers, daycare centers, and preschools around the St Louis region using the Preschool Feelings Checklist[35] to oversample children with depression. Exclusion criteria were chronic illness, neurologic disorders or autism spectrum disorders, and speech, language, or cognitive delays. Of those 416 eligible child-caregiver dyads, 306 participated.[36] Children underwent 12 approximately annual assessments; 292 were included in behavioral analyses and 152 completed 1 to 3 neuroimaging sessions and were included in neuroimaging analyses (90 completed all 3 scans) approximately 18 months apart (**Table 1**). Follow-up was completed on August 14, 2017. Participants were compensated. The institutional review board of Washington University in St Louis approved all procedures. Written parental consent and child assent were obtained before participation.

Observational Performance Monitoring

The Impossibly Perfect Circles task, part of the Laboratory Temperament Assessment Battery,[37] was administered at baseline of the Preschool Depression Study and used for observational coding of performance monitoring. The experimenter instructed the child to draw a "perfect" circle and repeatedly criticized the drawn circles for imperfections. Although the critiques were specific (ie, "that one is flat on the side"), they were not meant to help fix the errors. After 3 minutes of negative feedback, the experimenter admitted to being harsh and praised the child's circles. The task was originally designed to rate negative emotionality and persistence during negative feedback; however, it also elicits performance monitoring during a performance-focused task.

Performance monitoring was coded using a novel scheme developed by one of us (K.E.G.). Items included modified scoring of frustration from 1.00 (no signs of frustration) to 4.00 (multiple clear facial, verbal, and/or behavioral signs of frustration), an indicator from the Laboratory Temperament Assessment Battery manual and previously published work,[37,38] and novel dimensions that included the child's diligence, care, and deliberateness in circle drawing from 1.00 (hurried, not paying attention) to 4.00 (very diligent, very deliberate, and slow in circle drawing), observed intensity in performing the

task from 1.00 (not at all, none) to 4.00 (definitely, a lot), and child self-criticism from 1.00 (not at all, none) to 4.00 (definitely, a lot). A mean of the 4 dimensions was calculated to create a composite of performance monitoring, with average internal consistency (Cronbach α = .69) and lower Cronbach α's if any item was deleted. Two coders (including M.E.B.) overlapped coding of approximately two-thirds of tapes, and intraclass correlations revealed acceptable interrater reliability for individual dimensions (mean intraclass correlation, 0.60) and the composite (intraclass correlation, 0.71). For analyses, each coder contributed approximately half of the ratings.

Psychiatric Diagnoses and Dimensional Severity Scores

Trained staff conducted in-person diagnostic assessments with primary caregivers at baseline through 7 years of age using the Preschool Age Psychiatric Assessment (PAPA),[39] the Child and Adolescent Psychiatric Assessment[40] to caregivers when the child was 8 years of age and to caregivers and children from 9 years of age to the final assessment, and the Kiddie Schedule for Affective Disorders and Schizophrenia[41] to caregivers and children at the final assessment. Interviews were reviewed for reliability as detailed elsewhere.[34] Categorical *DSM-5* diagnoses were obtained at each assessment. A child was considered to have OCD if they met criteria at any assessment point. Baseline severity scores of anxiety and externalizing symptoms summed the total number of core *DSM*-based symptoms endorsed using the PAPA. Specifically, the anxiety severity score was the sum of separation anxiety disorder and generalized anxiety disorder symptoms, whereas the externalizing severity score was the sum of attention-deficit/hyperactivity disorder, oppositional defiant disorder, and conduct disorder symptoms of the PAPA. Although a full OCD diagnosis was not obtained in the PAPA, baseline compulsions symptoms were summed to create a compulsions severity score (eMethods in the Supplement provides details on diagnostic assessments, reliability, and the compulsions severity score).

Neuroimaging and Image Processing

Three neuroimaging sessions used the same magnetic resonance imaging scanner (model 3.0T total imaging matrix Trio; Siemens Healthcare GmbH). The structural imaging sequence included acquiring 2 sagittal 3-dimensional T1-weighted magnetization-prepared rapid gradient-echo (MPRAGE) scans using a 12-channel head coil (repetition time, 24 000 milliseconds; echo time, 3.16 milliseconds; inversion time, 1200 milliseconds; flip angle, 8°; 160 sections; 256 × 256 matrix; field of view, 256 mm; 1.0 mm^3 voxels; 6:18 minutes per scan). The 2 MPRAGE scans were visually assessed, and the best was selected for further processing. Whole-brain volume and segmenting of each participant's anatomical image was completed using the longitudinal stream in the FreeSurfer software package (version 5.3; surfer.nmr.mgh.harvard.edu).[42] This process includes several processing steps, including skill stripping, Talairach transformations, atlas registration, and spherical surface maps and parcellations that use common information from an unbiased within-patient template and reduces bias that would be present in selecting a single scan.[43] Processing used the Desikan-Killiany-Tourville protocol[44] to estimate the left and right dACC volumes and was taken from the bilateral caudal anterior cingulate parcellation.

