Supplementary Materials for

Physical-Digital and Social-Nonsocial Extracurricular Engagement: Differential Effects on Brain Development and Psychological Outcomes in Children

Description of Supplementary Files

This file includes:
Supplementary Methods 1-5.
Supplementary Results 1-3.
Supplementary Figures and Legends 1-19.
Supplementary Tables and Legends 1-12.

Other Supplementary Materials for this manuscript include the following:
Supplemental Table 2 (Separate file *sheet 1*).
Supplemental Table 6 (Separate file *sheet 2*).
Supplemental Table 7 (Separate file *sheet 3*).
Supplemental Table10 (Separate file *sheet 4*).
Supplemental Table 11 (Separate file *sheet 5*).

Table of Contents

Supplementary Table 10. Standardized Path Coefficients from CLPM Analysis Between Activity Engagement and Mental Health Symptoms

Supplementary Table 11. *P* values and FDR-corrected *P* values from CLPM Analysis Between Activity Engagement and Mental Health Symptoms

Supplementary Table 12. Standardized Estimate effects and *P* values in Mediation Analysis

Supplementary Methods 1. Measurement Resources and Preprocessing Details for Weekly Activity Engagement

Digital activities

Detailed item information and response scales for the six screen time activities measured in the ABCD Youth Screen Time Survey are provided in Table S1. Participants' engagement with each type of digital activity (screen media activity) was assessed through separate inquiries regarding weekday and weekend use:
For instance, for the activity type "watching TV shows or movies," participants were asked:

- "On a typical weekday, how many hours do you spend watching TV shows or movies?"
- "On a typical weekend day, how many hours do you spend watching TV shows or movies?"

Participants reported their engagement using seven options: none, less than 30 minutes, 30 minutes, 1 hour, 2 hours, 3 hours, and 4 or more hours[1]. We converted these categorical responses to numerical values (0, 0.25, 0.5, 1, 2, 3, and 4 respectively) for standardized analysis. Overall weekly engagement for each digital activity was calculated as: (weekday engagement hours × 5) + (weekend engagement hours × 2) [2].

Physical activities

Children's engagement in physical activities was assessed using caregiver-reported information from the Sports and Activities Involvement Questionnaire (SAI-Q). The SAI-Q, adapted from the Vermont Health and Behavioral Questionnaire (VHBQ) and the Dutch Health Behavioral Questionnaire (DHBQ), evaluates participation in various activities over the lifetime and during the past year. Caregivers were asked to provide details about their child's most active period of participation in each activity, including: (1) the number of minutes per session (***tspent***), (2) the number of days per week (***perwk***), and (3) the number of months per year (***nmonth***) [3]. For example, children's engagement in a specific activity type was recorded through caregiver-reported responses to the following questions:

- **Minutes per session (*tspent*):** "About how many minutes per session?"
  - Responses were coded as: 0 (none), 1 (<30 minutes), 2 (30 minutes), 3 (45 minutes), 4 (60 minutes/1 hour), 5 (90 minutes/1.5 hours), 6 (120 minutes/2 hours), 7 (150 minutes/2.5 hours), 8 (180 minutes/3 hours), 9 (>3 hours), and 999 (Don't know).
- **Days per week (*perwk*):** "About how many days per week?
  - Responses were coded as: 0 (none); 1–7 = exact number of days; 8 = once every 2 weeks; 9 = one day every month; 10 = less than one day per month; and 999 = Don't know.
- **Months per year (*nmonth*):** "About how many months per year did your child participate?"
  - Responses were recorded across 13 categories: months 1–12 and 999 (Don't know).

After excluding participants with responses coded as 999, we recoded the responses for ***tspent*** and ***perwk*** to ensure that higher values represented greater engagement duration, as follows:

- ***Tspent:*** Session durations were coded in hours, 0 = 0 hours, <0.5 = 0.25 hours, 0.5 = 0.5 hours, 0.75 = 0.75 hours, 1 = 1 hour, 1.5 = 1.5 hours, 2 = 2 hours, 2.5 = 2.5 hours, 3 = 3 hours, and >3 = 3.5 hours.
- ***Perwk:*** Responses were mapped to weekly engagement values: 0–7 days were retained as exact counts, "once every two weeks" was recoded as 0.5 days/week, "one day every month" as 0.23 days/week, and "less than one day per month" as 0.033 days/week.

The average weekly engagement hours for a specific activity were calculated using the recoded responses with the formula: (tspent × perwk × nmonth) / (12 × 60) [4].

Supplementary Methods 2. Description of Mental Health, Psychiatric Diagnoses and Imaging Measures

Mental Health Measures

We analyzed behavioral measures using the Child Behavior Checklist (CBCL), which comprises three primary domains: internalizing problems, externalizing problems, and problem behaviors. Each domain contains symptom-specific scales. The severity of behavioral problems was indicated by higher scores, with values exceeding 60 considered clinically significant for potential disorders. The following CBCL metrics were incorporated in our analysis:

- Internalizing Problems:
    - Anxious/Depressed
    - Withdrawn/Depressed
    - Somatic Complaints
    - Internalizing Problems Total
- Externalizing Problems:
    - Rule-Breaking Behavior
    - Aggressive Behavior
    - Externalizing Problems Total
- Problem behaviors:
    - Social Problems
    - Thought Problems
    - Attention Problems
- Mental Health Total Problems

Psychiatric Diagnoses Assessment

To evaluate the relationship between activity engagement and psychiatric diagnoses, we preprocessed Wave 1 (baseline) records from the ABCD Parent Diagnostic Interview for DSM-5 Full, producing two primary outputs: (1) the Symptoms/Comments Report, which details individual symptom endorsements, and (2) the Diagnosis Report, which categorizes current and past diagnoses using ICD-10 codes[5]. Initially, 145 diagnostic items were retained, from which 112 clinically meaningful items were selected based on predefined exclusion criteria. These items were further categorized into 17 diagnostic groups following the KSADS-COMP modular taxonomy[6]. For statistical analyses, we focused on mental health-relevant diagnostic groups, as defined by the Hierarchical Taxonomy of Psychopathology (HiTOP) framework[7]. After applying this classification, 15 diagnostic groups and their corresponding diagnostic items (106 items) were retained for analysis, with items of extremely low prevalence (≤1 case in the total sample) excluded. A complete workflow diagram is available in Fig. S3, and detailed variable information is provided in Table S2.

Imaging Acquisition and Preprocessing

Neuroimaging data in the ABCD study were acquired using harmonized protocols across sites with 3T MRI scanners (Siemens, Phillips, or General Electric) equipped with 32-channel head coils. All participants underwent T1-weighted structural imaging at 1-mm isotropic resolution. The ABCD Data Analysis and Informatics Core's preprocessing pipeline included gradient nonlinearity correction for T1/T2-weighted images, T2 to T1 image registration using mutual information, B1-bias field correction for signal inhomogeneity, and spatial normalization to a standardized template (for preprocessing details, see Hagler et al[8]). FreeSurfer v5.3 was then employed for cortical surface reconstruction and subcortical segmentation to generate morphometric measures. In the current study, we focused on analyzing regional gray matter volumes across 68 cortical regions as defined by the Desikan-Killiany atlas[9].

Supplementary Methods 3. Neurosynth Decoding

To elucidate the functional significance of brain volumetric patterns associated with different extracurricular activity engagement profiles, we conducted meta-analytic decoding using Neurosynth (https://github.com/neurosynth/neurosynth), which aggregates over 15,000 fMRI studies. This platform facilitates cognitive interpretation of brain activity patterns by establishing probabilistic relationships between reported neural activation coordinates and psychological constructs through automated text-mining of neuroimaging literature. The inference framework enables systematic mapping between spatial activation patterns and their associated cognitive states or functions based on the statistical co-occurrence of brain regions and psychological terms across the literature. We focused on 42 terms across three primary functional domains: Mental and Physical Health (N=18; such as depression, anxiety, psychosis, sleep, and pain), Attention and Executive Function (N=9; such as maintenance, focus, and attention), and Social Cognition and Communication (N =15; such as face recognition, facial expression, empathy, communication, social interaction, and social cognitive).Decoding was performed by correlating brain volumetric t-maps derived from each extracurricular engagements pattern with the 42 term-specific meta-analytic maps, following procedures in the Neurosynth repository (https://github.com/neurosynth/neurosynth) [10].

Supplementary Methods 4. Sensitivity Analysis

To evaluate the robustness of the primary baseline and longitudinal associations between activity engagement, mental health symptoms, and cortical gray matter volume, a series of sensitivity analyses were conducted, encompassing alternative activity definitions and temporal specifications of digital engagement, as well as additional covariate controls including intracranial volume and family structure.

Sensitivity analyses excluding potentially ambiguous activity items

To evaluate whether the primary associations were influenced by activity items with potentially ambiguous conceptual classification, sensitivity analyses were performed under alternative activity definitions. Two alternative exclusion strategies were implemented. In the first, tennis was excluded from the physical non-social category and video games were excluded from the digital non-social category (Fig. S8). In the second, a more conservative definition was applied by additionally excluding running and going to the gym from the physical non-social category (Fig. S9). All other analytic specifications matched those used in the primary association analyses.

Sensitivity analyses of weekday versus weekend digital activity engagement

To examine whether associations were sensitive to how digital activity engagement was temporally aggregated, digital social and digital non-social activity were decomposed into weekly total, weekday, and weekend measures. Associations with mental health symptoms and cortical gray matter volume were re-estimated for each temporal specification using the same modeling approach as in the main analyses (Fig. S10). In addition, sensitivity analyses of group differences in digital activity engagement between psychiatric diagnostic groups and matched controls were conducted for weekly, weekday, and weekend measures using the same group-comparison procedures as in the corresponding primary analyses (Fig. S11). CLPM and mediation analyses were similarly re-estimated for weekday and weekend measures using the same covariates and modeling specifications as in the main longitudinal analyses (Fig. S12-S13).

Sensitivity analyses controlling for intracranial volume

To determine whether activity–brain associations reflected regional cortical variation rather than global differences in head size, sensitivity analyses of cortical gray matter volume were conducted with intracranial volume (ICV) included as an additional covariate. All other modeling components were identical to those used in the primary cortical association analyses (Fig. S14).

To formally quantify the similarity between the original and ICV-adjusted cortical maps, we computed region-wise correlations of t-statistics across the Desikan–Killiany atlas. Strong spatial concordance was observed for all activity categories (Spearman $r \geqslant 0.97$). Statistical significance of these correlations was assessed using BrainSMASH to account for spatial autocorrelation (10,000 permutations; all $P < .001$) (Fig. S15). These results indicate that the cortical associations were not attributable to differences in overall brain size.

Sensitivity analyses controlling for within-family relatedness

Given the presence of twins and siblings in the ABCD cohort, sensitivity analyses were performed to account for family structure in baseline association models following established ABCD practices[11]. Family ID (*rel_family_id*) was included as a random intercept to model shared familial variance, and relationship type (*rel_relationship*; sibling, twin, or triplet) was included as a fixed-effect covariate (Fig. S16). These models otherwise matched the primary baseline association analyses. For longitudinal analyses, CLPM and mediation models were specified analogously, with family ID and relationship type included as covariates to account for within-family relatedness (Fig. S17–S18).

For all sensitivity analyses involving cortical gray matter volume, spatial correspondence between sensitivity-derived and primary cortical effect-size maps was formally evaluated using BrainSMASH, a generative modeling framework that accounts for spatial autocorrelation in cortical surface data[12] All spatial correlations exceeded $r = 0.83$ ($P < 0.0001$), following the same procedure applied in the analyses controlling for intracranial volume.

Supplementary Methods 5. Nonlinear Analyses of Activity Engagement and Mental Health Symptoms.

To examine potential nonlinear associations between activity engagement and mental health symptoms, we conducted supplementary analyses using generalized additive mixed models (GAMMs) on Wave 1 data. These analyses were implemented using the *mgcv* R package (v 1.9.1)[13] and were specified to parallel the primary linear mixed-effects modeling framework.

For each activity domain, separate GAMMs were fitted for each CBCL symptom measure. Activity engagement variables were log-transformed *log10*(x+1) to reduce skewness and were mean-centered prior to analysis. Mental health symptom scores were standardized. Nonlinear effects of activity engagement were modeled using penalized smooth terms based on thin-plate regression splines.

All models adjusted for the same fixed-effect covariates as in the primary linear mixed-effects analyses, including age, sex assigned at birth, race/ethnicity, family income, parental education, pubertal status, and body mass index (BMI). Study site was included as a random-effect smooth term to account for clustering across data collection sites. Model parameters were estimated using restricted maximum likelihood (REML). The statistical significance of nonlinear effects was evaluated using the F statistic associated with each smooth term. To account for multiple testing across activity–symptom combinations, false discovery rate (FDR) correction was applied to the resulting p values. For associations exhibiting significant nonlinearity, smooth functions were visualized with 95% confidence intervals.

