OPEN ACCESS

Saudi Journal of Medical and Pharmaceutical Sciences

Abbreviated Key Title: Saudi J Med Pharm Sci
ISSN 2413-4929 (Print) | ISSN 2413-4910 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article **Biological Sciences**

Age Moderation of Associations Between Autism Symptom Domains and Subcortical Volumes: A Multi-Site ABIDE I Study

Ruslan Kurmashev[1]*

[1]Department of Biological Sciences, Munster Technological University, Cork, Ireland

DOI: https://doi.org/10.36348/sjmps.2025.v11i12.019 | **Received:** 03.09.2025 | **Accepted:** 27.11.2025 | **Published:** 30.12.2025

***Corresponding author:** Ruslan Kurmashev
Department of Biological Sciences, Munster Technological University, Cork, Ireland

Abstract

Subcortical morphometric findings in autism are heterogeneous, and diagnosis-level comparisons may obscure associations involving symptom dimensions and age. We examined whether Autism Diagnostic Interview-Revised reciprocal social interaction, verbal communication, and restricted or repetitive behavior scores were associated with seven bilateral subcortical volumes and whether age moderated these associations. This cross-sectional secondary analysis included 355 autistic participants aged 7-49 years from 16 Autism Brain Imaging Data Exchange I sites. Public precomputed FreeSurfer v6 volumes were analyzed using log-transformed measures and total brain volume. Models adjusted for age, sex, total brain volume, and site, with HC3 standard errors. Benjamini-Hochberg correction was applied separately to 21 age-independent domain-region tests and 21 domain-by-age interaction tests. None of the age-independent associations survived false-discovery-rate correction. One age interaction survived correction: the reciprocal-social-interaction association with bilateral caudate volume became more negative with increasing age (beta = -0.002933 per 1-SD score per year, 95% CI [-0.004804, -0.001061], p = 0.0021285, q = 0.044699). The coefficient remained negative and nominally significant in all 16 leave-one-site-out analyses. However, the interaction was not supported in participants aged 18 years or younger (N = 287; beta = 0.001548, p = 0.600141), and the estimate weakened when the upper age range was restricted. These findings provide qualified evidence of cross-sectional age heterogeneity in the reciprocal-social-interaction-caudate association, rather than an age-independent subcortical symptom signature. The pediatric null result, site-age imbalance, threshold-proximal corrected result, and absence of external replication require cautious interpretation and longitudinal confirmation.

Keywords: Autism spectrum disorder; Autism Brain Imaging Data Exchange; structural magnetic resonance imaging; subcortical volume; caudate nucleus; age moderation; Autism Diagnostic Interview-Revised; reciprocal social interaction.

INTRODUCTION

Autism is a heterogeneous neurodevelopmental condition in which social-communication features and restricted or repetitive behaviors vary substantially among individuals. Structural magnetic resonance imaging has been used extensively to investigate whether this clinical variability is accompanied by differences in brain morphology, including the anatomy of the amygdala, hippocampus, basal ganglia, thalamus, and nucleus accumbens. Large collaborative datasets have improved statistical power and anatomical coverage, but they have not identified a uniform subcortical profile of autism. In the ENIGMA Autism Working Group analysis, average case-control differences in subcortical volumes were small, and no diagnosis-by-age interactions were detected for the subcortical measures [1]. An independent ABIDE analysis similarly found few overall diagnostic effects while identifying age- and sex-dependent heterogeneity [2]. These findings indicate that diagnosis-level mean differences alone may obscure meaningful interindividual variation and cannot establish whether regional morphology covaries with the expression of particular autism-related features.

A dimensional approach can complement case-control comparisons by testing whether variation in behavior is associated with variation in brain structure within autistic individuals. This distinction is important because reciprocal social interaction, communication, and restricted or repetitive behavior are related but non-equivalent constructs, and combining them into a single overall score may conceal domain-specific neuroanatomical associations. Previous dimensional studies have linked autism-related characteristics to

distributed gray-matter covariance patterns and to partially distinct cortical thickness and surface-area patterns [3, 4]. Other work has related social-communication and repetitive-behavior measures to amygdala subnuclei during adolescence [5]. However, evidence is not uniformly positive: in a population-based sample of 7,005 children, associations between autistic traits and putamen or nucleus accumbens volumes did not persist after adjustment for global brain size [6]. Differences in population, behavioral instruments, age ranges, morphometric outcomes, and brain-size adjustment therefore limit direct comparison across dimensional studies.

The striatum provides a particularly relevant example of both the promise and inconsistency of symptom-oriented neuroimaging. In small autistic samples, greater repetitive-behavior scores have been associated with larger caudate or putamen volumes, whereas a study of young children reported associations between greater repetitive behavior and smaller volumes in several basal-ganglia and thalamic regions [7, 8]. Voxel-based morphometry has also linked caudate gray-matter volume to both repetitive behavior and combined social-communication difficulties [9], while shape analysis associated medial caudate deformation with reciprocal social and communication impairment in autistic boys [10]. In a larger ABIDE sample, restricted and repetitive behavior was related to pallidal surface area, although no overall volumetric differences were detected [11]. More recent connectivity-based parcellation has further suggested expansion of matrix-like striatal compartments in autism, underscoring that findings may depend on the anatomical phenotype examined [12]. Collectively, these studies implicate corticostriatal and related subcortical systems but do not establish a consistent volumetric association specific to any single symptom domain.

Age and global brain size are additional sources of variation that can alter subcortical inferences. Cross-sectional studies have reported age-dependent differences in striatal morphology, including the caudate, putamen, and pallidum, yet findings have varied across samples and morphometric measures [2, 11, 13]. Longitudinal work has also reported faster caudate growth in autistic children than in controls and an association between faster striatal growth and more severe early repetitive behavior [14]. Moreover, age distributions often differ between contributing sites in retrospectively aggregated datasets, making age-related effects difficult to separate from site composition. This concern is reinforced by an attempted out-of-sample replication of autism-related gray-matter covariance patterns in which conclusions were sensitive to site-by-group heterogeneity [15]. Regional-volume results also depend on how global brain size is handled: analyses of ABIDE I demonstrated that alternative total-brain-volume adjustments can change apparent subcortical group differences [16]. To our knowledge, literature publicly available through 30 April 2025 had not systematically integrated continuous ADI-R reciprocal-social, verbal-communication, and restricted/repetitive symptom dimensions with a prespecified bilateral subcortical region-of-interest set, explicit log-scale global brain-size adjustment, age-moderation testing, multiple-comparison control, and multi-site leave-one-site-out robustness in a large autistic-only ABIDE I analysis.

The present cross-sectional study therefore examined whether three Autism Diagnostic Interview-Revised (ADI-R) symptom dimensions-reciprocal social interaction, verbal communication, and restricted or repetitive behavior-were associated with bilateral subcortical volumes in 355 autistic participants from 16 ABIDE I sites, and whether these associations differed with age. Seven regions were evaluated within a common framework: the amygdala, hippocampus, caudate, putamen, pallidum, thalamus, and nucleus accumbens. Age-independent associations and symptom-by-age interactions were treated as separate test families with false-discovery-rate control, and leave-one-site-out analyses assessed the internal robustness of any corrected association. We hypothesized that the three symptom dimensions would show partially distinct subcortical associations; that restricted or repetitive behavior would be preferentially associated with basal-ganglia structures, particularly the caudate, putamen, and pallidum; that reciprocal-social and verbal-communication features would be preferentially associated with limbic structures, particularly the amygdala; and that age would moderate symptom-subcortical associations.

MATERIALS AND METHODS

Study design and data sources

This study was a cross-sectional secondary analysis of de-identified data from the Autism Brain Imaging Data Exchange I (ABIDE I), a multi-site resource that aggregated phenotypic and neuroimaging data collected by participating institutions [17]. The primary analyses were restricted to autistic participants and examined continuous associations between core autism symptom domains and subcortical volumes; typically developing participants were not included in these dimensional analyses. No new participants were recruited, and no longitudinal observations were analyzed. Phenotypic data were obtained from the ABIDE I preprocessed phenotypic release. Structural measures were obtained from publicly available, precomputed ABIDE I FreeSurfer v6 derivatives containing aggregated volumetric statistics for 1,035 participants. The scientific literature used to frame the study was restricted to sources first publicly available on or before 30 April 2025; this restriction applied only to source eligibility and did not imply that the analysis or manuscript preparation occurred before that date.