Statistical Analysis

A univariable, followed by a multivariable, logistic regression was performed to examine whether preschool-aged observed performance monitoring was associated with onset of OCD. Bivariate analyses solely included observed performance monitoring, and multivariable analyses adjusted for baseline age, income to needs, use of psychotropic medication, externalizing, anxiety, and compulsions symptoms and preschool onset of depression. Results of these analyses were reported as exponentiated coefficients to obtain odds ratios (ORs) and 95% CIs. Two longitudinal multilevel linear models examined the association between performance monitoring and left and right dACC volume. Models included random intercept and slope components (with an unstructured covariance matrix), and performance monitoring was used to indicate variation in intercept (mean) left and right dACC volume. Time was coded as age at scan, centered at 7 years. Both models included covariates of psychotropic medication use at each scan (1 indicates yes; 0, no), sex (1 indicates male; 0, female), preschool onset of depression (1 indicates major depressive disorder; 0, no major depressive disorder), baseline ratio of income to needs, baseline externalizing severity score, baseline anxiety severity score, baseline compulsions severity score, and whole-brain volume at each scan (all mean centered). eMethods in the Supplement provides 2 exploratory models testing change of dACC volume over time. Logistic regression models were performed using SPSS software (version 25; IBM Corp), and longitudinal multilevel linear models were implemented in SAS software (version 9.4; SAS Institute Inc). eMethods in the Supplement provides additional analyses on diagnostic and brain volumetric specificity. *P* values from the logistic regression models and multilevel linear models were significant at $P < .05$.

Results

Among the 292 children who participated (150 boys [51.4%] and 142 girls [48.6%]; mean [SD] age, 4.5 [0.8] years) (Table 1), we found a normal distribution of observationally coded performance monitoring scores (mean [SD], 2.31 [0.68]; range, 1.00-4.00), with no differences in the observational indicator of performance monitoring as a function of sex or baseline externalizing or anxiety characteristics. However, older age ($r = 0.40$; $P < .001$), higher income-to-needs ($r = 0.13$; $P = .03$), baseline compulsions ($r = 0.14$; $P = .02$), and white race ($t_{290} = 2.95$; $P = .003$) were associated with higher observed performance monitoring (Table 1). Because we found a high association between race and the ratio of income to needs ($t_{217.49} = 10.49$; $P < .001$), we did not include race as a covariate to avoid multicollinearity.

Thirty-five children developed OCD in the study (**Table 2**). Univariable logistic regressions indicated that preschoolers showing increased theorized performance monitoring were more than 2 times more likely to experience onset of OCD

Table 2. Characteristics of Children Who Developed OCD During the Course of the Longitudinal Study

Characteristic	Study Sample	
	OCD (n = 35)	No OCD (n = 257)
Baseline		
Female, No. (%)	16 (44.7)	126 (49.0)
Age, mean (SD), y	4.6 (0.8)	4.4 (0.8)
White, No. (%)	14 (40.0)	121 (47.1)
Income-to-needs ratio[a]	2.13 (1.20)	2.08 (1.17)
Use of psychotropic medication, No. (%)	5 (14.3)	19 (7.4)
Preschool onset of depression, No. (%)	20 (57.1)[b]	79 (30.7)
Compulsions severity symptom score, mean (SD)[c]	0.56 (1.48)	0.13 (0.72)
Externalizing severity symptom score, mean (SD)[d]	10.31 (8.35)[b]	6.85 (6.79)
Anxiety severity symptom score, mean (SD)[e]	3.51 (3.90)[b]	2.02 (2.49)
Performance monitoring score, mean (SD)[f]	2.63 (0.63)[b]	2.27 (0.68)
Scan 1		
No. of patients	25	113
Whole-brain volume, cm^3	1 159 153.58 (120455.42)	1 149 437.13 (98279.56)
Right dACC volume, cm^3	2436.96 (483.31)	2633.92 (584.87)
Left dACC volume, cm^3	3932.96 (789.47)[b]	3643.51 (610.32)
Scan 2		
No. of patients	22	102
Whole-brain volume, cm^3	1 133 382.50 (88229.38)	1 152 481.99 (101173.83)
Right dACC volume, cm^3	2318.18 (514.57)[b]	2645.59 (583.31)
Left dACC volume, cm^3	3733.27 (617.84)	4578.79 (616.42)
Scan 3		
No. of patients	21	89
Whole-brain volume, cm^3	1 142 194.36 (113965.95)	1 135 554.85 (102168.72)
Right dACC volume, cm^3	2253.29 (497.92)[b]	2296.56 (611.95)
Left dACC volume, cm^3	3598.67 (533.79)	3515.39 (647.82)

Abbreviations: dACC, dorsal anterior cingulate cortex; OCD, obsessive-compulsive disorder.