Supplementary Results 1. Neurosynth Functional Annotations for Category-Specific Volume Alteration Patterns

Neurosynth term correlation analyses revealed systematic associations between activity-specific gray matter volume and brain regions supporting mental health, executive function, and social cognitive processes (Table S9). The strongest associations were observed in mental health-related terms, where physical social and digital non-social activities showed differential associations with pain ($r = -0.186$ and $r = 0.229$, respectively), stress ($r = -0.132$ and $r = 0.157$, respectively), and anxiety ($r = -0.109$ and $r = 0.143$, respectively). Other mental health indicators, including depression, psychosis, and addiction, showed associations of smaller magnitude ($|r| < 0.10$) across all activity categories. In the domain of attention and executive function, attention-related processes showed notable associations with both physical social ($r = 0.109$) and digital non-social ($r = -0.140$) activities, while executive components including maintenance ($r = 0.071$) and updating ($r = 0.061$) demonstrated specific associations with physical social activities. Analysis of social cognitive processes revealed activity-specific patterns, with face recognition showing differential associations with physical activities (social: $r = 0.102$; non-social: $r = -0.119$), and mentalizing processes demonstrating associations with both physical social ($r = 0.085$) and digital social ($r = -0.104$) activities. Higher-order social cognitive processes, including judgment and inference, showed consistent associations across physical activities ($|r|$ range, 0.051-0.098), while digital activities demonstrated relatively modest associations ($|r| < 0.05$) in these domains. Collectively, these findings suggest that different activity categories may influence child development through activity-specific modulation of gray matter volume in brain regions supporting key developmental functions.

Supplementary Results 2. Sensitivity Analysis of Development Association Patterns Across Activity Categories

To mitigate potential bias from the left-skewed distribution of weekly participation hours, we implemented a sensitivity analysis focusing on participants with non-zero engagement (>0 hours/week) across activity categories. Among participants with non-zero engagement, digital non-social activities showed the highest median weekly participation (median [IQR], 17.0 [9.2-30.5] hours; n=8,198), followed by digital social activities (median [IQR], 3.5 [1.8-6.0] hours; n=4,649). Physical activities showed comparable patterns, with non-social (median [IQR], 2.2 [1.0-4.0] hours; n=6,071) and social activities (median [IQR], 2.0 [1.0-3.5] hours; n=6,041). Critically, our sensitivity analysis corroborated the primary findings, with consistent mental health (Fig. S5, Table S5) and neuroanatomical associations (Fig. S6), thereby substantiating the robustness of our original observations.

Supplementary Results 3. Nonlinear Associations Between Activity Engagement and Mental Health Symptoms.

The GAMM analyses focused on activity domains that showed the strongest associations in the primary linear mixed-effects models (Fig. S19). Across CBCL symptom measures, physical social activity exhibited predominantly linear associations with internalizing, externalizing, and total mental health problems, as indicated by effective degrees of freedom (EDF) values close to 1 for the corresponding smooth terms. In contrast, digital non-social activity showed clear nonlinear associations with all three symptoms, characterized by higher EDF values and U-shaped patterns in the estimated smooth functions. Specifically, both low and high levels of digital non-social activity engagement were associated with higher symptom scores, whereas intermediate levels were associated with relatively lower symptom severity. Together, these findings suggest that nonlinear relationships may be particularly relevant for digital non-social activity engagement, whereas associations involving physical social activity appear largely linear within the observed range of participation.

Supplementary References

1 Bagot, K. S., Tomko, R. L., Marshall, A. T., Hermann, J., Cummins, K., Ksinan, A. *et al.* Youth screen use in the ABCD study. *Developmental cognitive neuroscience* **57**, 101150 (2022).

2 Nagata, J. M., Smith, N., Alsamman, S., Lee, C. M., Dooley, E. E., Kiss, O. *et al.* Association of Physical Activity and Screen Time With Body Mass Index Among US Adolescents. *JAMA network open* **6**, e2255466 (2023).

3 Huppertz, C., Bartels, M., de Zeeuw, E. L., van Beijsterveldt, C. E. M., Hudziak, J. J., Willemsen, G. *et al.* Individual Differences in Exercise Behavior: Stability and Change in Genetic and Environmental Determinants From Age 7 to 18. *Behavior genetics* **46**, 665-679 (2016).

4 Ku, B. S., Yuan, Q., Arias-Magnasco, A., Lin, B. D., Walker, E. F., Druss, B. G. *et al.* Associations Between Genetic Risk, Physical Activities, and Distressing Psychotic-like Experiences. *Schizophrenia bulletin* (2024).

5 Townsend, L., Kobak, K., Kearney, C., Milham, M., Andreotti, C., Escalera, J. *et al.* Development of Three Web-Based Computerized Versions of the Kiddie Schedule for Affective Disorders and Schizophrenia Child Psychiatric Diagnostic Interview: Preliminary Validity Data. *Journal of the American Academy of Child & Adolescent Psychiatry* **59**, 309-325 (2020).

6 Barch, D. M., Albaugh, M. D., Baskin-Sommers, A., Bryant, B. E., Clark, D. B., Dick, A. S. *et al.* Demographic and mental health assessments in the adolescent brain and cognitive development study: Updates and age-related trajectories. *Developmental cognitive neuroscience* **52**, 101031 (2021).

7 Cicero, D. C., Ruggero, C. J., Balling, C. E., Bottera, A. R., Cheli, S., Elkrief, L. *et al.* State of the Science: The Hierarchical Taxonomy of Psychopathology (HiTOP). *Behavior therapy* **55**, 1114-1129 (2024).

8 Hagler, D. J., Jr., Hatton, S., Cornejo, M. D., Makowski, C., Fair, D. A., Dick, A. S. *et al.* Image processing and analysis methods for the Adolescent Brain Cognitive Development Study. *Neuroimage* **202**, 116091 (2019).

9 Desikan, R. S., Segonne, F., Fischl, B., Quinn, B. T., Dickerson, B. C., Blacker, D. *et al.* An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage* **31**, 968-980 (2006).

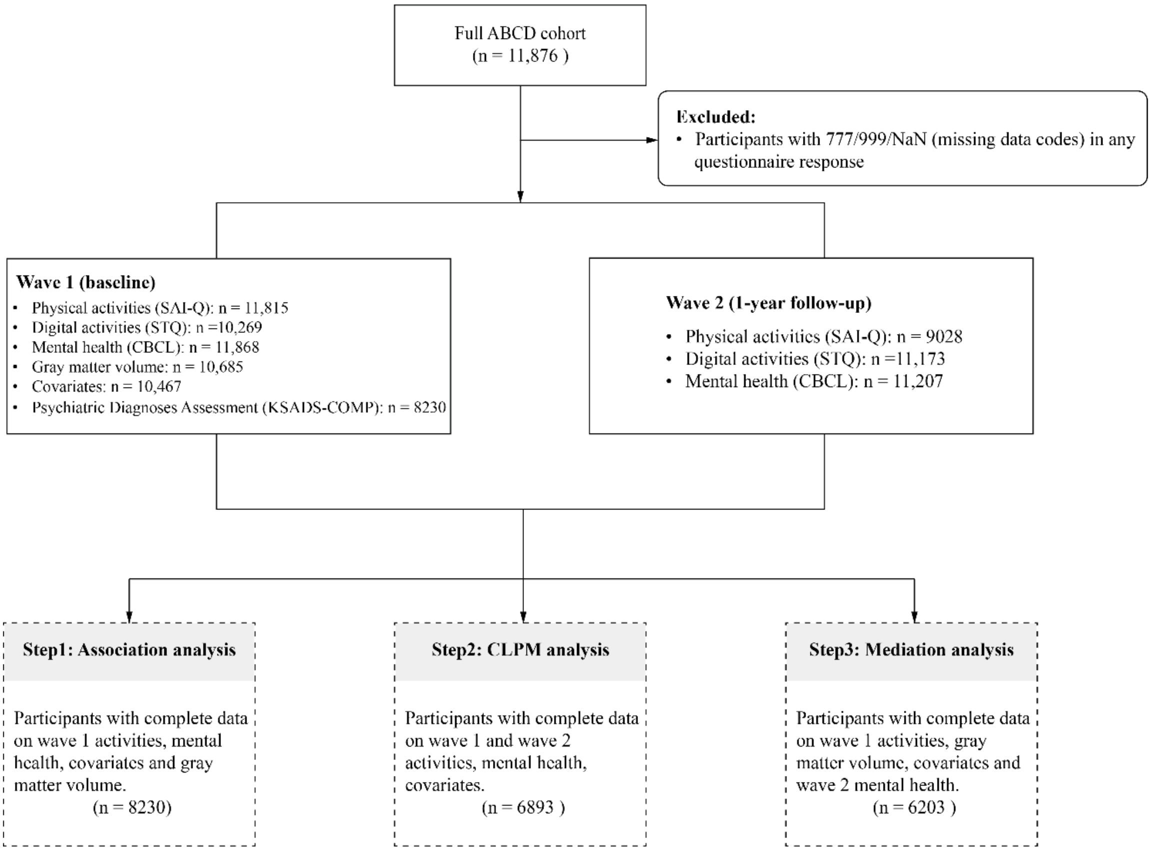
10 Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C. & Wager, T. D. Large-scale automated synthesis of human functional neuroimaging data. *Nature methods* **8**, 665-670 (2011).

11 Miller, A. P., Baranger, D. A. A., Paul, S. E., Garavan, H., Mackey, S., Tapert, S. F. *et al.* Neuroanatomical Variability and Substance Use Initiation in Late Childhood and Early Adolescence. *JAMA Network Open* **7**, e2452027-e2452027 (2024).

12 Burt, J. B., Helmer, M., Shinn, M., Anticevic, A. & Murray, J. D. Generative modeling of brain maps with spatial autocorrelation. *NeuroImage* **220**, 117038 (2020).

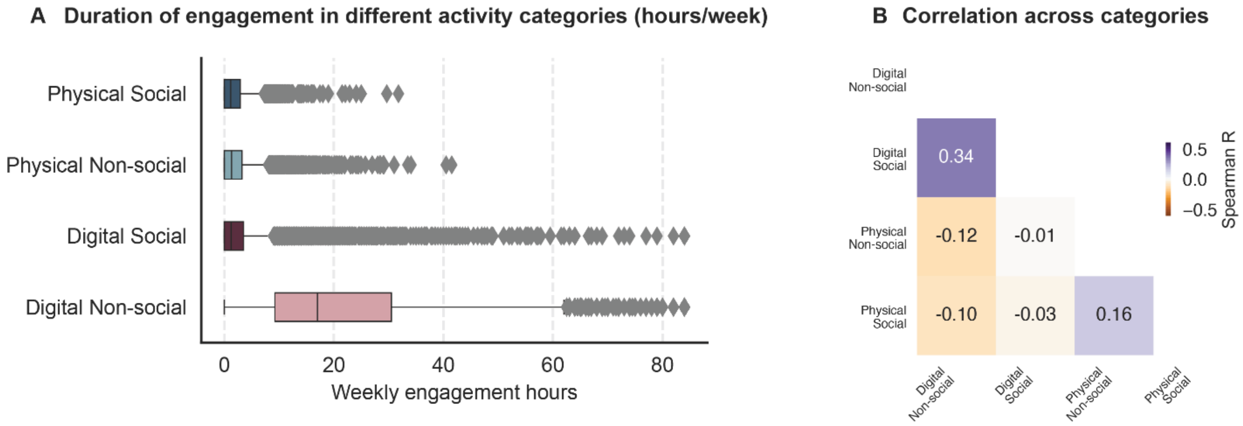
13 Wood, S. & Wood, M. S. Package ‘mgcv’. *R package version* **1**, 729 (2015).

Supplementary Figure 1. Flowchart of Participant Selection



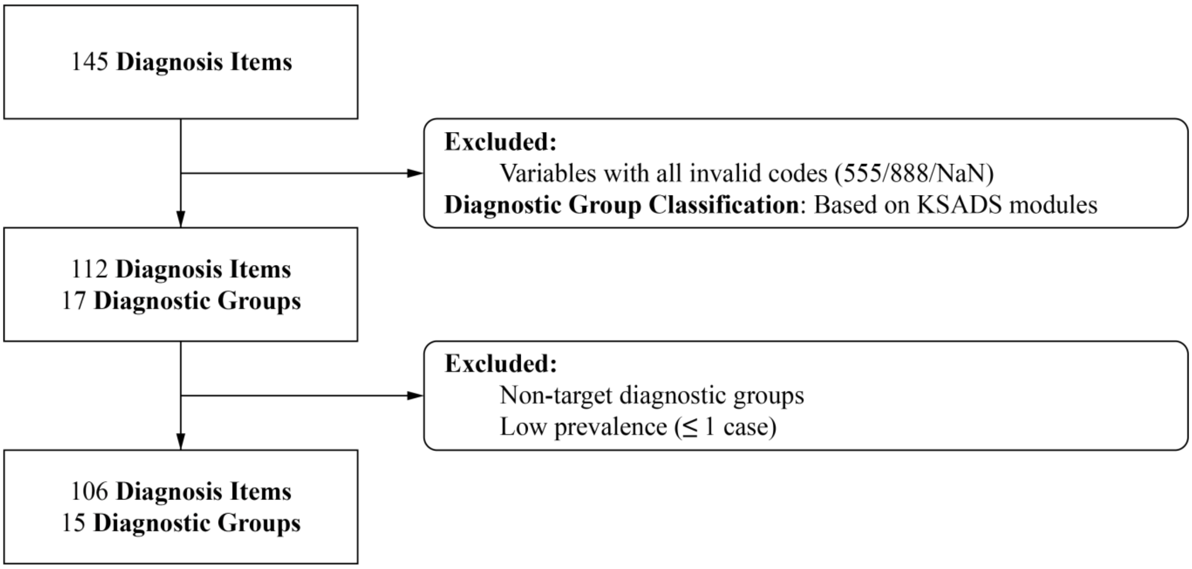
Note: This flowchart outlines the inclusion and exclusion criteria starting from the full ABCD cohort (n = 11,876), with exclusion of participants who had missing data codes (777/999/NaN) in any required questionnaire response. It details the number of participants with available data for physical activities (Sports and Activities Involvement Questionnaire, SAI-Q), digital activities (Screen Time Survey, STQ), mental health (Child Behavior Checklist, CBCL), gray matter volume (Structural T1-weighted MRI), covariates, and Psychiatric Diagnoses Assessment (Kiddie Schedule for Affective Disorders and Schizophrenia, KSADS-COMP) at Wave 1 (baseline) and Wave 2 (1-year follow-up). We further highlight the final analytic sample sizes for three major analyses: Step 1 (association analysis, n = 8230, requiring complete baseline data on activities, mental health, covariates, and gray matter volume), Step 2 (CLPM analysis, n = 6893, requiring complete data across Wave 1 and Wave 2 for activities, mental health, and covariates), and Step 3 (mediation analysis, n = 6203, requiring complete Wave 1 data on activities, gray matter volume, and covariates plus complete Wave 2 mental health data).