Participants

The ABIDE I phenotypic dataset contained 1,112 records, including 539 participants coded in the autistic diagnostic group. Eligibility for the primary symptom-morphometry analysis required an autistic-group designation (DX_GROUP=1), nonmissing age at scan and sex, and valid values for all three selected Autism Diagnostic Interview-Revised (ADI-R) symptom domains [18]. Values were required to fall within the documented ranges of 0-30 for reciprocal social interaction, 0-26 for verbal communication, and 0-12 for restricted/repetitive behavior. Records with missing or out-of-range values were excluded rather than imputed or manually corrected. Full-scale IQ and the ADI-R research-reliability indicator were not required for primary inclusion and were evaluated in sensitivity analyses. These criteria identified 376 phenotype-valid autistic participants. Of these, 355 had a one-to-one match to the structural derivative dataset and formed the final analytic sample across 16 sites; 21 phenotype-valid participants lacked a matching derivative record.

Symptom-domain measures

The three primary symptom variables were the ADI-R Reciprocal Social Interaction total (ADI_R_SOCIAL_TOTAL_A), Verbal Communication total (ADI_R_VERBAL_TOTAL_BV), and Restricted and Repetitive Behavior total (ADI_RRB_TOTAL_C). The communication variable therefore represented verbal communication rather than a complete communication domain or a nonverbal communication score. Each domain was standardized within the final analytic sample to a mean of zero and a standard deviation of one. Consequently, model coefficients for symptom terms represented differences associated with a one-standard-deviation increase in the corresponding domain score.

Structural MRI measures

The structural measures were derived from public ABIDE I FreeSurfer v6 outputs rather than from new image processing conducted for this study. FreeSurfer's automated whole-brain segmentation assigns neuroanatomical labels to the bilateral subcortical structures examined here [19]. Seven subcortical regions were selected a priori: amygdala, hippocampus, caudate, putamen, pallidum, thalamus, and nucleus accumbens. For each region, the left- and right-hemisphere FreeSurfer volumes were summed to obtain one bilateral measure. The thalamic measure used the left and right thalamus-proper fields, and the accumbens measure used the left and right accumbens-area fields. All seven bilateral volumes were available for every participant in the final analytic sample. Hemisphere-specific associations were not included in the primary testing framework.

Global brain-size adjustment

Total brain volume (TBV) was operationalized as the sum of cortical white-matter volume and total gray-matter volume. The aggregated intracranial-volume field contained severely implausible values in a subset of records and was therefore not retained as the primary global-size covariate. This decision was based on data quality rather than on comparative model results. Each bilateral regional volume and TBV were natural-log transformed, and log(TBV) was entered as a covariate rather than forming regional-volume-to-TBV ratios. This log-scale adjustment was selected to account for global brain-size variation while avoiding proportional normalization, which can distort regional inferences when regional and global volumes do not scale isometrically [16].

Primary statistical analysis

Age at scan was the primary age variable because an alternative MRI-acquisition-age field was available for only 53 of the 355 participants. Age at scan was centered at the final-sample mean of 14.906 years and modeled continuously. For each combination of three symptom domains and seven bilateral regions, an age-independent model regressed log-transformed regional volume on the standardized symptom score, centered age, sex, log-transformed TBV, and categorical site indicators. A corresponding age-moderation model additionally included the interaction between the standardized symptom score and centered age. Site was modeled using fixed categorical effects because an initially considered random-intercept formulation produced boundary or singular fits. Heteroskedasticity-consistent HC3 standard errors were used for primary inference [20].

The age-independent analyses comprised 21 domain-region tests, and the age-moderation analyses comprised a separate family of 21 domain-by-age interaction tests. Benjamini-Hochberg false-discovery-rate correction was applied separately within these two families [21]. An association was considered statistically significant when the FDR-adjusted q value was below 0.05. Nominal p values were not used as the primary multiplicity decision criterion. Because regional outcomes were analyzed on the natural-log scale, a symptom main-effect coefficient represented the adjusted difference in log regional volume per one-standard-deviation higher symptom score at the mean age. An interaction coefficient represented the yearly change in that symptom-volume association and did not represent longitudinal regional volume loss or within-person change.

Secondary joint-domain analysis

To examine whether associations were distinguishable after accounting for covariance among symptom domains, secondary models included all three standardized ADI-R domain scores simultaneously. These models retained centered age, sex, log-transformed TBV, and categorical site indicators and used HC3 standard errors. Pairwise correlations and variance inflation factors were used to characterize

overlap among the three domain scores. The joint-domain estimates were treated as explanatory secondary results and were not incorporated into the primary FDR families.

Robustness and sensitivity analyses

Internal robustness of the FDR-significant age interaction was assessed using leave-one-site-out analysis, in which the primary interaction model was refitted 16 times after omitting one site at a time. This analysis evaluated whether the estimate depended strongly on any single contributing site and was not treated as independent replication. Additional sensitivity analyses refitted the interaction after adjustment for centered full-scale IQ among participants with available data; restriction to participants marked as ADI-R research reliable; restriction to participants aged 18 years or younger or older than 18 years; restriction to male participants; restriction to sites contributing at least 10 participants; and truncation of the sample at maximum ages of 25, 30, and 35 years.

Because age distributions differed markedly among sites, further analyses excluded sites in which more than 80% of participants were older than 18 years, restricted the sample to sites contributing at least five participants aged 18 years or younger and at least five participants older than 18 years, and replaced overall age centering with centering within site. A separate sensitivity analysis excluded participants who were marked as an anatomical quality-control failure by any available rater field. This exclusion did not constitute complete project-specific manual inspection of all segmentations. Cluster-robust standard errors by site were examined as a supplementary diagnostic; interpretation was limited because only 16 site clusters were available. Sensitivity-analysis p values were treated as descriptive and nominal unless explicitly stated otherwise.

Potential nonlinearity in age moderation was assessed in a supplementary model using a cubic B-spline representation of age with four degrees of freedom and degree three. The interaction between the standardized reciprocal-social score and the complete set of spline basis terms was evaluated using a joint Wald test. This model was used as a flexible sensitivity analysis rather than as evidence of a longitudinal developmental trajectory, and estimates at sparsely represented older ages were interpreted cautiously.

Data quality and missing data

The primary analyses used complete cases for the required phenotype, demographic, and regional-volume variables; no values were imputed. Full-scale IQ was available for 344 participants and was included only in its corresponding sensitivity analysis. The ADI-R research-reliability indicator was positive for 326 participants and likewise was not a primary inclusion criterion. Publicly available anatomical quality-control flags were used only for a sensitivity analysis. The study did not perform complete manual visual inspection of the 355 final FreeSurfer segmentations, and the historical raw-image checks conducted for selected sites were not part of the primary structural-data workflow.

Ethics and data availability

This study used de-identified, openly shared ABIDE I data and involved no new participant contact or data collection. Ethical oversight and consent procedures for the original data collections were the responsibility of the contributing institutions, as documented by the ABIDE initiative. No local ethics approval, exemption, or protocol number is asserted here. The phenotypic data are available through the ABIDE I portal. The exact public FreeSurfer v6 structural derivative source is available through the FreeSurfer v6 derivative repository.

RESULTS

Sample derivation and characteristics

Of the 1,112 ABIDE I records, 539 belonged to the autistic diagnostic group and 376 met the phenotype-validity criteria. Structural derivative records were available for 355 of these participants, yielding a final analytic sample from 16 sites; 21 phenotype-valid participants lacked a matching structural record. Site sample sizes ranged from 5 to 66. The final sample included 309 male and 46 female participants. Mean age was 14.91 years (SD 6.30; median 13.31; range 7-49), with 287 participants aged 18 years or younger and 68 older than 18 years. Full-scale IQ was available for 344 participants and had a mean of 105.81 (SD 16.28). Symptom-domain and regional-volume distributions are reported in Table 1.