[a] Calculated by dividing the total family income by the federal poverty level based on family size for the year of data collection.

[b] $P < .05$ compared with the group without OCD using the χ^2 test for preschool depression and t test for symptom severity scores.

[c] Scores range from 0 to 7, with higher scores indicating higher compulsions severity.

[d] Scores range from 0 to 32, with higher scores indicating more externalizing symptoms.

[e] Scores range from 0 to 13, with higher scores indicating more anxiety symptoms.

[f] Scores range from 1.00 to 4.00, with higher scores indicating greater levels of performance monitoring.

(OR, 2.23; 95% CI, 1.28-3.89; $P = .005$) (**Table 3**). Adjusting for baseline clinical, medication, and demographic variables, multivariable logistic regressions indicated preschoolers with preschool onset of depression had a nonsignificantly higher likelihood of developing OCD (OR, 2.41; 95% CI, 0.97-5.96; $P = .06$). Children demonstrating heightened observed performance monitoring were again 2 times more likely to develop OCD (OR, 2.00; 95% CI, 1.06-3.78; $P = .03$). Examining individual dimensions of the performance-monitoring composite demonstrated that only observed self-criticism was associated with OCD onset when adjusting for covariates (eResults in the Supplement). Analyses testing diagnostic specificity indicated that performance monitoring was not associated with other disorders that exhibit aberrant performance monitoring (eResults in the Supplement).

Longitudinal multilevel linear models examining the association of theorized performance monitoring with left and right dACC volume showed significant decreases in left (intercept estimate, −0.05; SE, 0.003; $t = 15.92$; $P < .001$) and right (intercept estimate, −0.02; SE, 0.002; $t = −8.86$; $P < .001$) dACC volume as children aged (**Table 4**). Greater baseline anxiety sum scores were also significantly associated with smaller right dACC volume (estimate, −0.06; SE, 0.02; $t = −2.98$; $P = .003$). Above and beyond these associations, observed performance monitoring was significantly associated with decreased right dACC volume (intercept estimate, −0.14; SE, 0.07; $t = −2.17$; $P = .03$) but not left dACC volume (intercept estimate, 0.02; SE, 0.07; $t = 0.33$; $P = .74$) (**Figure**). Sixteen children developed OCD before the first scan. When these children were excluded from analyses, results were identical: heightened performance monitoring continued to be associated with right dACC reductions ($P = .04$) but not left dACC reductions. Post hoc exploratory analyses testing specificity indicated performance monitoring was associated with larger left thalamus volume but not other OCD-associated brain volumes (eResults in the Supplement).

Discussion

These longitudinal findings provide preliminary support that an observationally coded and theorized indicator of performance monitoring in preschool-aged children may be an early emerging risk factor for OCD. Preschool-aged children who demonstrated elevated observed performance monitoring were twice as likely to develop OCD during the next 12 years. These children also exhibited reduced right dACC volume, a region associated with performance monitoring and implicated in OCD, across 3 waves of magnetic resonance imaging scans. These findings provide longitudinal diagnostic and neuroimaging data to support observed heightened performance monitoring as a precursor that increases the risk for OCD. Importantly, this information could inform identification of children at high risk for developing OCD at early ages.

Table 3. Logistic Regressions for Association of Onset of OCD With Observed Heightened Performance Monitoring[a]