Supplementary Figure 2. Data Distribution and Correlations of Four Activity Categories at Wave1



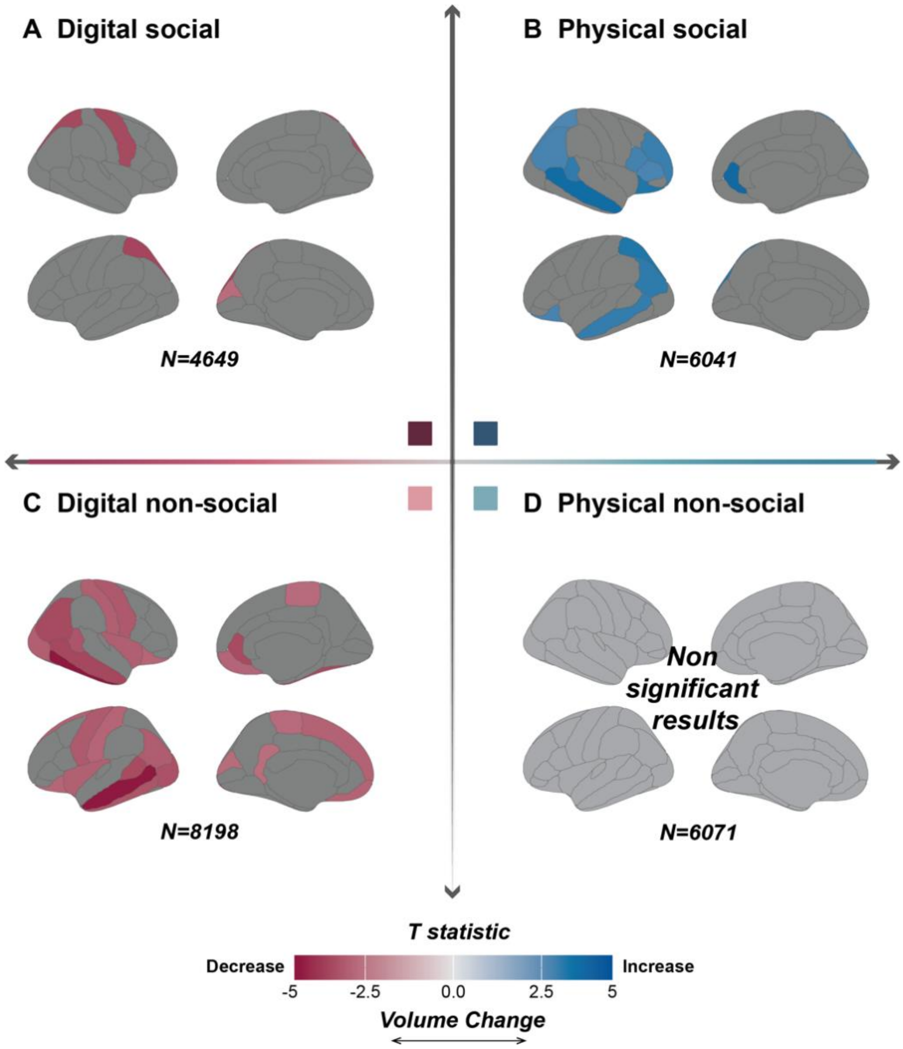
***Note*: (A)** Each box displays the first quartile, median and third quartile of engagement duration within specific categories. The whiskers represent the non-outlier endpoints of the distribution, and the crosses denote outliers. (**B)** The heatmap shows Spearman correlation coefficients across four categories.

Supplementary Figure 3. Diagnostic Variable Selection and Grouping Workflow



Note: The flowchart shows the inclusion of diagnostic items and groups.

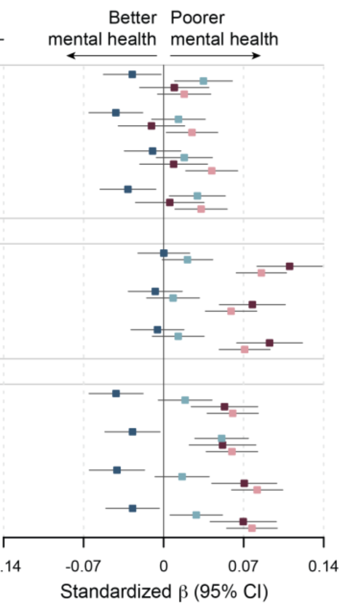
Supplementary Figure 4. Significant Associations Between Regional Gray Matter Volume and Weekly Activity Engagement Across Categories (FDR-Corrected *P* < 0.05)



Note**:** T-maps for regions with significant associations between gray matter volume and weekly activity engagement: (**A**) digital social, (**B**) physical social, (**C**) digital non-social, and (**D**) physical non-social. Corresponding estimate effects, *t*-values, and *p*-values are provided in Table S8.

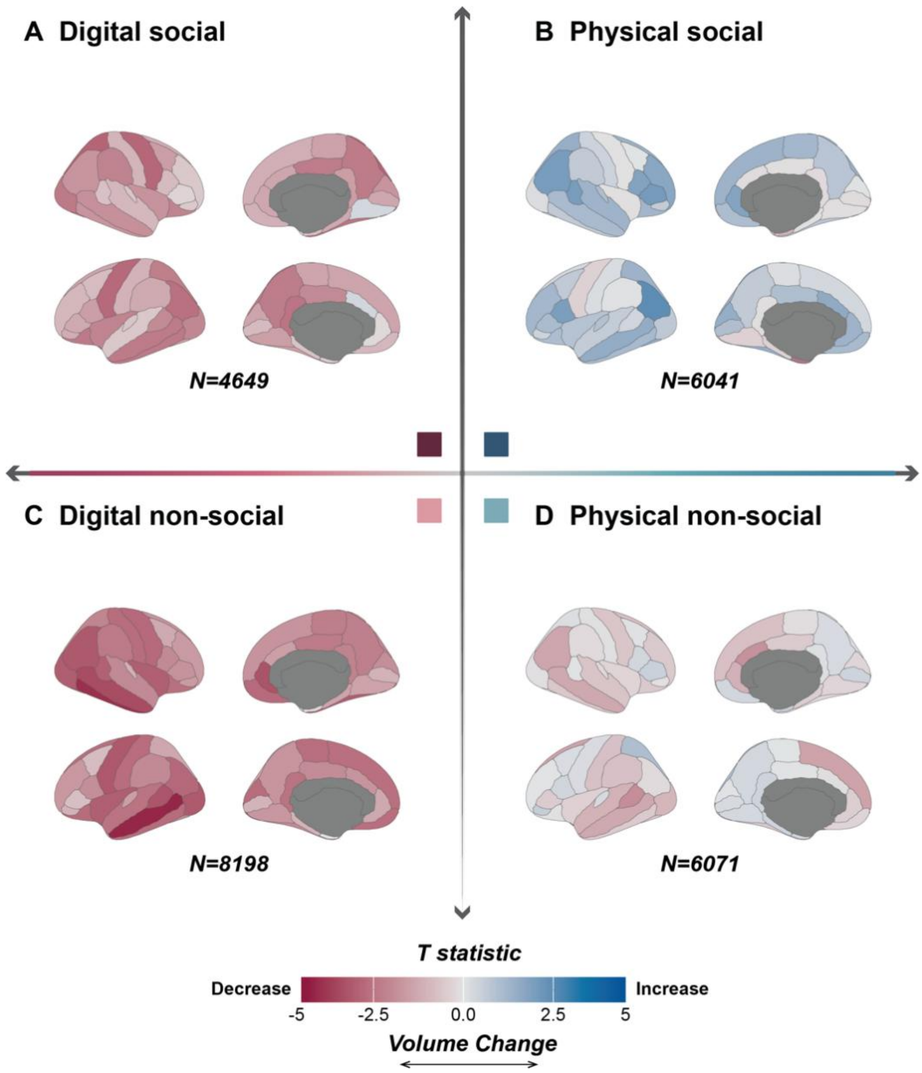
Supplementary Figure 5. Forest Plot showing Associations Between the Weekly Engagement Duration (>0 hour/week) Across Activity Categories and Mental Health Symptoms (Sensitivity Analysis)

Mental health outcome	Physical social N=6041	Physical nonsocial N=6071	Digital social N=4649	Digital nonsocial N=8198
Internalizing problems				
Anxious and depressed	-0.03(-0.05 to -0.00)	0.03(0.01 to 0.06)	0.01(-0.02 to 0.04)	0.02(-0.01 to 0.04)
Withdrawn and depressed	-0.04(-0.07 to -0.02)	0.01(-0.01 to 0.04)	-0.01(-0.04 to 0.02)	0.02(0.00 to 0.05)
Somatic complaints	-0.01(-0.03 to 0.02)	0.02(-0.01 to 0.04)	0.01(-0.02 to 0.04)	0.04(0.02 to 0.06)
Total score	-0.03(-0.06 to -0.01)	0.03(0.01 to 0.05)	0.01(-0.02 to 0.04)	0.03(0.01 to 0.06)
Externalizing problems				
Rule-breaking behaviors	0.00(-0.02 to 0.02)	0.02(-0.00 to 0.04)	0.11(0.08 to 0.14)	0.09(0.06 to 0.11)
Aggressive behaviors	-0.01(-0.03 to 0.02)	0.01(-0.01 to 0.03)	0.08(0.05 to 0.11)	0.06(0.04 to 0.08)
Total score	-0.01(-0.03 to 0.02)	0.01(-0.01 to 0.04)	0.09(0.06 to 0.12)	0.07(0.05 to 0.09)
Problem behaviors				
Social problems	-0.04(-0.07 to -0.02)	0.02(-0.00 to 0.04)	0.05(0.02 to 0.08)	0.06(0.04 to 0.08)
Thought problems	-0.03(-0.05 to -0.00)	0.05(0.03 to 0.07)	0.05(0.02 to 0.08)	0.06(0.04 to 0.08)
Attention problems	-0.04(-0.07 to -0.02)	0.02(-0.01 to 0.04)	0.07(0.04 to 0.10)	0.08(0.06 to 0.10)
Mental health problem total score	-0.03(-0.05 to -0.00)	0.03(0.01 to 0.05)	0.07(0.04 to 0.10)	0.08(0.06 to 0.10)



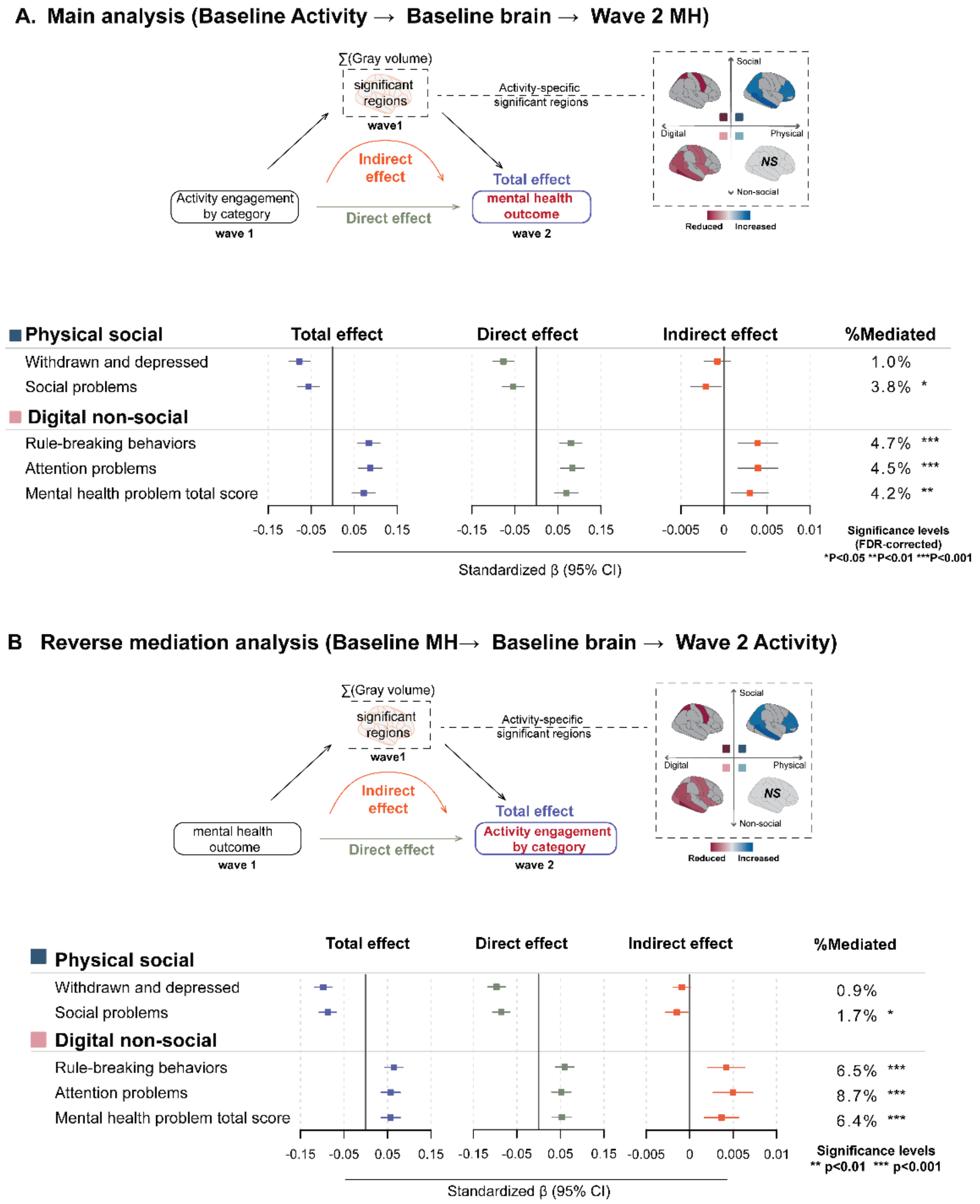
Note: *β* (95% CI) and *P* values were estimated using linear mixed-effects regression analyses, based on data from subgroup samples with weekly engagement duration (>0 hours/week) and their CBCL symptom measures. The modeling details and covariate adjustments were consistent with those described in the main analysis. Sample sizes for each association are specified in the text annotations. *P* values are provided in Table S5.