Participant derivation for the autistic-only dimensional analysis. Of 1,112 ABIDE I phenotypic records, 539 were classified in the autistic diagnostic group, 376 met the phenotype-validity criteria, and 355 had a one-to-one match to the public FreeSurfer v6 structural derivatives across 16 sites. ASD, autism spectrum disorder; ADI-R, Autism Diagnostic Interview-Revised; ABIDE I, Autism Brain Imaging Data Exchange I.

Age coverage differed substantially across sites. CALTECH, CMU, and SBL contributed predominantly adult participants, whereas only NYU, PITT, and TRINITY included at least five participants aged 18 years or younger and at least five participants older than 18 years. Complete site-specific age distributions are reported in Supplementary Table S3.

Supplementary Table S3. Site-specific age structure

Site	N	Age range, years	Mean age, years	N ≤18	N >18	Age-overlap criterion
CALTECH	15	17.50–39.20	24.56	1	14	No
CMU	14	19.00–39.00	26.36	0	14	No
KKI	19	8.09–12.54	10.01	19	0	No
MAX_MUN	5	7.00–12.00	9.40	5	0	No
NYU	66	7.13–29.98	13.74	53	13	Yes
OHSU	11	9.42–15.23	11.74	11	0	No
PITT	25	9.33–33.86	18.79	15	10	Yes
SBL	8	22.00–49.00	32.88	0	8	No
SDSU	12	12.13–17.15	14.66	12	0	No
STANFORD	18	7.53–12.94	10.09	18	0	No
TRINITY	22	12.00–23.08	16.81	14	8	Yes
UCLA_1	41	8.36–17.94	13.10	41	0	No
UCLA_2	12	10.04–16.47	12.71	12	0	No
UM_1	52	8.50–18.60	12.69	51	1	No
UM_2	13	12.80–17.40	14.88	13	0	No
YALE	22	7.00–17.75	12.64	22	0	No

Note: The age-overlap criterion required at least five participants aged 18 years or younger and at least five participants older than 18 years.

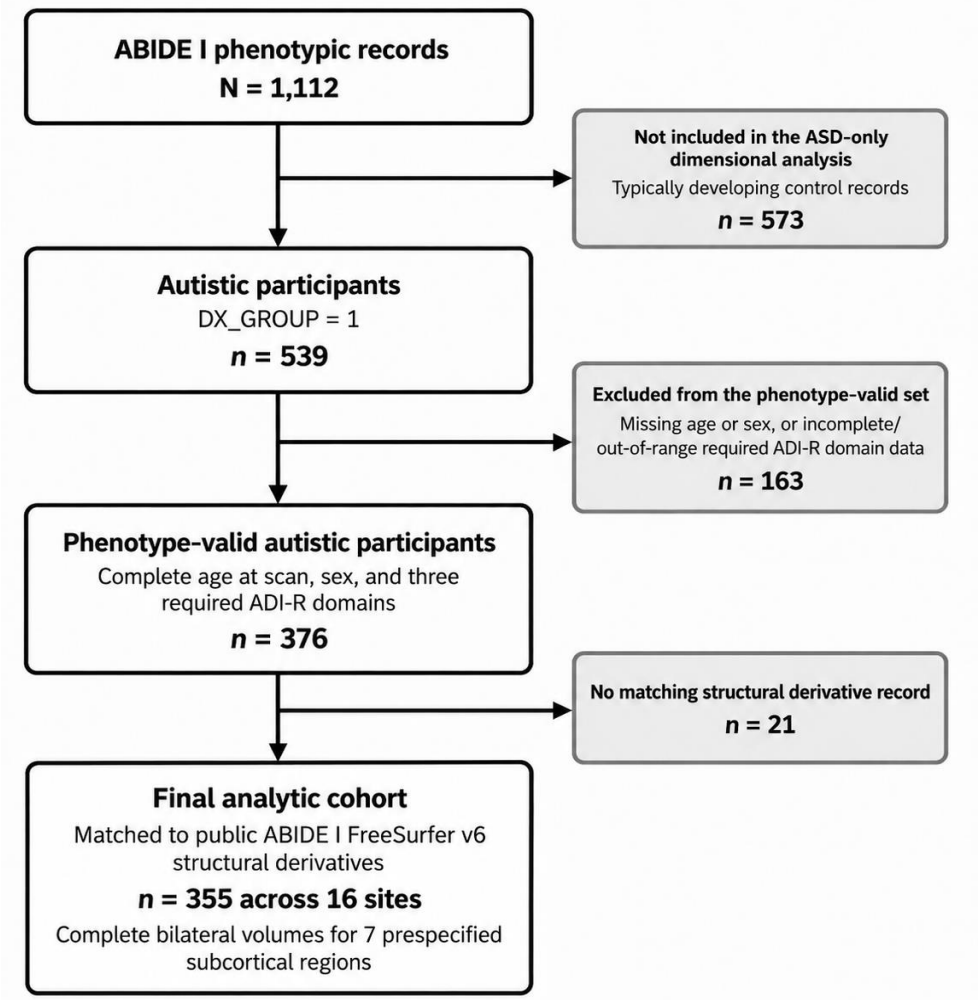

Figure 1: Derivation of the final analytic cohort from the ABIDE I phenotypic dataset.

Table 1: Characteristics of the final analytic sample

Characteristic	N	Mean (SD)	Median [IQR]	Range
Male sex	309	87.04%	-	-
Female sex	46	12.96%	-	-
Age ≤18 years	287	80.85%	-	-
Age >18 years	68	19.15%	-	-
Age, years	355	14.91 (6.30)	13.31 [10.89-16.77]	7.00-49.00
FIQ	344	105.81 (16.28)	105.00 [94.75-118.00]	61.00-148.00
ADI-R Reciprocal Social Interaction	355	19.68 (5.54)	20.00 [16.00-24.00]	2.00-30.00
ADI-R Verbal Communication	355	15.66 (4.63)	16.00 [12.00-19.00]	0.00-26.00
ADI-R RRB	355	6.01 (2.54)	6.00 [4.00-8.00]	0.00-12.00
TBV, mm³	355	1,193,041.93 (162,868.00)	1,206,898.48[1,105,822.24-1,292,542.58]	543,394.88-1,666,961.08
Bilateral Amygdala, mm³	355	3,418.44 (697.91)	3,418.00 [3,000.00-3,877.00]	447.00-5,668.00
Bilateral Hippocampus, mm³	355	8,308.01 (1,261.28)	8,429.00 [7,663.00-9,058.50]	3,083.00-12,047.00
Bilateral Caudate, mm³	355	8,152.78 (1,320.26)	8,199.00 [7,426.50-8,941.50]	2,977.00-12,883.00
Bilateral Putamen, mm³	355	13,179.24 (1,825.32)	13,236.00 [12,047.00-14,403.00]	5,166.00-18,249.00
Bilateral Pallidum, mm³	355	3,595.88 (546.93)	3,612.00 [3,283.50-3,957.00]	1,174.00-5,047.00
Bilateral Thalamus, mm³	355	14,700.93 (1,811.08)	14,580.00[13,624.00-15,826.50]	8,009.00-20,198.00
Bilateral Accumbens, mm³	355	1,633.82 (390.12)	1,653.00 [1,402.00-1,894.00]	43.00-2,762.00

Note: Percentages are reported in the Mean (SD) column for categorical characteristics. ADI-R, Autism Diagnostic Interview-Revised; FIQ, full-scale IQ; IQR, interquartile range; RRB, restricted/repetitive behavior; TBV, total brain volume.

Primary age-independent associations

None of the 21 age-independent symptom-domain associations with bilateral subcortical volume survived Benjamini-Hochberg correction. The smallest nominal p value was observed for verbal communication and caudate volume (beta = 0.012486, SE = 0.008036, 95% CI [-0.003264, 0.028237], p = 0.120244, q = 0.680854). The complete age-independent test family is reported in Supplementary Table S1.