Logistic Regression	Estimate, B (SE)	Wald Statistic (*df*)	OR (95% CI)	*P* Value[b]
Univariable				
Heightened performance monitoring	0.80 (0.28)	7.94 (1)	2.23 (1.28-3.89)	.005
Multivariable				
Age	−0.02 (0.26)	0.008 (1)	1.02 (0.61-1.72)	.93
Income-to-needs ratio	0.15 (0.18)	0.68 (1)	1.16 (0.82-1.65)	.41
Baseline use of psychotropic medication	−0.46 (0.77)	0.36 (1)	0.63 (0.14-2.85)	.55
Preschool onset of depression	0.88 (0.46)	3.62 (1)	2.41 (0.97-5.96)	.06
Baseline compulsions severity symptoms	0.16 (0.18)	0.84 (1)	1.17 (0.83-1.65)	.36
Baseline externalizing severity symptoms	0.02 (0.03)	0.30 (1)	1.02 (0.95-1.09)	.58
Baseline anxiety severity symptoms	0.08 (0.07)	1.45 (1)	1.08 (0.95-1.23)	.23
Heightened performance monitoring	0.69 (0.33)	4.53 (1)	2.00 (1.06-3.78)	.03

Abbreviations: OCD, obsessive-compulsive disorder; OR, odds ratio.

[a] Includes 35 patients with a diagnosis of OCD.

[b] Calculated using logistic regression test.

Table 4. Multilevel Models of dACC Volume

dACC Hemispheric Volume	Intercept Estimate (SE)	*t* Value	*P* Value[a]
Right dACC			
Intercept	2.52 (0.08)	33.46	<.001
Age[b]	−0.02 (0.002)	−8.86	<.001
Income-to-needs ratio	0.01 (0.01)	0.90	.37
Male	0.05 (0.09)	0.52	.60
Use of psychotropic medication[c]	0.02 (0.02)	0.79	.43
Preschool onset of depression	0.04 (0.10)	0.36	.72
Baseline compulsions severity score	−0.03 (0.05)	−0.67	.51
Baseline externalizing severity score	0.01 (0.01)	0.63	.53
Baseline anxiety severity score	−0.06 (0.02)	−2.98	.003
Whole-brain volume[c]	0.002 (0.0002)	8.07	<.001
Heightened performance monitoring	−0.14 (0.07)	−2.17	.03
Left dACC			
Intercept	3.62 (0.08)	43.01	<.001
Age[b]	−0.05 (0.003)	−15.92	<.001
Income-to-needs ratio	0.01 (0.01)	0.47	.64
Male	−0.10 (0.10)	−1.01	.32
Use of psychotropic medication[c]	0.04 (0.03)	1.52	.13
Preschool onset of depression	0.10 (0.12)	0.83	.41
Baseline compulsions severity score	−0.002 (0.06)	−0.04	.97
Baseline externalizing sum score	0.003 (0.01)	0.30	.76
Baseline anxiety sum score	−0.02 (0.02)	−1.10	.28
Whole-brain volume[c]	0.003 (0.0003)	9.53	<.001
Heightened performance monitoring	0.02 (0.07)	0.33	.74

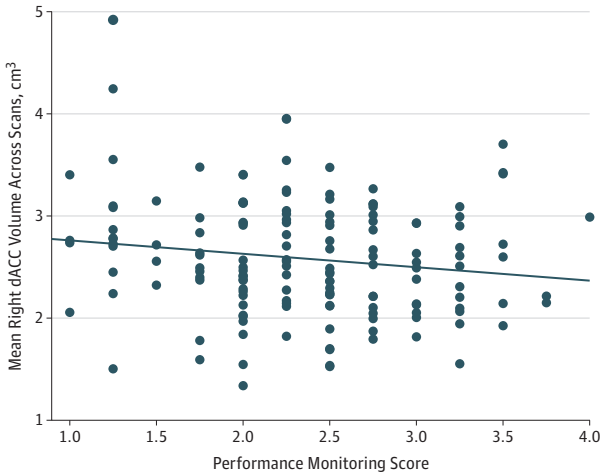
Abbreviation: dACC, dorsal anterior cingulate cortex.

[a] Calculated from the multilevel model.

[b] Used as a time variable.

[c] Indicates time-covarying variable (lifetime through the time of scan).

Figure. Association Between Mean Right dACC Volume Across Scans and Behaviorally Coded Performance Monitoring



Performance monitoring was scored as the mean of items including frustration; diligence, care, and deliberateness in circle drawing; observed intensity; and self-criticism. Scores for each item and the mean score ranged from 1.00 to 4.00, with higher scores indicating higher levels of performance monitoring. dACC indicates dorsal anterior cingulate cortex. Data points indicate individual patients; diagonal line, best-fitting linear association between performance monitoring and dACC volume.

The observed measure of performance monitoring was observationally coded from an ecologically valid task in which the child was asked to draw a circle, followed by repeated critical feedback about its imperfections. Patients with OCD in particular struggle with simple vs complex tasks, because performance monitoring is most elevated during simpler tasks.[45] As such, this simple and cost-efficient task appeared to activate heightened performance monitoring in young children and demonstrated initial long-term validity as an early indicator of performance monitoring. Interestingly, the individual indicator from the performance monitoring composite demonstrating the strongest association with OCD was self-criticism. Self-criticism was not associated with depression (eResults in the Supplement) and was exhibited when the child was already facing experimenter criticism. As such, this observational indicator of performance monitoring may be especially characterized by the child's negative perception of his or her performance.