Supplementary Figure 6. Neuroanatomical Characteristics Across Activity Engagement (>0 hour/week) Categories (Sensitivity Analysis)



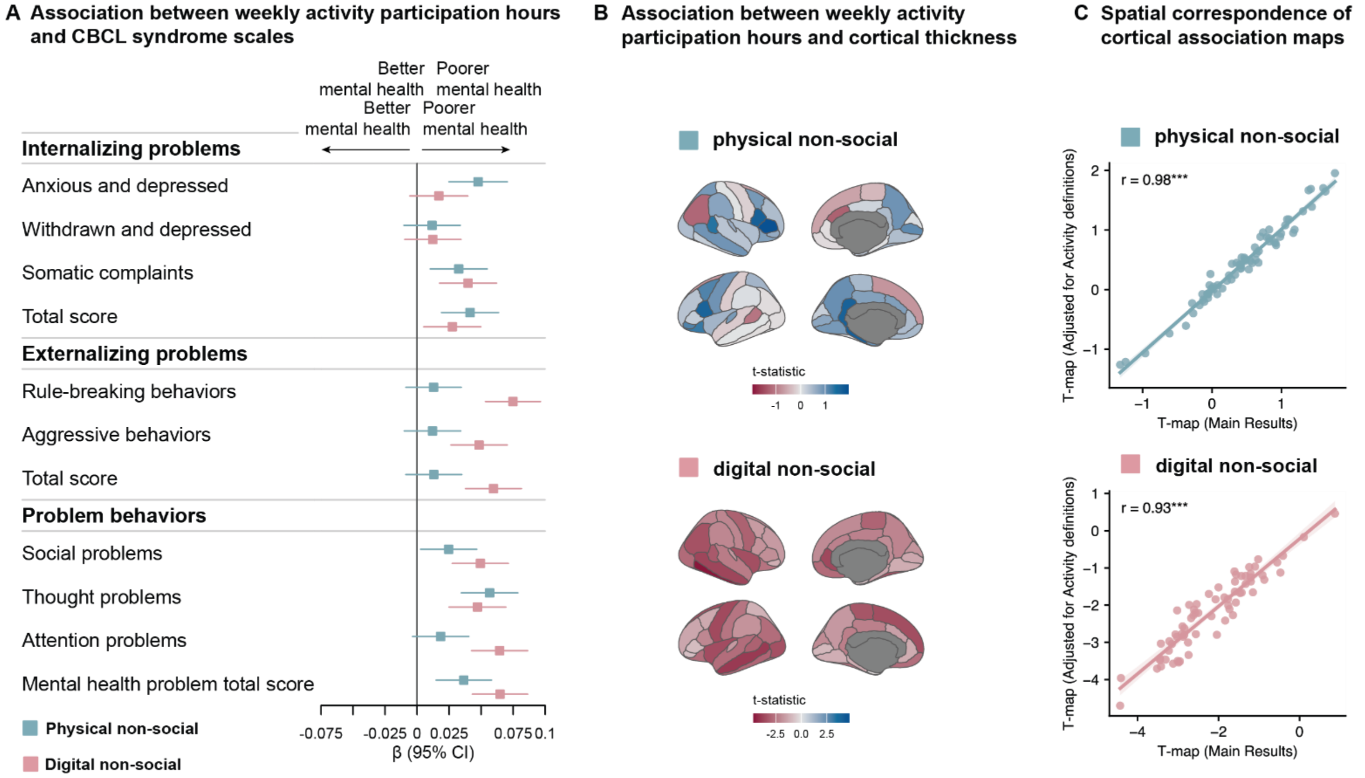
Note**:** T-maps for associations between gray matter volume and weekly activity engagement based on data from subgroup samples with weekly engagement duration (>0 hours/week): (**A**) digital social, (**B**) physical social, (**C**) digital non-social, and (**D**) physical non-social. The modeling details and covariate adjustments were consistent with those described in the main analysis. Sample sizes for each association are specified in the text annotations.

Supplementary Figures 7. Comparison of Longitudinal Mediation Models in Forward and Reverse Directions



Note**: (A) Main Analysis (Forward Direction)**: Mediation models examining the prospective effect of baseline activity engagement on 1-year follow-up (Wave 2) mental health symptoms via baseline cortical gray matter volume. **(B) Reverse Mediation Analysis**: Supplementary models examining the reciprocal pathway from baseline mental health symptoms to 1-year follow-up (Wave 2) activity engagement via baseline cortical gray matter volume. To ensure methodological comparability, the mediator (Gray volume) in the reverse models was defined using the same cumulative regions identified in the main analysis (regions showing significant associations with baseline activity engagement). Forest plots display standardized estimates and 95% confidence intervals (CIs) for total, direct, and indirect effects. The percentage of the total effect mediated (%Mediated) is reported on the right. Significance levels are based on 5,000 bootstrap resamples. Note: This comparison focuses specifically on activity–symptom pairs that demonstrated significant bidirectional longitudinal associations in the main CLPM analysis.

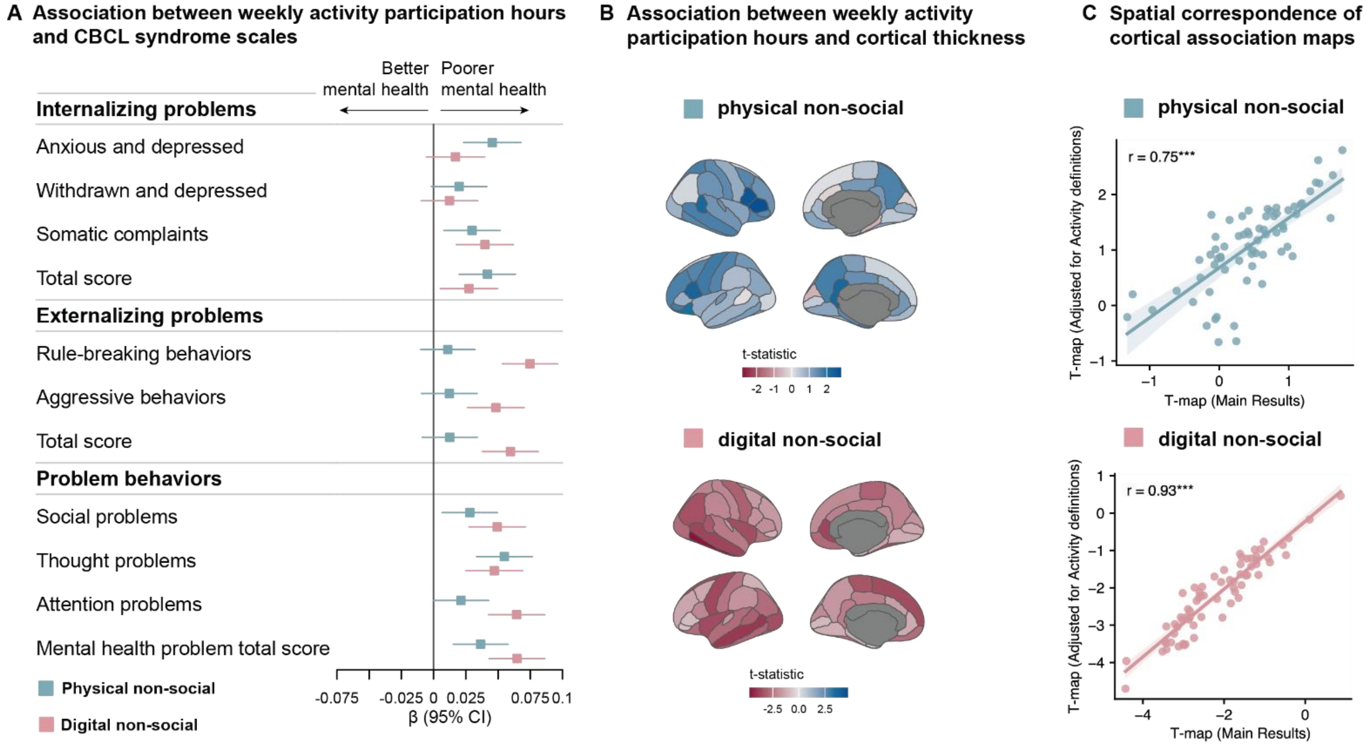
Supplementary Figures 8. Sensitivity Analyses Excluding Potentially Ambiguous Activity Items (Tennis and Video Games) (Sensitivity Analysis)



Note: Excluded two activities with ambiguous social categorization:
Play video games on a computer, console, phone or other device (Digital Non-social) and Tennis (Physical Non-social).

Note**:** All linear mixed-effects models were specified identically to those in the main analyses, with the only modification being the exclusion of tennis from the physical non-social category and video games from the digital non-social category. (A) Associations between weekly activity participation duration and CBCL syndrome scores after excluding the above items. Effect estimates are shown as standardized β coefficients with 95% confidence intervals. (B) Associations between weekly activity participation duration and cortical gray matter volume. Cortical effect-size maps are presented as t-statistics mapped onto the Desikan–Killiany atlas. (C) Scatter plot illustrating the spatial correspondence between cortical *t*-statistic maps derived from the primary models and those estimated after excluding potentially ambiguous activity items (tennis and video games; corresponding to panel B). Each point represents one cortical region from the Desikan–Killiany atlas. Strong spatial concordance was observed between the primary and item-excluded models. Statistical significance was assessed using BrainSMASH to correct for spatial autocorrelation (10,000 permutations; $P < 0.001$).

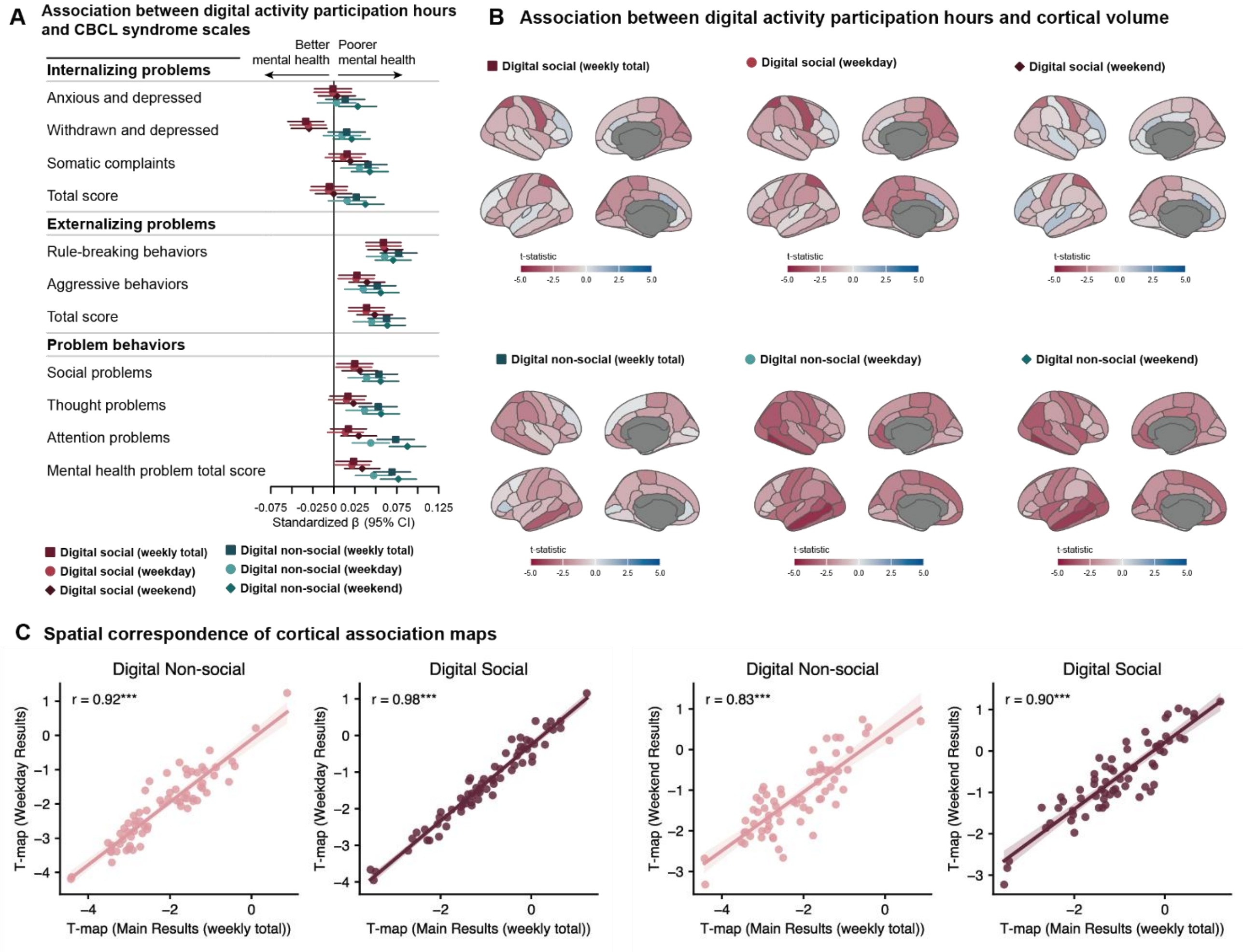
Supplementary Figures 9. Sensitivity Analyses Excluding Potentially Ambiguous Activity Items (Playing Video Games, Tennis, Running, and Going to the Gym) (Sensitivity Analysis)



Note: Excluded four activities with ambiguous social categorization: Play video games on a computer, console, phone or other device (Digital Non-social); Track, Running, Cross-country (Physical Non-social); Gymnastics (Physical Non-social); Tennis (Physical Non-social).