Supplementary Table S1. Primary age-independent symptom-domain associations with bilateral subcortical volume

Domain	ROI	Beta	SE	95% CI	p	q	FDR significant
Reciprocal social interaction	Amygdala	-0.010392	0.009248	[-0.028518, 0.007734]	0.261153	0.680854	No
Reciprocal social interaction	Hippocampus	-0.007669	0.006098	[-0.019621, 0.004282]	0.208478	0.680854	No
Reciprocal social interaction	Caudate	0.006573	0.007130	[-0.007403, 0.020548]	0.356638	0.680854	No
Reciprocal social interaction	Putamen	0.000471	0.005653	[-0.010610, 0.011551]	0.933662	0.971944	No
Reciprocal social interaction	Pallidum	-0.005856	0.007093	[-0.019757, 0.008045]	0.408983	0.715721	No
Reciprocal social interaction	Thalamus	0.007052	0.004748	[-0.002254, 0.016357]	0.137468	0.680854	No
Reciprocal social interaction	Accumbens	-0.017518	0.012230	[-0.041488, 0.006452]	0.152037	0.680854	No
Verbal communication	Amygdala	0.005532	0.011215	[-0.016448, 0.027512]	0.621815	0.864040	No
Verbal communication	Hippocampus	0.003171	0.007169	[-0.010881, 0.017222]	0.658316	0.864040	No
Verbal communication	Caudate	0.012486	0.008036	[-0.003264, 0.028237]	0.120244	0.680854	No
Verbal communication	Putamen	0.006469	0.006248	[-0.005776, 0.018714]	0.300458	0.680854	No
Verbal communication	Pallidum	-0.006147	0.006347	[-0.018587, 0.006294]	0.332858	0.680854	No
Verbal communication	Thalamus	0.000489	0.005894	[-0.011064, 0.012041]	0.933912	0.971944	No
Verbal communication	Accumbens	0.004032	0.013679	[-0.022777, 0.030842]	0.768161	0.948904	No
Restricted/repetitive behavior	Amygdala	0.000875	0.009052	[-0.016867, 0.018617]	0.923010	0.971944	No
Restricted/repetitive behavior	Hippocampus	-0.002706	0.006029	[-0.014524, 0.009111]	0.653534	0.864040	No
Restricted/repetitive behavior	Caudate	0.000259	0.007377	[-0.014199, 0.014718]	0.971944	0.971944	No
Restricted/repetitive behavior	Putamen	0.005886	0.005414	[-0.004725, 0.016496]	0.276962	0.680854	No
Restricted/repetitive behavior	Pallidum	0.007705	0.006737	[-0.005499, 0.020910]	0.252736	0.680854	No
Restricted/repetitive behavior	Thalamus	0.005565	0.004758	[-0.003761, 0.014891]	0.242200	0.680854	No
Restricted/repetitive behavior	Accumbens	-0.008688	0.011923	[-0.032057, 0.014682]	0.466236	0.753150	No

Note: Beta is the standardized symptom-domain coefficient at the mean age. Benjamini–Hochberg q values were calculated across the 21 age-independent tests.

Primary age-moderation results

One of the 21 symptom-domain-by-age interactions survived FDR correction (Table 2). The interaction between reciprocal social-interaction severity and age was associated with bilateral caudate volume

(beta = -0.002933, SE = 0.000955, 95% CI [-0.004804, -0.001061], p = 0.0021285, q = 0.044699). On the log-volume scale, the adjusted association between a one-standard-deviation higher reciprocal-social score and bilateral caudate volume became 0.002933 more negative per additional year of age, corresponding approximately to a 0.293% yearly shift in the symptom-volume association. This estimate describes cross-sectional age moderation and not within-person caudate-volume change. The estimated symptom-volume association across the observed age range is presented in Figure 2.

Two additional interactions had nominal p values below 0.01 but did not survive FDR correction: restricted/repetitive behavior by age for caudate volume (beta = -0.003215, p = 0.005595, q = 0.053793) and verbal communication by age for thalamic volume (beta = 0.001894, p = 0.007685, q = 0.053793). These associations were therefore not classified as statistically significant.

Table 2: Primary symptom-domain-by-age associations with bilateral subcortical volume

Domain	ROI	Beta	SE	95% CI	p	q	FDR significant
Reciprocal social interaction	Amygdala	-0.000745	0.001050	[-0.002803, 0.001314]	0.478132	0.669384	No
Reciprocal social interaction	Hippocampus	-0.000716	0.000759	[-0.002204, 0.000772]	0.345703	0.518554	No
Reciprocal social interaction	Caudate	-0.002933	0.000955	[-0.004804, -0.001061]	0.002129	0.044699	Yes
Reciprocal social interaction	Putamen	-0.001591	0.000726	[-0.003015, -0.000167]	0.028564	0.121238	No
Reciprocal social interaction	Pallidum	-0.000875	0.000869	[-0.002577, 0.000828]	0.314011	0.518554	No
Reciprocal social interaction	Thalamus	0.001055	0.000639	[-0.000198, 0.002308]	0.098856	0.296568	No
Reciprocal social interaction	Accumbens	-0.002295	0.001733	[-0.005691, 0.001101]	0.185372	0.432534	No
Verbal communication	Amygdala	0.000035	0.001322	[-0.002557, 0.002627]	0.978764	0.978764	No
Verbal communication	Hippocampus	0.000032	0.000893	[-0.001717, 0.001781]	0.971351	0.978764	No
Verbal communication	Caudate	-0.002063	0.001068	[-0.004156, 0.000031]	0.053484	0.187195	No
Verbal communication	Putamen	-0.001006	0.000855	[-0.002682, 0.000670]	0.239479	0.457188	No
Verbal communication	Pallidum	-0.000464	0.000905	[-0.002239, 0.001311]	0.608452	0.751617	No
Verbal communication	Thalamus	0.001894	0.000710	[0.000501, 0.003286]	0.007685	0.053793	No
Verbal communication	Accumbens	-0.001987	0.001614	[-0.005151, 0.001177]	0.218429	0.457188	No
Restricted/repetitive behavior	Amygdala	-0.000686	0.001148	[-0.002935, 0.001564]	0.550199	0.722136	No
Restricted/repetitive behavior	Hippocampus	0.000038	0.000906	[-0.001739, 0.001814]	0.966923	0.978764	No
Restricted/repetitive behavior	Caudate	-0.003215	0.001160	[-0.005490, -0.000941]	0.005595	0.053793	No
Restricted/repetitive behavior	Putamen	-0.000908	0.000937	[-0.002744, 0.000928]	0.332237	0.518554	No
Restricted/repetitive behavior	Pallidum	-0.001354	0.000998	[-0.003309, 0.000601]	0.174566	0.432534	No
Restricted/repetitive behavior	Thalamus	-0.000336	0.000742	[-0.001790, 0.001118]	0.650483	0.758897	No
Restricted/repetitive behavior	Accumbens	-0.003726	0.001705	[-0.007068, -0.000384]	0.028866	0.121238	No

Note: Beta is the coefficient for the standardized symptom-domain-by-centered-age interaction in a model of natural-log bilateral ROI volume. Benjamini-Hochberg q values were calculated across the 21 interaction tests. FDR, false discovery rate; ROI, region of interest; SE, heteroskedasticity-consistent HC3 standard error.