Parallel findings demonstrated a consistent association of elevated observational performance monitoring with smaller right dACC volume during 3 scans across childhood development, beyond controlling for whole-brain volume. The dACC has repeatedly been implicated in the pathogenesis of OCD,[14] is directly associated with performance monitoring,[15,17] and shows volumetric reductions in OCD samples across meta-analyses and mega-analyses.[32,33,46] In our contribution to this literature, we demonstrate an association between reduced dACC volume in childhood and a theorized indicator of performance monitoring. We conjecture that these volumetric reductions underlie the emergence of OCD. Although follow-up analyses demonstrated that performance monitoring was associated with reduced dACC volume when children who developed OCD before their first neuroimaging scan were excluded, this temporal claim is speculative. Our study design did not allow us to test mediation because OCD onsets occurred in parallel to (ie, before, between, and after) the 3 scans. Previous work has demonstrated volumetric reductions before disorder onset,[47] and we have now independently linked the underlying mechanism of performance monitoring to volumetric reductions. However, future work would benefit from further elucidation of temporal specificity among performance monitoring, dACC volume, and OCD, including testing whether dACC volumetric reductions mediate the association between performance monitoring and OCD onset. In a related matter, we were unable to address how dACC volume is associated with dACC activity during performance monitoring. Given that patients with OCD have demonstrated dACC hyperactivation during error processing,[26] future work should address how dACC volume reduction is associated with dACC activity in OCD, especially across development, when dACC volume normatively declines as cognitive functioning improves.[48]

This study is the first, to our knowledge, that establishes observed performance monitoring, a purported endophenotype of OCD,[4] as directly contributing to the pathogenesis of the disorder. Importantly, this association held after controlling for the effects of baseline generalized anxiety, separation anxiety, dimensional compulsions, and preschool depression, all of which increase the risk for OCD.[49-53] Little is understood of prevention and early intervention in OCD,[5] especially possible mechanisms of change. Given initial evidence that neural performance monitoring can be modified via experimental manipulation in OCD and intervention in chronic worriers,[54,55] our findings suggest that heightened performance monitoring may be a prime mechanistic target for early childhood intervention, while these tendencies are still malleable.

Limitations

Our study has limitations. First, children did not undergo baseline neuroimaging scans. Thus, we do not know whether dACC volume was reduced at baseline when performance monitoring was assessed. Second, OCD is not fully assessed in the PAPA, and thus was not diagnosed at the first 3 preschool assessment waves. Although a clinical diagnosis of OCD at younger than 6 years is uncommon, and although we statistically controlled for baseline compulsions and anxiety symptoms, some children may have exhibited a baseline diagnosis. Third, we did not see bilateral volumetric reductions in the dACC. Meta-analyses have demonstrated right,[46] left,[32] and bilateral[33] ACC volume reductions, so specificity to the right dACC is premature. Fourth, left dACC volume was significantly larger in children with OCD at scan 1, counter to hypotheses. Interestingly, scan 1 was also the only scan in which right dACC volume was not significantly smaller in OCD, suggesting future research is warranted to better address ACC volumetric trajectories across development. Fifth, the present study did not include other neural or behavioral indicators of performance monitoring to validate the observed measure. Future research should examine associations of observed, neural (error-related negativity), and behavioral performance monitoring. Sixth, the study population was oversampled for preschool depression, indicating more impairment and higher risk for OCD,

thus limiting generalizability to the general population. Last, monitoring performance is inherently adaptive because it aids in learning from mistakes. We are unable to determine a cut-point when performance monitoring transitions from adaptive to indicative of pathology. Future research should aim to elucidate when performance monitoring becomes excessive.

Conclusions

Observational performance monitoring evident in early childhood is associated with onset of OCD and reduced dACC volume across child development. Identifying preschoolers who exhibit heightened performance monitoring may lead to better identification of children at high risk for developing OCD. Moreover, interventions targeting heightened performance monitoring in early childhood could change trajectories of neural development and performance monitoring tendencies, leading to more adaptive outcomes across the lifespan. Study findings provide preliminary evidence of an early-emerging observational risk factor for OCD and highlight the need to identify methods to clinically intervene on the underlying mechanism of heightened performance monitoring in early childhood.

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