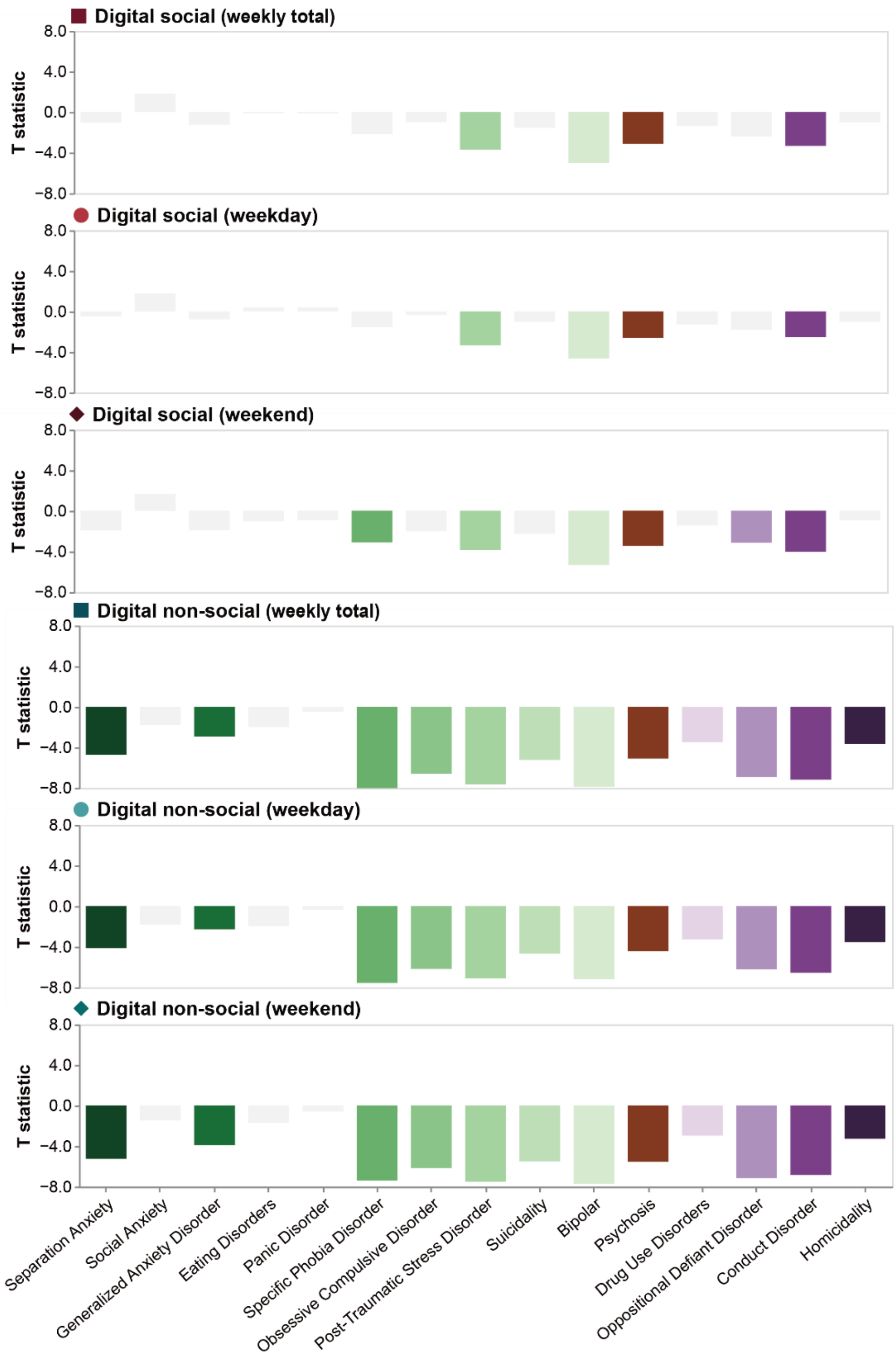
Note**:** All linear mixed-effects models were specified identically to those in the main analyses, with the only modification being the exclusion of potentially ambiguous activity items, including tennis, running, and going to the gym from the physical non-social category, and video games from the digital non-social category. (A) Associations between weekly activity participation duration and CBCL syndrome scores after excluding the above items. Effect estimates are shown as standardized *β* coefficients with 95% confidence intervals. (B) Associations between weekly activity participation duration and cortical gray matter volume. Cortical effect-size maps are presented as t-statistics mapped onto the Desikan–Killiany atlas. (C) Scatter plot illustrating the spatial correspondence between cortical *t*-statistic maps derived from the primary models and those estimated after excluding potentially ambiguous activity items (playing video games, tennis, running, and going to the gym); corresponding to panel B). Each point represents one cortical region from the Desikan–Killiany atlas. Strong spatial concordance was observed between the primary and item-excluded models. Statistical significance was assessed using BrainSMASH to correct for spatial autocorrelation (10,000 permutations; $P < 0.001$).

Supplementary Figures 10. Associations Between Digital Activity Engagement (Weekly Total, Weekday, and Weekend) and Mental Health Symptoms and Cortical Gray Matter Volume (Sensitivity Analysis)



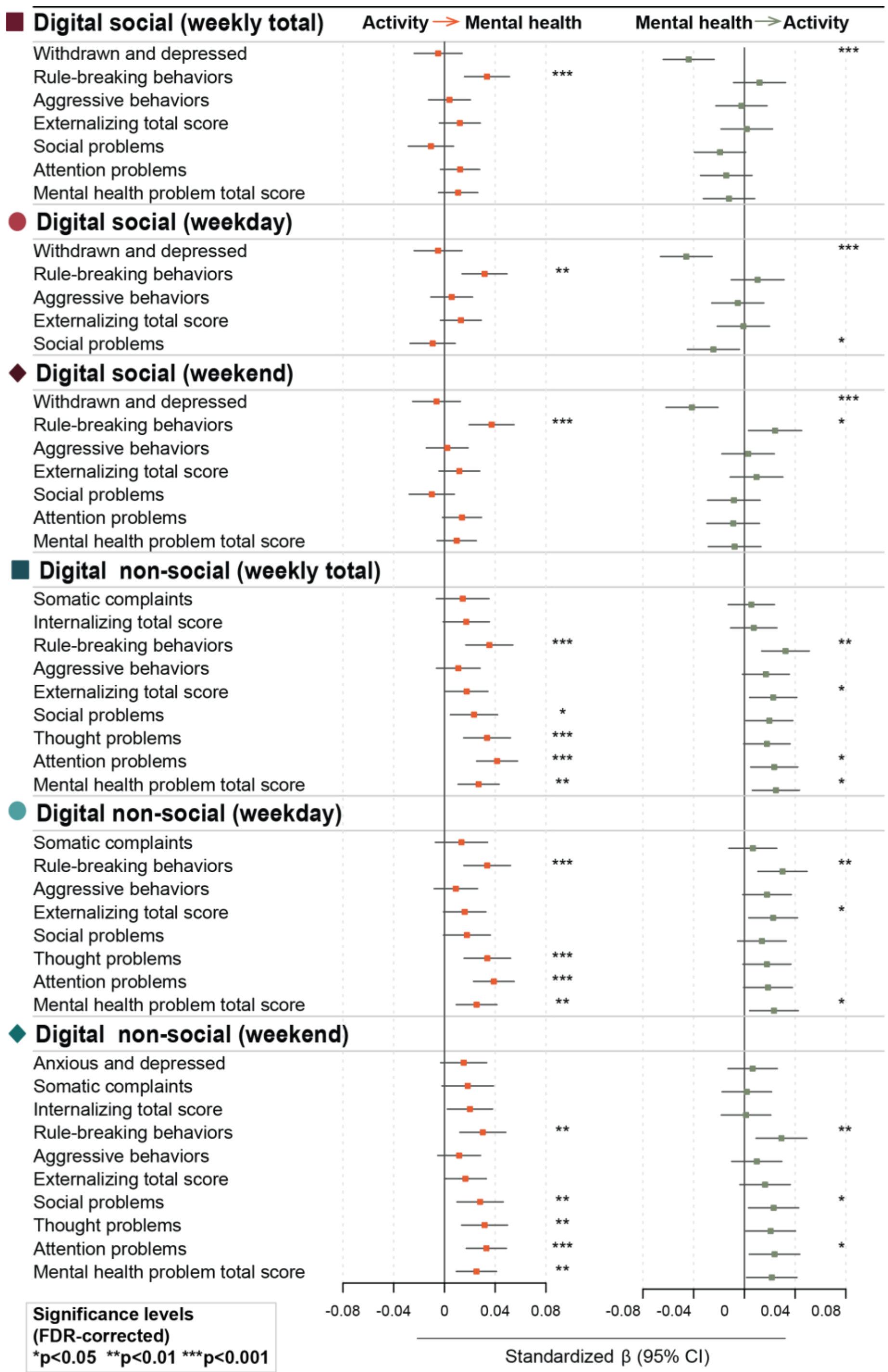
Note: All LMM models were estimated under the same specifications as in the main analyses. (A) Associations between digital activity engagement and child mental health symptoms, assessed using CBCL syndrome scales (higher scores indicate more severe symptoms). Six activity indicators are shown: weekly digital social and digital non-social activity (as in the main analysis), and their corresponding weekday and weekend measures. Colors and shapes denote activity categories, consistent with the main manuscript. Across all specifications, weekday and weekend results closely mirrored the weekly aggregated associations. (B) Associations between cortical gray matter volume and the same six digital activity indicators, displayed as t-statistics mapped onto the Desikan–Killiany atlas. (C) Scatter plots illustrating the spatial correspondence between cortical *t*-statistic maps derived from different temporal models (weekly total, weekday, and weekend; corresponding to panel B). Each point represents one cortical region from the Desikan–Killiany atlas. Strong spatial concordance was observed between the main weekly-total results and those obtained from weekday- and weekend-specific models. Statistical significance was assessed using BrainSMASH to correct for spatial autocorrelation (10,000 permutations; all $P < 0.001$).