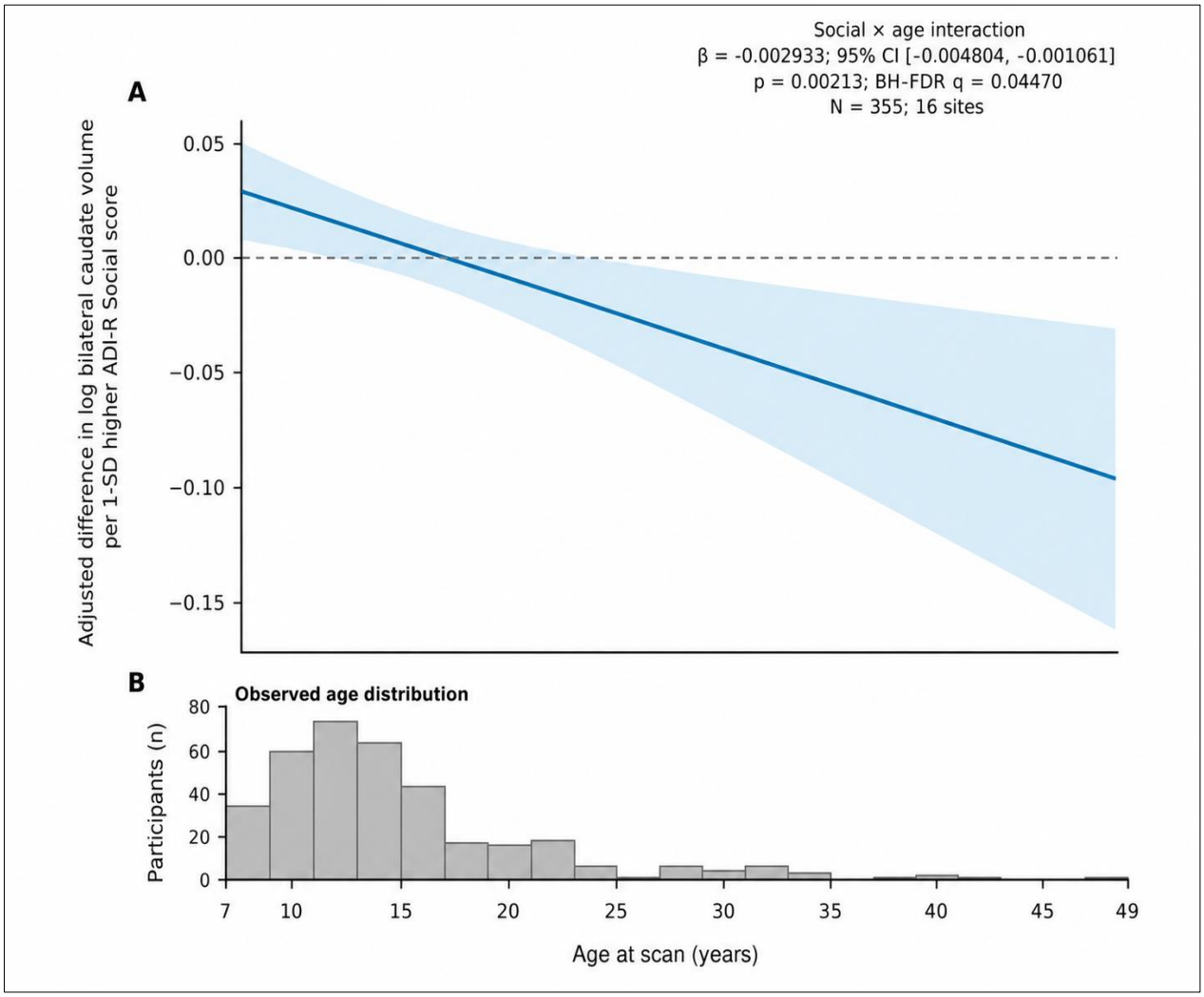

Figure 2: Age-specific adjusted association between reciprocal-social-interaction severity and bilateral caudate volume. Panel A shows the estimated difference in natural-log bilateral caudate volume per 1-SD higher ADI-R Reciprocal Social Interaction score across age, with pointwise 95% confidence intervals. Panel B shows the observed age distribution for 355 participants. The FDR-corrected interaction was beta = -0.002933 per 1-SD score per year (95% CI [-0.004804, -0.001061], p = 0.002129, q = 0.044699). The estimates describe a cross-sectional interaction and do not define a longitudinal trajectory or a significant age window

Secondary joint-domain models

Reciprocal social-interaction and verbal-communication scores were correlated (r = 0.703), whereas correlations involving restricted/repetitive behavior were smaller (social interaction: r = 0.326; verbal communication: r = 0.368). Variance inflation factors ranged from 1.169 to 2.067. In the secondary models containing all three symptom domains simultaneously, none of the 21 domain coefficients had a nominal p value below 0.05; the smallest p value was observed for reciprocal social interaction and accumbens volume (beta = -0.037116, SE = 0.022543, 95% CI [-0.081300, 0.007068], p = 0.099677). Complete joint-domain estimates are reported in Supplementary Table S2.

Supplementary Table S2. Secondary joint-domain models

ROI	Predictor	Beta	SE	95% CI	p
Amygdala	Reciprocal social interaction	-0.026845	0.017135	[-0.060428, 0.006738]	0.117184
Amygdala	Verbal communication	0.023902	0.020506	[-0.016289, 0.064093]	0.243768

Amygdala	Restricted/repetitive behavior	0.000959	0.010904	[-0.020412, 0.022330]	0.929926
Hippocampus	Reciprocal social interaction	-0.018157	0.011636	[-0.040963, 0.004649]	0.118662
Hippocampus	Verbal communication	0.016902	0.012961	[-0.008500, 0.042304]	0.192195
Hippocampus	Restricted/repetitive behavior	-0.002923	0.006972	[-0.016588, 0.010742]	0.675034
Caudate	Reciprocal social interaction	-0.002870	0.011171	[-0.024764, 0.019024]	0.797216
Caudate	Verbal communication	0.016253	0.012435	[-0.008119, 0.040625]	0.191194
Caudate	Restricted/repetitive behavior	-0.004825	0.008323	[-0.021139, 0.011488]	0.562107
Putamen	Reciprocal social interaction	-0.008011	0.009020	[-0.025691, 0.009669]	0.374501
Putamen	Verbal communication	0.010328	0.009769	[-0.008819, 0.029476]	0.290421
Putamen	Restricted/repetitive behavior	0.004722	0.006178	[-0.007386, 0.016831]	0.444624
Pallidum	Reciprocal social interaction	-0.004839	0.010388	[-0.025200, 0.015522]	0.641373
Pallidum	Verbal communication	-0.007156	0.009773	[-0.026311, 0.011999]	0.464053
Pallidum	Restricted/repetitive behavior	0.011984	0.008126	[-0.003942, 0.027910]	0.140265
Thalamus	Reciprocal social interaction	0.012009	0.008134	[-0.003933, 0.027952]	0.139841
Thalamus	Verbal communication	-0.009784	0.009293	[-0.027998, 0.008429]	0.292390
Thalamus	Restricted/repetitive behavior	0.005189	0.005144	[-0.004892, 0.015271]	0.313020
Accumbens	Reciprocal social interaction	-0.037116	0.022543	[-0.081300, 0.007068]	0.099677
Accumbens	Verbal communication	0.033052	0.024762	[-0.015480, 0.081584]	0.181939
Accumbens	Restricted/repetitive behavior	-0.008573	0.014377	[-0.036752, 0.019606]	0.550976

Note: All three standardized symptom-domain scores were entered simultaneously. These explanatory estimates were not included in either primary FDR family.

Leave-one-site-out robustness

The reciprocal-social-interaction-by-age coefficient for bilateral caudate volume remained negative in all 16 leave-one-site-out analyses and had a nominal p value below 0.05 in all 16 analyses. Coefficients ranged from -0.003076 to -0.002581, and p values ranged from 0.0009435 to 0.0365419. The least precise omitted-site estimate occurred after exclusion of NYU (beta = -0.002581, 95% CI [-0.005001, -0.000162], p = 0.036542). The complete estimates are presented in Supplementary Table S4 and Figure 3.