Supplementary Figures 11. T-Statistics Comparing Digital Activity Engagement Between Psychiatric Diagnostic Groups and Matched Controls (Weekly Total, Weekday, and Weekend) (Sensitivity Analysis)



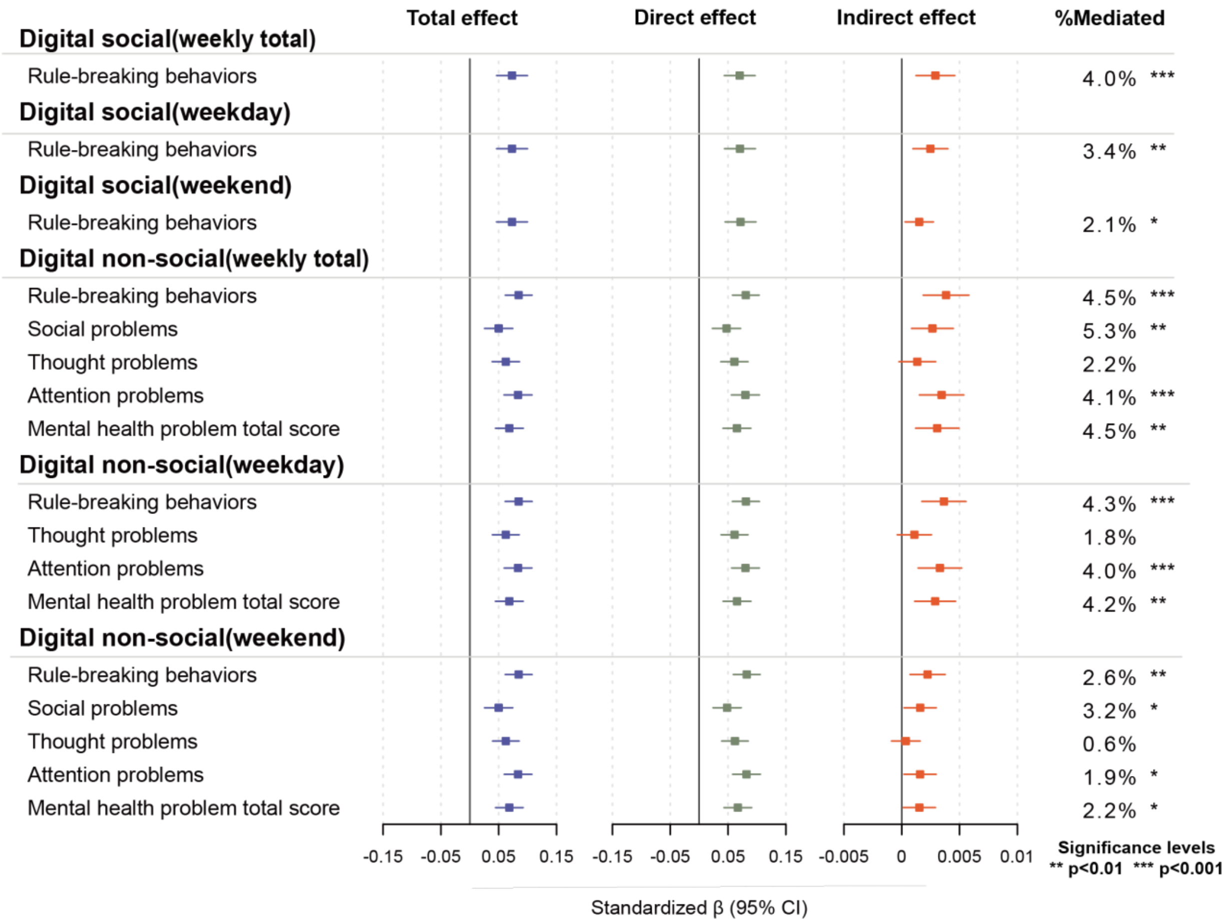
Note**:** Weekday- and weekend-specific analyses followed the same specifications as the weekly models in the main analysis, which are shown for reference. Two-sided Welch's t-tests compared six indicators of digital activity (social and non-social × weekly, weekday, weekend) between each of the 15 diagnostic groups and matched controls. Diagnostic categories were organized into Internalizing (green), Externalizing (purple), and Thought Disorder (brown) spectra based on HiTOP. Positive t-values indicate greater engagement in controls; negative values indicate greater engagement in clinical groups. Colored bars reflect significant differences (FDR-corrected $P < .05$), and gray bars denote nonsignificant effects. Weekday–weekend patterns closely matched those from weekly totals.

Supplementary Figures 12. Cross-Lagged Model Estimates for Weekly, Weekday, and Weekend Digital Activity Engagement and Mental Health Measures (Sensitivity Analysis)



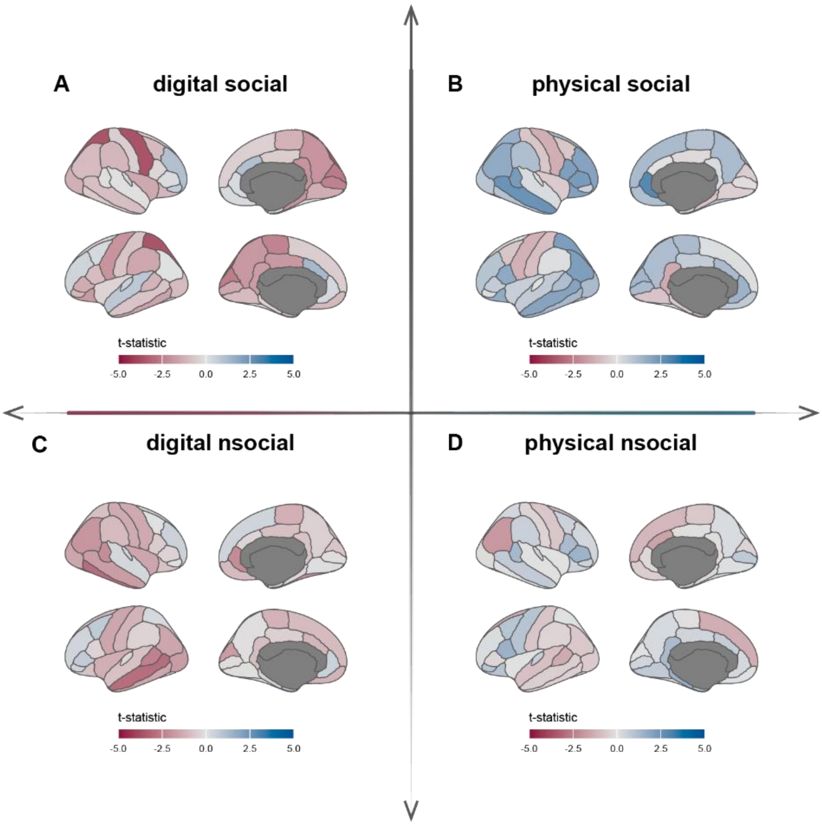
Note: Weekday- and weekend-specific CLPMs were specified identically to the weekly total models in the main analyses, and weekly total estimates are shown alongside these models to facilitate direct comparison. For each digital activity category (weekly total, weekday, weekend), cross-lagged models were estimated with the corresponding CBCL symptom scales. Only activity–symptom pairs that showed significant baseline associations in the LMM analysis (FDR-corrected $P < .05$) were carried forward for directional testing. Path b represents the effect of baseline digital activity on mental health symptoms one year later, and path c represents the reverse direction (baseline symptoms predicting digital activity at follow-up). All models adjusted for stable covariates (sex, race/ethnicity, site, parental education) and time-varying covariates (age, family income, BMI, pubertal status). Plotted values indicate standardized β coefficients with 95% CIs; asterisks denote significant cross-lagged paths (FDR-corrected $P < .05$). Weekday- and weekend-specific estimates closely reproduced the directional patterns observed for weekly aggregates.

Supplementary Figures 13. Mediation Between Baseline Digital Activity Engagement, Gray Matter Volumes And 1-Year Follow-up Mental Health Outcomes (weekly total, weekday, and weekend) (Sensitivity Analysis)



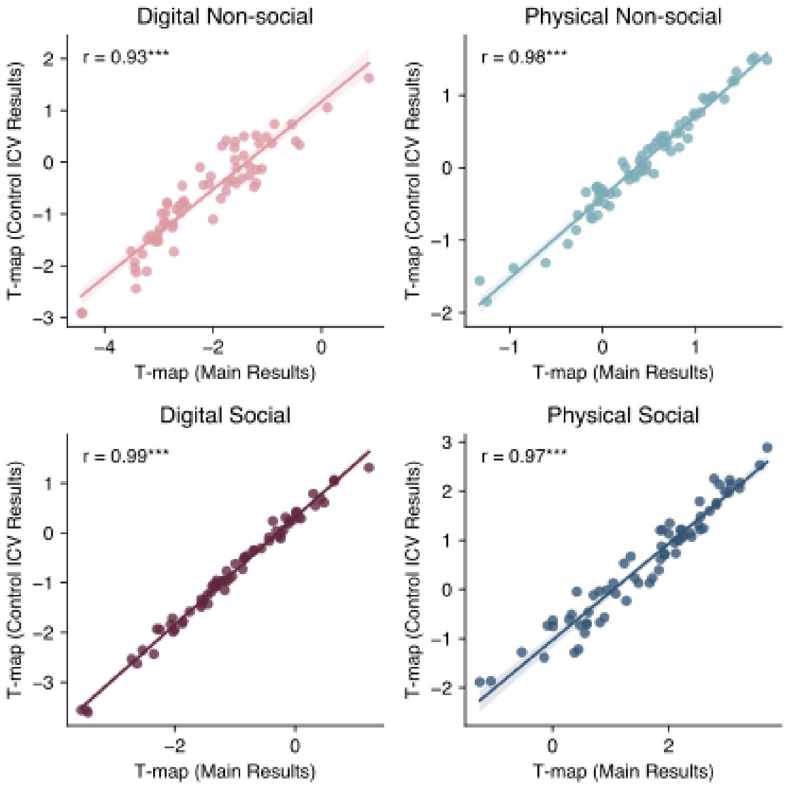
***Note*:** Weekday- and weekend-specific analyses followed the same specifications as the weekly models in the main analysis, which are shown for reference. For each digital activity–mental health symptom pair showing significant prospective associations in the CLPM analysis (FDR-corrected $P < .05$), mediation analyses tested whether baseline cortical gray matter volume (composite score summarizing regions significantly associated with each activity category in the LMMs) mediated the relationship between baseline digital activity engagement (weekly total, weekday, weekend) and 1-year follow-up CBCL symptom scores. Standardized β coefficients (95% CI) are presented for total, direct, and indirect effects. Statistical significance was evaluated using 5,000 bootstrap resamples, with asterisks indicating significant effects. Mediation patterns were consistent across weekly, weekday, and weekend specifications, aligning with the main results.

Supplementary Figures 14. Associations Between Activity Engagement and Cortical Gray Matter Volume After Adjusting for Intracranial Volume (ICV) (Sensitivity Analysis)



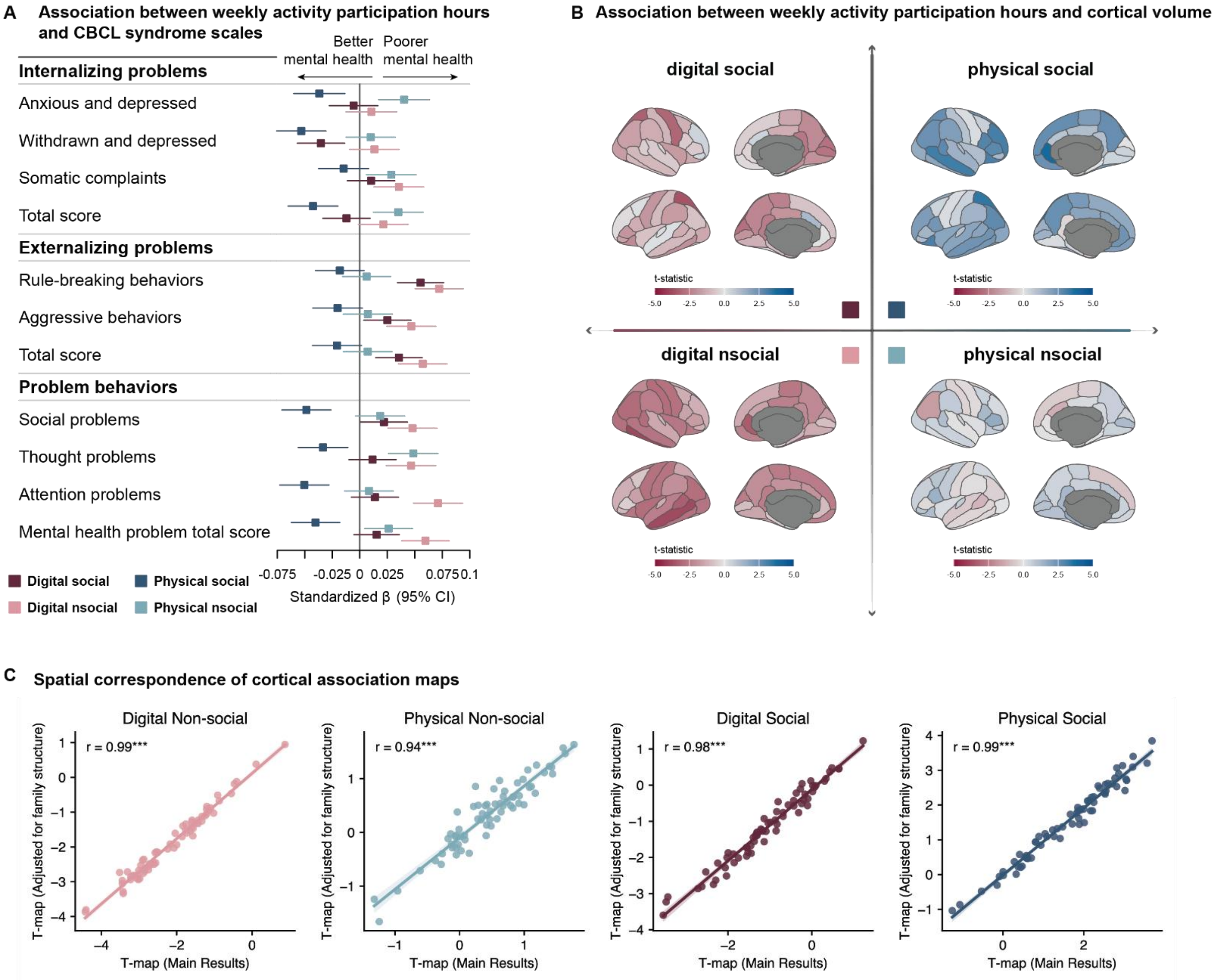
Note**:** Cortical effect-size maps from baseline linear mixed-effects models including ICV are shown for each activity category (digital non-social, digital social, physical non-social, physical social). All other model specifications match those of the main analyses.

Supplementary Figures 15. Robustness of Cortical Activity–Brain Associations After Adjusting for Intracranial Volume (ICV) (Sensitivity Analysis)



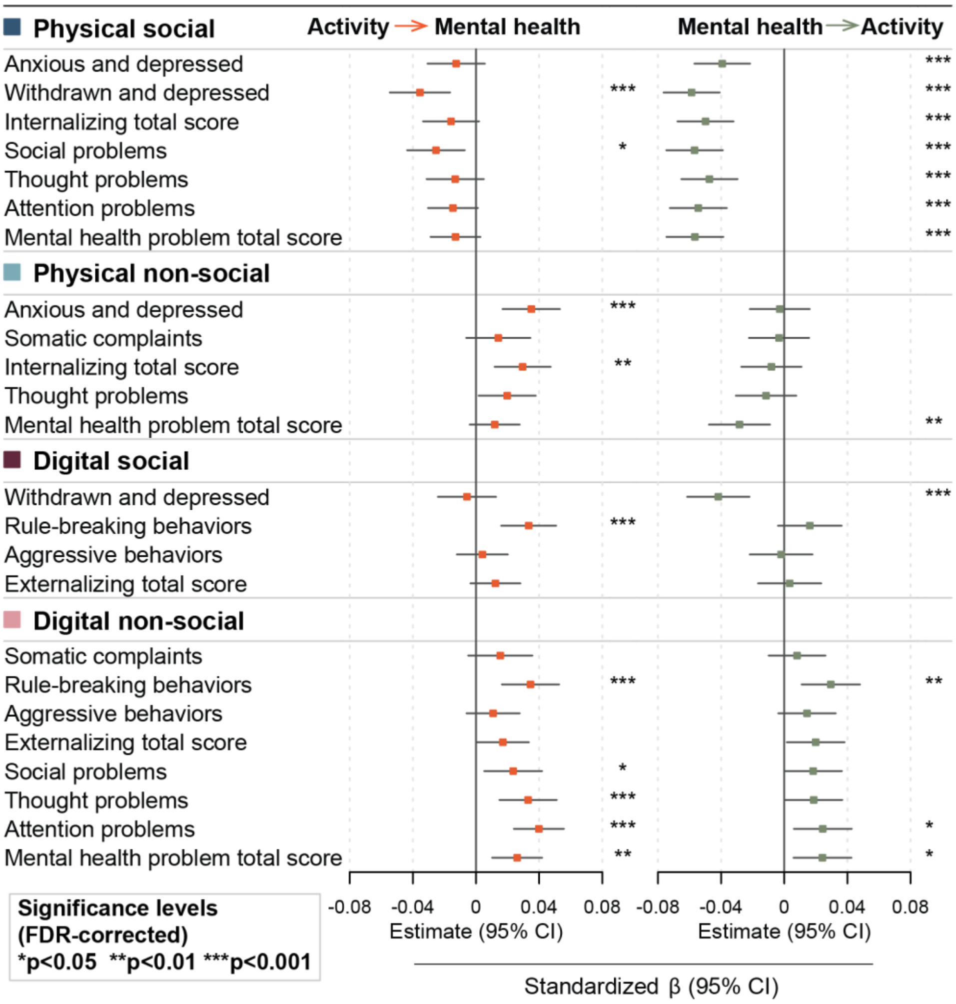
Note: Scatter plots illustrate the consistency between cortical *t*-statistic maps from the main analyses and those from models additionally adjusting for intracranial volume (ICV), across four activity categories. Each point represents a cortical region from the Desikan–Killiany atlas. Strong spatial concordance was observed between the original and ICV-adjusted maps (Spearman $r \geq 0.97$), with significance assessed after correcting for spatial autocorrelation using BrainSMASH (10,000 permutations; all $P < .001$).

Supplementary Figures 16. Associations Between Activity Engagement, Mental Health, and Cortical Gray Matter Volume After Accounting for Within-Family Relatedness (Sensitivity Analysis)



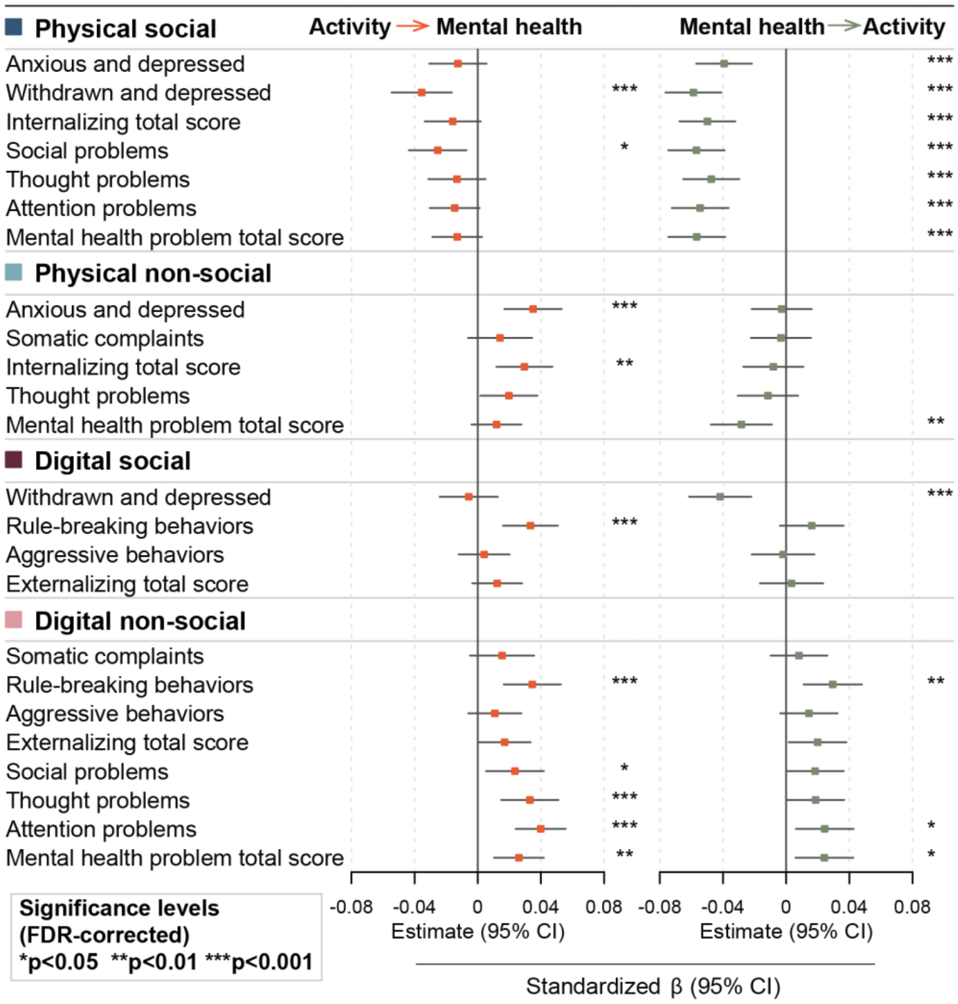
Note: Baseline associations between activity engagement and (A) mental health symptoms and (B) cortical gray matter volume were re-estimated using LMMs additionally accounting for within-family relatedness by including family ID as a random intercept and relationship type as a fixed-effect covariate. The overall association patterns were consistent with the primary analyses, with physical social activity showing protective associations with mental health and positive associations with widespread cortical gray matter volume, whereas digital non-social activity showed the opposite pattern. (C) Scatter plots illustrate the consistency between cortical *t*-statistic maps from the main analyses and those from models additionally adjusting for family structure, across four activity categories. Each point represents a cortical region from the Desikan–Killiany atlas. Strong spatial concordance was observed between the original and adjusted maps (Spearman $r \geq 0.94$), with significance assessed after correcting for spatial autocorrelation using BrainSMASH (10,000 permutations; all $P < .001$).

Supplementary Figures 17. CLPM Analyses Controlling for Within-Family Relatedness (Sensitivity Analysis)



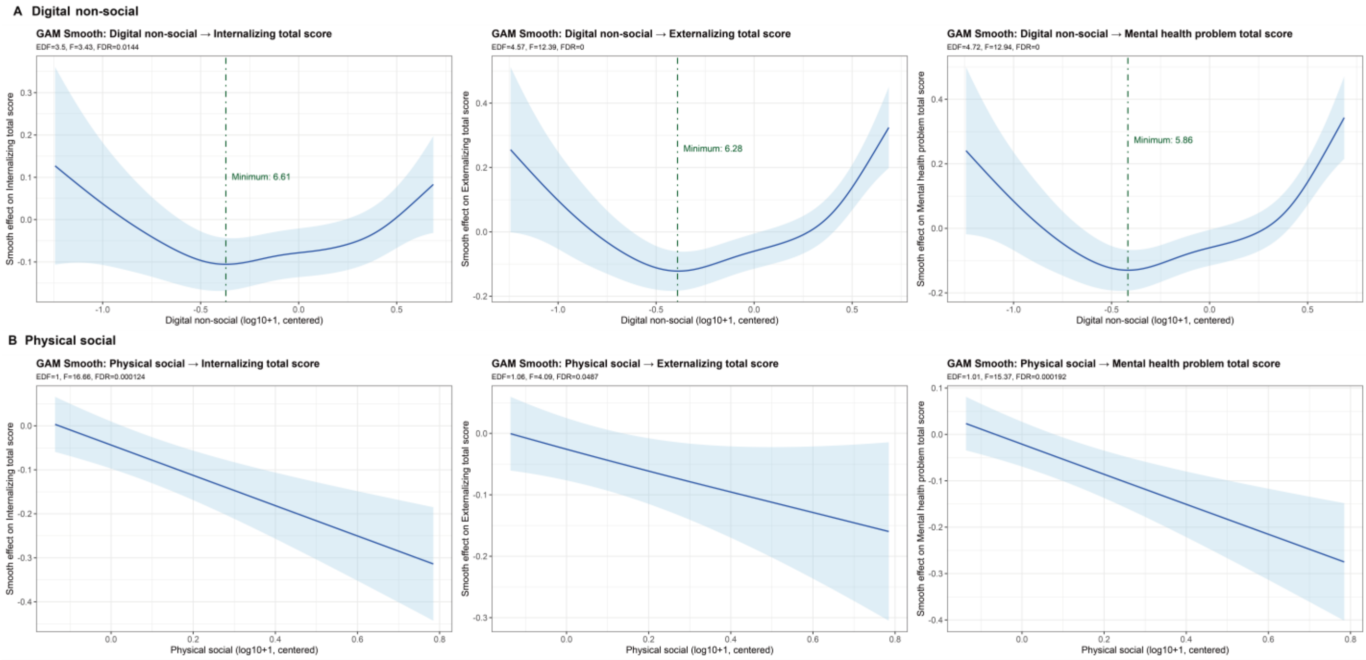
Note**:** CLPMs were re-estimated based on the main analyses with additional covariate adjustment for within-family relatedness (family ID and relationship type). The longitudinal bidirectional associations were consistent with the primary findings, such that greater engagement in physical social activity predicted fewer subsequent mental health symptoms over time, whereas greater engagement in digital non-social activity predicted increased symptoms. Standardized β (95% CI) for cross-lagged paths, with statistical significance indicated by asterisks.

Supplementary Figures 18. Mediation Analyses Controlling for Within-Family Relatedness (Sensitivity Analysis)



***Note*:** Mediation analyses were repeated using the main analytic framework with additional adjustment for family structure (family ID and relationship type as covariates). All significant mediation effects identified in the primary analyses remained robust. Standardized β (95% CI) for total, direct, and indirect effects, with statistical significance assessed using 5,000 bootstrap resamples and indicated by asterisks.

Supplementary Figures 19. Nonlinear Associations Between Activity Engagement and Mental Health Symptoms.



Note**:** Generalized additive mixed models (GAMMs) were used to examine baseline nonlinear associations between activity engagement and mental health symptom scores for the two activity domains showing the strongest linear effects in the primary analyses: digital non-social (A) and physical social (B) activities. Solid lines represent the estimated smooth functions, with shaded bands indicating 95% confidence intervals. For each panel, the effective degrees of freedom (EDF) quantify the complexity of the estimated smooth term, with EDF values close to 1 indicating an approximately linear association and larger EDF values reflecting increasing nonlinearity. The F statistic tests the overall significance of the smooth term after adjustment for covariates, and *P* values (FDR-corrected across the six GAMMs analyses corresponding to the displayed activity–mental health associations) indicate the statistical significance of the overall smooth effect. For associations exhibiting significant nonlinearity, vertical dashed lines mark estimated turning points where the first derivative of the smooth function approaches zero, providing empirical indications of potential threshold or saturation ranges. Models were otherwise specified identically to the primary linear mixed-effects analyses, adjusting for age, sex assigned at birth, race/ethnicity, family income, parental education, pubertal status, and BMI, with study site included as a random effect. Activity engagement variables were log-transformed and mean-centered, and mental health symptom scores were standardized.