Supplementary Table S4. Leave-one-site-out estimates for the reciprocal-social-interaction-by-age association with bilateral caudate volume

Omitted site	N	Beta	SE	95% CI	p
CALTECH	340	-0.003034	0.001018	[-0.005029, -0.001039]	0.002872
CMU	341	-0.002811	0.001051	[-0.004871, -0.000752]	0.007470
KKI	336	-0.002934	0.000990	[-0.004874, -0.000993]	0.003051
MAX_MUN	350	-0.003027	0.000952	[-0.004893, -0.001161]	0.001475
NYU	289	-0.002581	0.001234	[-0.005001, -0.000162]	0.036542
OHSU	344	-0.002974	0.000968	[-0.004871, -0.001076]	0.002135
PITT	330	-0.002966	0.001056	[-0.005036, -0.000895]	0.004995
SBL	347	-0.003076	0.001161	[-0.005350, -0.000801]	0.008039
SDSU	343	-0.003075	0.000930	[-0.004897, -0.001252]	0.000944
STANFORD	337	-0.002904	0.000939	[-0.004745, -0.001064]	0.001982
TRINITY	333	-0.002928	0.000992	[-0.004871, -0.000984]	0.003150
UCLA_1	314	-0.003038	0.000977	[-0.004952, -0.001123]	0.001872
UCLA_2	343	-0.002887	0.000966	[-0.004780, -0.000995]	0.002792
UM_1	303	-0.002702	0.000930	[-0.004525, -0.000880]	0.003651
UM_2	342	-0.003002	0.000942	[-0.004848, -0.001156]	0.001434
YALE	333	-0.003018	0.000986	[-0.004951, -0.001085]	0.002213

Note: Each estimate was obtained after omitting the named site. These analyses assess internal robustness and are not independent replications.

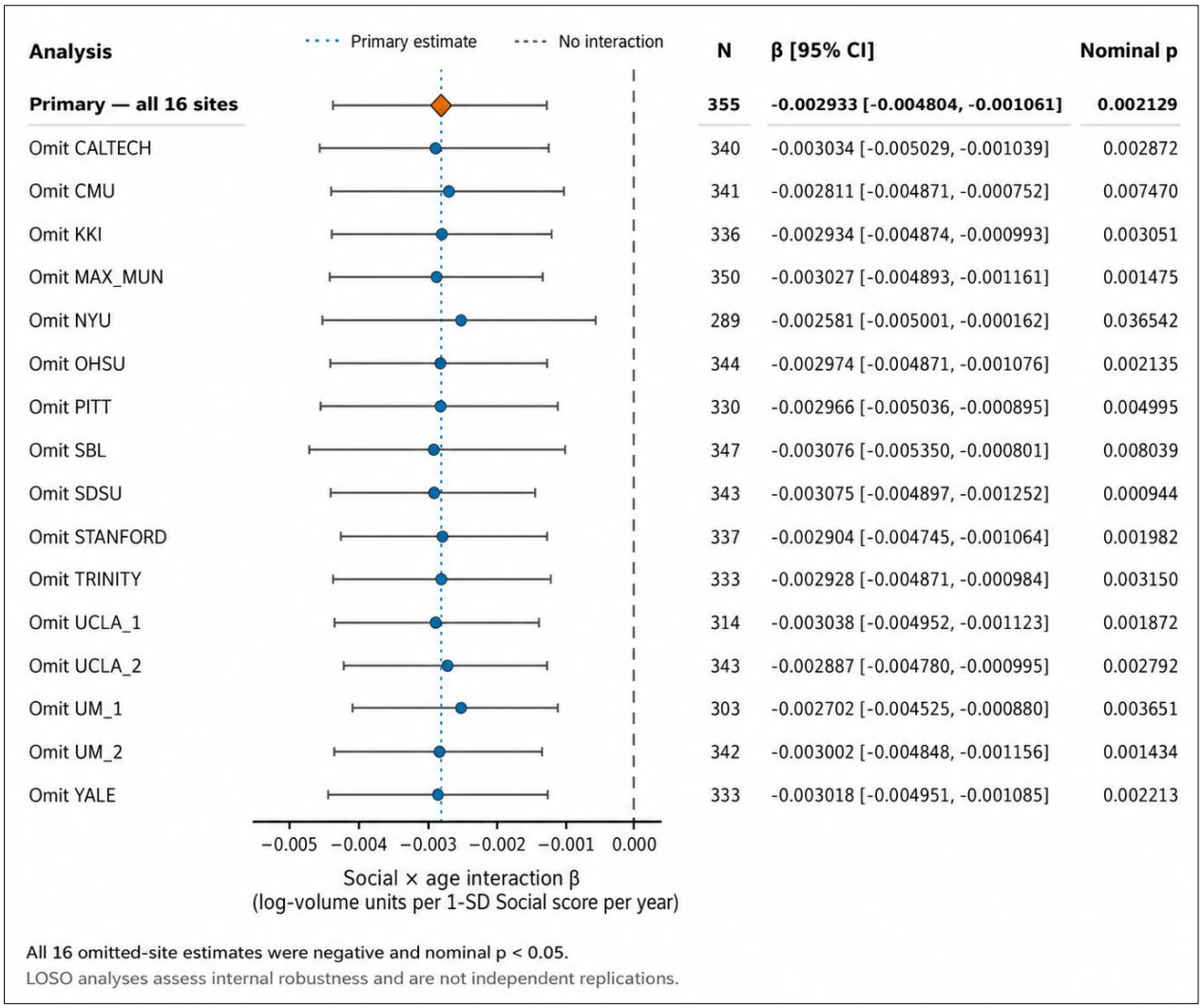

Figure 3: Leave-one-site-out robustness of the reciprocal-social-interaction-by-age association with bilateral caudate volume. The diamond denotes the primary estimate, and circles denote the 16 estimates obtained after omitting one site at a time; horizontal bars are 95% confidence intervals. The dashed vertical line marks zero, and the dotted line marks the primary estimate. All omitted-site estimates were negative and nominally significant. Because the refitted samples overlap, these estimates are internal robustness checks rather than independent replications

Sensitivity analyses

The reciprocal-social-interaction-by-age estimate remained negative with nominal p values below 0.05 after adjustment for full-scale IQ among the 344 participants with available data (beta = -0.002857, p = 0.010470), restriction to the 326 participants marked as ADI-R research reliable (beta = -0.003435, p = 0.002470), restriction to male participants (beta = -0.002877, p = 0.004820), and restriction to sites with at least 10 participants (beta = -0.003218, p = 0.005537). The estimate also remained negative after excluding adult-dominant sites (beta = -0.003032, p = 0.038824), restricting the analysis to the three sites satisfying the age-overlap criterion (beta = -0.004486, p = 0.013121), centering age within site (beta = -0.003683, p = 0.010000), and excluding participants with any available anatomical quality-control failure (beta = -0.002615, p = 0.015436).

The interaction was not supported in the subgroup aged 18 years or younger (N = 287; beta = 0.001548, 95% CI [-0.004241, 0.007337], p = 0.600141). In participants older than 18 years, the coefficient was negative but its confidence interval included zero (N = 68; beta = -0.003587, 95% CI [-0.007294, 0.000119], p = 0.057818). The estimate also weakened when the upper age range was truncated at 25 years (beta = -0.001927, p = 0.260765) or 30 years (beta = -0.002010, p = 0.078988), while the analysis capped at 35 years retained a negative nominal association (beta = -0.002190, p = 0.032090). All sensitivity estimates are reported in Table 3.

The supplementary cluster-by-site diagnostic produced the same point estimate as the primary model (beta = -0.002933, SE = 0.000453, 95% CI [-0.003899, -0.001967], p = 1.06×10^{-5}). Because only 16 site

clusters were available, this result was treated as a diagnostic rather than as the primary inferential analysis.

Table 3: Sensitivity analyses for the reciprocal-social-interaction-by-age association with bilateral caudate volume

Analysis	N	Sites	Beta	SE	95% CI	p
Primary	355	16	-0.002933	0.000955	[-0.004804, -0.001061]	0.002129
+FIQ	344	15	-0.002857	0.001116	[-0.005045, -0.000670]	0.010470
ADI-R reliable=1	326	13	-0.003435	0.001135	[-0.005659, -0.001211]	0.002470
Age ≤18	287	14	0.001548	0.002954	[-0.004241, 0.007337]	0.600141
Age >18	68	7	-0.003587	0.001891	[-0.007294, 0.000119]	0.057818
Males only	309	16	-0.002877	0.001020	[-0.004877, -0.000876]	0.004820
Sites N≥10	342	14	-0.003218	0.001160	[-0.005491, -0.000944]	0.005537
Age ≤ 25	330	16	-0.001927	0.001713	[-0.005285, 0.001431]	0.260765
Age ≤ 30	341	16	-0.002010	0.001144	[-0.004253, 0.000233]	0.078988
Age ≤ 35	350	16	-0.002190	0.001022	[-0.004193, -0.000187]	0.032090
Exclude adult-dominant sites (>80% age>18)	318	13	-0.003032	0.001468	[-0.005908, -0.000156]	0.038824
Only sites with ≥5 ≤18 and ≥5 >18	113	3	-0.004486	0.001808	[-0.008030, -0.000941]	0.013121
Within-site centered age	355	16	-0.003683	0.001430	[-0.006485, -0.000881]	0.010000
Exclude any explicit anatomical QC fail	285	16	-0.002615	0.001080	[-0.004732, -0.000499]	0.015436

Note: These sensitivity p values are nominal and descriptive; no additional multiplicity family was defined. FIQ, full-scale IQ; QC, quality control; SE, HC3 standard error unless otherwise specified.

Nonlinear age sensitivity

In the cubic B-spline sensitivity analysis, the joint interaction between reciprocal social-interaction severity and the four age basis terms yielded a Wald statistic of 11.046 (df = 4, p = 0.026051). The nonlinear estimates were interpreted as a sensitivity assessment over the sampled age distribution; individual estimates in the sparsely represented older age range were not used to define a specific developmental pattern.

DISCUSSION

In this cross-sectional analysis of 355 autistic participants from 16 ABIDE I sites, none of the 21 age-independent symptom-domain associations with bilateral subcortical volume survived FDR correction. One of the 21 symptom-by-age interactions did: the adjusted association between reciprocal social-interaction scores and bilateral caudate volume became more negative with increasing age. The interaction coefficient remained negative in all leave-one-site-out analyses and in several sensitivity analyses, but it was not supported in participants aged 18 years or younger and weakened when the upper age range was restricted. The findings therefore provide limited evidence for age-dependent heterogeneity in a symptom-volume association, rather than a general domain-specific subcortical signature.

The null age-independent findings are an important part of this interpretation. They did not support the proposed broad mapping of repetitive behavior to basal-ganglia volumes or reciprocal-social and verbal-communication features to limbic volumes under the tested additive models. This does not establish anatomical equivalence across symptom levels or exclude smaller, nonlinear, or spatially distributed associations. Studies using distributed gray-matter covariance and cortical measures have identified relationships with behavioral dimensions that are not directly comparable to whole-region bilateral volumes [3, 4]. Conversely, the absence of robust brain-size-adjusted subcortical associations in a large population-based study of autistic traits provides relevant negative evidence, although its population and symptom measure differed from ours [6]. Case-control findings of small or inconsistent average differences offer additional context, but diagnosis contrasts and within-autism dimensional analyses address different questions [1, 2].

The caudate result should be situated within existing symptom-oriented striatal research rather than presented as a new anatomical link. Earlier studies reported repetitive-behavior associations with caudate or putamen volumes, with differing directions across samples and behavioral measures [7, 8]. Caudate morphology has also been associated with social and communication difficulties using voxel-based and shape-based approaches [9, 10]. Thus, our result extends this literature by identifying an age interaction within a common, multiplicity-controlled regional-volume framework; it does not overturn the prior repetitive-behavior literature or identify a cellular mechanism. Importantly, only the social interaction passed the chosen FDR threshold, but significance in one domain and not another does not demonstrate a difference between domain coefficients. The domains were analyzed separately in the primary interaction models, and social and verbal-communication scores were

correlated. The secondary joint-domain models assessed additive associations, not mutually adjusted age interactions. Consequently, the present analyses do not establish that the age-dependent caudate association is uniquely attributable to reciprocal-social symptoms.

The age sensitivities materially constrain the finding. The interaction was unsupported in the pediatric-only sample ($p = 0.600141$), while the adult-only estimate had a confidence interval that included zero. Restricting the upper age limit to 25 or 30 years also attenuated the estimate. A narrower age range, fewer older observations, and changes in site composition could contribute to these differences, but these explanations were not distinguished empirically. Differences between subgroup p values are not themselves evidence of an age-group difference. The cubic B-spline joint test provided nominal support for an age-varying association under a more flexible model, but did not test whether a nonlinear interaction improved on the linear interaction. It therefore cannot identify a specific turning point or developmental window. Previous cross-sectional and longitudinal striatal findings and the absence of subcortical diagnosis-by-age effects in ENIGMA concern different estimands and cannot independently validate this within-autism interaction [1, 13, 14]. The negative coefficient describes variation between participants of different ages, not caudate shrinkage or within-person symptom-related change.

Multisite robustness also requires a qualified interpretation. Directional consistency and nominal significance in all 16 leave-one-site-out analyses make strong dependence on any single contributing site less likely. However, the refitted samples overlap extensively, so these estimates are correlated internal checks rather than independent replications. Persistence after excluding adult-dominant sites, restricting to sites with age overlap, and centering age within site provides additional sensitivity evidence. These checks nevertheless leave limited age overlap: only three sites met the specified child-adult overlap criterion. Fixed site indicators adjust site-specific mean differences but cannot ensure that scanner characteristics, recruitment practices, or unmeasured participant factors are unrelated to the symptom-by-age association. HC3 standard errors likewise do not resolve residual confounding or within-site dependence; the cluster-by-site calculation was only a supplementary diagnostic with 16 clusters. The site-sensitive gray-matter covariance findings reported by Mei *et al.,*[15] illustrate why stability within an aggregated dataset and generalizability to a new cohort should remain distinct claims.

Global brain-size adjustment defines another important boundary of inference. We modeled regional volumes conditional on operational TBV using log-transformed measures, rather than interpreting absolute regional size or regional-to-global ratios. Williams *et al.,*[16] showed that alternative brain-size adjustments can alter subcortical conclusions in ABIDE I, making this specification relevant to comparisons with earlier studies. The use of TBV here followed implausible values in the aggregated intracranial-volume field; TBV and intracranial volume are not interchangeable quantities. Although the models estimated a log-scale brain-size coefficient for each regional outcome, this was a covariate-adjustment strategy, not a comprehensive investigation of scaling differences across symptom levels, ages, or sexes. The observed interaction should therefore be understood as conditional on this global-size definition and model, without assuming that it would be unchanged under other defensible brain-size measurements.

Several design features support the interpretability of the analysis. All three symptom domains were assessed across the same seven bilateral regions in the same complete-case sample, allowing consistent comparisons within the specified framework. Separate FDR correction for the additive and interaction families reduced selective emphasis on isolated nominal associations, and the complete primary families were reported alongside favorable and unfavorable sensitivity results. Site adjustment and complementary restrictions on age, site composition, IQ availability, ADI-R reliability, and anatomical quality-control flags exposed important dependencies of the main finding. These features strengthen transparency and internal assessment, but neither the number of sensitivity analyses nor their consistency supplies external confirmation of an association selected from the primary test family.

Additional limitations should temper inference. Only one interaction passed FDR correction, with $q = 0.044699$ close to the specified threshold; follow-up sensitivity p values were nominal and should not be interpreted as separately corrected confirmations. Complete-case inclusion and the requirement for a valid verbal-communication score may select a subgroup that is not representative of the broader autistic population. The sample was predominantly male, included only 68 adults, and contained sparse observations at older ages. Full-scale IQ adjustment was restricted to participants with available values, and residual confounding by unmodeled clinical or participant characteristics remains possible. The temporal correspondence between the ADI-R scores and MRI was not established in this analysis, so the scores should not be assumed to represent symptom state at the exact scan date. Public aggregated structural derivatives were used without complete project-specific manual inspection of the final segmentations. Excluding explicit anatomical quality-control failures cannot rule out unflagged segmentation error. Bilateral whole-region volumes may also obscure lateralized or localized variation, as illustrated by prior surface-based findings [10, 11]. Finally, no external

cohort was analyzed, and no diagnostic, prognostic, or treatment-related performance was evaluated.

Practice-oriented educational work has discussed structured visual supports for developing emotion understanding in autistic children [22]. The present analysis did not measure emotion recognition or intervention response; therefore, its symptom-volume associations should not be interpreted as evidence for the neural mechanisms or effectiveness of such approaches.

CONCLUSION

In conclusion, this study did not identify FDR-supported age-independent associations between the three ADI-R symptom domains and bilateral subcortical volumes. It identified one corrected reciprocal-social-interaction-by-age association with caudate volume that was internally stable to site omission, but limited by the pediatric null result, upper-age sensitivity, site-age imbalance, and absence of external replication. The appropriate next step is an independently tested, prospectively specified analysis with balanced age coverage, harmonized morphometry, and clearly timed behavioral assessments. Longitudinal data would be needed to determine whether the cross-sectional pattern corresponds to within-person change. Until then, the finding is best regarded as a qualified age-moderation result within this ABIDE I sample.

ACKNOWLEDGEMENT

This study used data from the Autism Brain Imaging Data Exchange I. We acknowledge the participants, their families, the contributing investigators, and the data-sharing infrastructure that made this resource available.

REFERENCES

1. van Rooij, D., Anagnostou, E., Arango, C., Auzias, G., Behrmann, M., Busatto, G. F., *et al.,*(2018). Cortical and subcortical brain morphometry differences between patients with autism spectrum disorder and healthy individuals across the lifespan: Results from the ENIGMA ASD Working Group. *American Journal of Psychiatry, 175*(4), 359-369. https://doi.org/10.1176/appi.ajp.2017.17010100
2. Zhang, W., Groen, W., Mennes, M., Greven, C., Buitelaar, J., & Rommelse, N. (2018). Revisiting subcortical brain volume correlates of autism in the ABIDE dataset: Effects of age and sex. *Psychological Medicine, 48*(4), 654-668. https://doi.org/10.1017/S003329171700201X
3. Mei, T., Llera, A., Floris, D. L., Forde, N. J., Tillmann, J., Durston, S., *et al.,*(2020). Gray matter covariations and core symptoms of autism: The EU-AIMS Longitudinal European Autism Project. *Molecular Autism, 11*(1), 86. https://doi.org/10.1186/s13229-020-00389-4
4. Seelemeyer, H., Gurr, C., Leyhausen, J., Berg, L. M., Pretzsch, C. M., Schäfer, T., *et al.,*(2025). Decomposing the brain in autism: Linking behavioral domains to neuroanatomical variation and genomic underpinnings. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging, 10*(10), 1067-1077. https://doi.org/10.1016/j.bpsc.2024.12.003
5. Seguin, D., Pac, S., Wang, J., Nicolson, R., Martinez-Trujillo, J., & Duerden, E. G. (2021). Amygdala subnuclei development in adolescents with autism spectrum disorder: Association with social communication and repetitive behaviors. *Brain and Behavior, 11*(8), e2299. https://doi.org/10.1002/brb3.2299
6. Sharp, T. H., Elsabbagh, M., Pickles, A., & Bedford, R. (2023). The subcortical correlates of autistic traits in school-age children: A population-based neuroimaging study. *Molecular Autism, 14*(1), 6. https://doi.org/10.1186/s13229-023-00538-5
7. Hollander, E., Anagnostou, E., Chaplin, W., Esposito, K., Haznedar, M. M., Licalzi, E., *et al.,*(2005). Striatal volume on magnetic resonance imaging and repetitive behaviors in autism. *Biological Psychiatry, 58*(3), 226-232. https://doi.org/10.1016/j.biopsych.2005.03.040
8. Estes, A., Shaw, D. W. W., Sparks, B. F., Friedman, S., Giedd, J. N., Dawson, G., *et al.,*(2011). Basal ganglia morphometry and repetitive behavior in young children with autism spectrum disorder. *Autism Research, 4*(3), 212-220. https://doi.org/10.1002/aur.193
9. Rojas, D. C., Peterson, E., Winterrowd, E., Reite, M. L., Rogers, S. J., & Tregellas, J. R. (2006). Regional gray matter volumetric changes in autism associated with social and repetitive behavior symptoms. *BMC Psychiatry, 6*, 56. https://doi.org/10.1186/1471-244X-6-56
10. Qiu, A., Adler, M., Crocetti, D., Miller, M. I., & Mostofsky, S. H. (2010). Basal ganglia shapes predict social, communication, and motor dysfunctions in boys with autism spectrum disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 49*(6), 539-551.e4. https://doi.org/10.1016/j.jaac.2010.02.012
11. Schuetze, M., Park, M. T. M., Cho, I. Y. K., MacMaster, F. P., Chakravarty, M. M., & Bray, S. L. (2016). Morphological alterations in the thalamus, striatum, and pallidum in autism spectrum disorder. *Neuropsychopharmacology, 41*(11), 2627-2637. https://doi.org/10.1038/npp.2016.64
12. Waugh, J. L., Hassan, A. O. A., Funk, A. T., & Maldjian, J. A. (2025). The striatal matrix compartment is expanded in autism spectrum disorder. *Journal of Neurodevelopmental Disorders, 17*(1), 8. https://doi.org/10.1186/s11689-025-09596-7
13. Langen, M., Schnack, H. G., Nederveen, H., Bos, D., Lahuis, B. E., de Jonge, M. V., *et al.,*(2009). Changes in the developmental trajectories of striatum in autism. *Biological Psychiatry, 66*(4), 327-333. https://doi.org/10.1016/j.biopsych.2009.03.017

14. Langen, M., Bos, D., Noordermeer, S. D. S., Nederveen, H., van Engeland, H., & Durston, S. (2014). Changes in the development of striatum are involved in repetitive behavior in autism. *Biological Psychiatry, 76*(5), 405-411. https://doi.org/10.1016/j.biopsych.2013.08.013
15. Mei, T., Llera, A., Forde, N. J., van Rooij, D., Floris, D. L., Beckmann, C. F., & Buitelaar, J. K. (2024). Gray matter covariations in autism: Out-of-sample replication using the ENIGMA autism cohort. *Molecular Autism, 15*(1), 3. https://doi.org/10.1186/s13229-024-00583-8
16. Williams, C. M., Peyre, H., Toro, R., Beggiato, A., & Ramus, F. (2020). Adjusting for allometric scaling in ABIDE I challenges subcortical volume differences in autism spectrum disorder. *Human Brain Mapping, 41*(16), 4610-4629. https://doi.org/10.1002/hbm.25145
17. Di Martino, A., Yan, C.-G., Li, Q., Denio, E., Castellanos, F. X., Alaerts, K., *et al.,*(2014). The autism brain imaging data exchange: Towards a large-scale evaluation of the intrinsic brain architecture in autism. *Molecular Psychiatry, 19*(6), 659-667. https://doi.org/10.1038/mp.2013.78
18. Lord, C., Rutter, M., & Le Couteur, A. (1994). Autism Diagnostic Interview-Revised: A revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *Journal of Autism and Developmental Disorders, 24*(5), 659-685. https://doi.org/10.1007/BF02172145
19. Fischl, B., Salat, D. H., Busa, E., Albert, M., Dieterich, M., Haselgrove, C., *et al.,*(2002). Whole brain segmentation: Automated labeling of neuroanatomical structures in the human brain. *Neuron, 33*(3), 341-355. https://doi.org/10.1016/S0896-6273(02)00569-X
20. MacKinnon, J. G., & White, H. (1985). Some heteroskedasticity-consistent covariance matrix estimators with improved finite sample properties. *Journal of Econometrics, 29*(3), 305-325. https://doi.org/10.1016/0304-4076(85)90158-7
21. Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B (Methodological), 57*(1), 289-300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x
22. Karaieva, M. (2023). Developing understanding of emotions in children with autism: A structured visual approach and its effectiveness in practice. *Актуальные исследования*, No. 47 (177). https://doi.org/10.51635/AI-47-177_s7z4h