Supplementary Table 1. List of Investigated Activities Across Four Categories

Activity categories	Activity types	Data elements
Physical Social (11)	Baseball, Softball	sai_ss_base
	Basketball	sai_ss_basket
	Field Hockey	sai_ss_fhock
	Ice Hockey	sai_ss_ihock
	Lacrosse	sai_ss_lax
	Rugby	sai_ss_rugby
	Soccer	sai_ss_soc
	Swimming, Water Polo	sai_ss_wpolo
	Volleyball	sai_ss_vball
	Drama, Theater, Acting, Film	sai_ss_drama
	Competitive Games like Chess, Cards, or Darts	sai_ss_chess
Physical Non-social (17)	Ballet, Dance	sai_ss_dance
	Climbing	sai_ss_climb
	Gymnastics	sai_ss_gym
	Ice or Inline Skating	sai_ss_iskate
	Martial Arts	sai_ss_m_arts
	Skateboarding	sai_ss_skate
	Skiing, Snowboarding	sai_ss_sboard
	Surfing	sai_ss_surf
	Horseback Riding, Polo	sai_ss_polo
	Tennis	sai_ss_tennis
	Track, Running, Cross-country	sai_ss_run
	Wresting, Mixed Martial Arts	sai_ss_mma
	Yoga, Tai Chi	sai_ss_yoga
	Musical Instrument	sai_ss_music
	Drawing, Painting, Graphic Art, Photography, Pottery, Sculpting	sai_ss_art
	Crafts like Knitting, Building Model Cars or Airplanes	sai_ss_crafts
	Hobbies like collecting stamps or coins	sai_ss_collect
Digital Social (3)	Text on a cell phone, tablet, or computer (weekday/weekend)	screen4_wkdy_y, screen10_wknd_y
	Visit social networking sites(weekday/weekend)	screen5_wkdy_y, screen11_wknd_y
	Video chat(weekday/weekend)	screen_wkdy_y, screen12_wknd_y
Digital Non-social (3)	Watch TV shows or movies(weekday/weekend)	screen1_wkdy_y, screen7_wknd_y
	Watch videos(weekday/weekend)	screen2_wkdy_y, screen8_wknd_y
	Play video games on a computer, console, phone or other device(weekday/weekend)	screen3_wkdy_y, screen9_wknd_y

Note: The data element names represent original variable names from two ABCD questionnaires. **Physical activities**: ABCD Parent Sports and Activities Involvement Questionnaire (SAIQ), detailed at https://nda.nih.gov/data-structure/abcd_spacss01 (baseline); https://nda.nih.gov/data-structure/abcd_lsssa01 (follow-up). **Digital activities**: ABCD Youth Screen Time Survey (STQ), detailed at https://nda.nih.gov/data-structure/abcd_stq01 (baseline and follow-up). Weekly engagement hours were calculated using parent-reported (***tspent***), (***perwk***), and (***nmonth***) from SAIQ for physical activities and combined weekday and weekend data from STQ for digital activities. For detailed method, see Supplementary Methods 1.

Supplementary Table 2. List of Investigated diagnostic items and groups

Supplementary Table 2 is provided in a separate Excel file (Sheet 1) due to length exceeding one page.

Description: Comprehensive list of investigated psychiatric diagnostic items and clinical subgroups, derived from the ABCD Parent Diagnostic Interview for DSM-5 Full (KSAD). Data element names correspond to original variable labels in the KSAD-5 instrument (NDA Structure: https://nda.nih.gov/data-structure/abcd_ksad01, baseline version). Full methodological details are provided in Supplementary Methods 2.

Supplementary Table 3. Description of Study Sites

Site ID	No. (%)	Site ID	No. (%)
site01	241(2.93%)	**site12**	385(4.68%)
site02	438(5.32%)	**site13**	488(5.93%)
site03	432(5.25%)	**site14**	464(5.64%)
site04	491(5.97%)	**site15**	258(3.13%)
site05	244(2.96%)	**site16**	810(9.84%)
site06	438(5.32%)	**site17**	404(4.91%)
site07	224(2.72%)	**site18**	275(3.34%)
site08	239(2.9%)	**site19**	371(4.51%)
site09	291(3.54%)	**site20**	523(6.35%)
site10	454(5.52%)	**site21**	422(5.13%)
site11	316(3.84%)	**site22**	22(0.27%)

Note: More information about Study Sites is available at the following link: https://abcdstudy.org/study-sites/.

Supplementary Table 4. *P* Values and FDR-Corrected *P* Values of Associations Between Weekly Engagement Duration Across Activity Categories and Mental Health Symptoms

Activity Type/Mental Health	**Physical social**		**Physical non-social**		**Digital social**		**Digital non-social**	
	P value	Corrected *P* value	*P* value	Corrected *P* value	*P* value	Corrected *P* value	*P* value	Corrected *P* value
Internalizing problems								
Anxious and depressed	**0.004**	**0.009**	**<0.001**	**<0.001**	0.932	0.932	0.253	0.300
Withdrawn and depressed	**<0.001**	**<0.001**	0.363	0.409	**0.002**	**0.006**	0.182	0.229
Somatic complaints	0.282	0.327	**0.009**	**0.018**	0.152	0.196	**<0.001**	**0.001**
Total score	**0.001**	**0.002**	**0.001**	**0.002**	0.634	0.648	**0.021**	**0.036**
Externalizing problems								
Rule-breaking behaviors	0.123	0.169	0.383	0.421	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Aggressive behaviors	0.074	0.109	0.474	0.496	**0.013**	**0.023**	**<0.001**	**<0.001**
Total score	0.069	0.105	0.417	0.447	**<0.001**	**0.001**	**<0.001**	**<0.001**
Problem behaviors								
Social problems	**<0.001**	**<0.001**	0.059	0.093	**0.022**	**0.038**	**<0.001**	**<0.001**
Thought problems	**0.005**	**0.011**	**<0.001**	**<0.001**	0.129	0.172	**<0.001**	**<0.001**
Attention problems	**<0.001**	**<0.001**	0.230	0.281	0.112	0.159	**<0.001**	**<0.001**
Mental health problem total score	**<0.001**	**0.002**	**0.004**	**0.009**	**0.030**	**0.049**	**<0.001**	**<0.001**

***Note*:** Results with *P*<0.05 are highlighted in **bold**.

Supplementary Table 5. *P* Values and FDR-Corrected *P* Values of Associations Between the Weekly Engagement Duration Across Activity Categories (>0 Hours/Week) and Mental Health Symptoms (Sensitivity Analysis)

Activity Type/Mental Health	**Physical social**		**Physical non-social**		**Digital social**		**Digital non-social**	
	P value	Corrected *P* value	*P* value	Corrected *P* value	*P* value	Corrected *P* value	*P* value	Corrected *P* value
Internalizing problems								
Anxious and depressed	**0.034**	0.053	**0.007**	**0.015**	0.547	0.601	0.130	0.185
Withdrawn and depressed	**<0.001**	**0.001**	0.277	0.349	0.475	0.560	**0.031**	0.050
Somatic complaints	0.446	0.545	0.149	0.205	0.562	0.603	**<0.001**	**<0.001**
Total score	**0.012**	**0.025**	**0.018**	**0.033**	0.724	0.741	**0.005**	**0.011**
Externalizing problems								
Rule-breaking behaviors	0.987	0.987	0.065	0.099	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Aggressive behaviors	0.545	0.601	0.484	0.560	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Total score	0.652	0.683	0.270	0.349	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Problem behaviors								
Social problems	**<0.001**	**0.001**	0.117	0.172	**<0.001**	**0.001**	**<0.001**	**<0.001**
Thought problems	**0.028**	**0.047**	**<0.001**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**<0.001**
Attention problems	**<0.001**	**0.002**	0.182	0.242	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Mental health problem total score	**0.023**	**0.041**	**0.015**	**0.029**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

***Note*:** Results with *P*<0.05 are highlighted in **bold**.

Supplementary Table 6. T-Test Results for Weekly Engagement in Activity Categories Across Psychiatric Groups and Control Groups

Supplementary Table 6 is provided in a separate Excel file (Sheet 2) due to length exceeding one page.

Description: Independent-samples t-tests results comparing weekly engagement in activity categories between psychiatric groups and control groups, with significant differences highlighted across behavioral domains (FDR-corrected $P < .05$).

Supplementary Table 7. T-Test Results for Weekly Engagement in Activity Categories Across Psychiatric Items and Control Groups

Supplementary Table 7 is provided in a separate Excel file (Sheet 3) due to length exceeding one page.

Description: Independent-samples t-tests results comparing weekly engagement in activity categories between psychiatric items and control groups, with significant differences highlighted across behavioral domains (FDR-corrected $P < .05$).

Supplementary Table 8. Effects from Brain Regions with Significant Gray Matter Volume Associations Across Activity Categories

Gray matter volume associations	Estimate (CI 95%)	*T* value	*P* value	FDR *P* value
Physical social				
right rostral anterior cingulate	0.0423 (0.0198, 0.0647)	3.69	< 0.001	0.014
right middle temporal	0.0380 (0.0171, 0.0589)	3.57	< 0.001	0.014
left superior parietal	0.0357 (0.0140, 0.0573)	3.22	0.001	0.021
right lateral orbitofrontal	0.0344 (0.0134, 0.0554)	3.21	0.001	0.021
left inferior parietal	0.0349 (0.0126, 0.0572)	3.06	0.002	0.028
right bankssts	0.0343 (0.0123, 0.0564)	3.05	0.002	0.028
left middle temporal	0.0327 (0.0115, 0.0539)	3.02	0.003	0.028
right rostral middle frontal	0.0320 (0.0108, 0.0531)	2.96	0.003	0.030
right pars opercularis	0.0326 (0.0103, 0.0549)	2.87	0.004	0.034
left lateral orbitofrontal	0.0307 (0.0094, 0.0521)	2.82	0.005	0.036
right inferior parietal	0.0305 (0.0093, 0.0517)	2.82	0.005	0.036
right pars triangularis	0.0317 (0.0093, 0.0540)	2.78	0.005	0.039
right superior parietal	0.0297 (0.0082, 0.0512)	2.70	0.007	0.043
Digital social				
left superior parietal	-0.0381 (-0.0592, -0.0170)	-3.55	< 0.001	0.014
right superior parietal	-0.0371 (-0.0580, -0.0162)	-3.48	0.001	0.014
right precentral	-0.0362 (-0.0568, -0.0155)	-3.43	0.001	0.014
left cuneus	-0.0297 (-0.0511, -0.0083)	-2.72	0.007	0.043
Digital non-social				
right inferior temporal	-0.0477 (-0.0689, -0.0266)	-4.43	< 0.001	0.001
left middle temporal	-0.0483 (-0.0697, -0.0268)	-4.41	< 0.001	0.001
right middle temporal	-0.0379 (-0.0591, -0.0168)	-3.52	< 0.001	0.014
right inferior parietal	-0.0378 (-0.0593, -0.0163)	-3.44	0.001	0.014
right fusiform	-0.0370 (-0.0581, -0.0159)	-3.44	0.001	0.014
left bankssts	-0.0396 (-0.0623, -0.0169)	-3.42	0.001	0.014
right rostral anterior cingulate	-0.0396 (-0.0624, -0.0169)	-3.42	0.001	0.014
left lateral occipital	-0.0355 (-0.0565, -0.0144)	-3.31	0.001	0.020
right bankssts	-0.0368 (-0.0592, -0.0145)	-3.23	0.001	0.021
left inferior temporal	-0.0353 (-0.0568, -0.0138)	-3.21	0.001	0.021
right precentral	-0.0346 (-0.0561, -0.0131)	-3.15	0.002	0.025
left precentral	-0.0340 (-0.0554, -0.0126)	-3.12	0.002	0.026
left inferior parietal	-0.0353 (-0.0579, -0.0127)	-3.06	0.002	0.028
right lateral occipital	-0.0319 (-0.0526, -0.0113)	-3.03	0.002	0.028
right postcentral	-0.0341 (-0.0562, -0.0120)	-3.02	0.003	0.028
right insula	-0.0323 (-0.0533, -0.0112)	-3.01	0.003	0.028
left insula	-0.0326 (-0.0541, -0.0112)	-2.98	0.003	0.029
left superior frontal	-0.0324 (-0.0539, -0.0109)	-2.95	0.003	0.030
left medial orbitofrontal	-0.0307 (-0.0515, -0.0100)	-2.91	0.004	0.033
left postcentral	-0.0321 (-0.0539, -0.0103)	-2.89	0.004	0.034
right medial orbitofrontal	-0.0321 (-0.0540, -0.0102)	-2.88	0.004	0.034
left lateral orbitofrontal	-0.0314 (-0.0531, -0.0098)	-2.85	0.004	0.035
right lateral orbitofrontal	-0.0309 (-0.0522, -0.0096)	-2.84	0.005	0.035
right paracentral	-0.0317 (-0.0542, -0.0091)	-2.75	0.006	0.042
left paracentral	-0.0313 (-0.0537, -0.0089)	-2.74	0.006	0.042
left cuneus	-0.0310 (-0.0534, -0.0087)	-2.72	0.006	0.043
left isthmus cingulate	-0.0296 (-0.0512, -0.0079)	-2.68	0.007	0.046

Supplementary Table 9. Correlations Between Activity Duration-Related Gray Matter Volume T-Maps and Neurosynth Terms

	Physical social	Physical non-social	Digital social	Digital non-social
Mental & Physical Health				
depression	-0.060	0.000	0.024	0.089
anxiety	-0.109	-0.060	0.082	0.143
psychosis	-0.004	-0.005	0.002	0.046
addiction	-0.080	-0.037	0.000	0.099
hyperactivity	-0.030	-0.008	0.027	0.074
impulsivity	0.001	-0.014	-0.001	0.028
fear	-0.098	-0.065	0.102	0.112
stress	-0.132	-0.014	0.034	0.157
distress	0.011	-0.007	-0.022	-0.007
mood	-0.023	-0.031	0.029	0.035
emotion	-0.056	-0.001	-0.005	0.113
valence	-0.039	0.000	-0.013	0.081
risk	-0.076	-0.029	0.029	0.120
trauma	-0.036	-0.013	0.021	0.061
pain	-0.186	-0.067	0.093	0.229
sleep	-0.111	-0.060	0.062	0.109
arousal	-0.053	-0.004	0.017	0.118
disability	0.011	0.003	-0.012	-0.036
Attention & Executive Function				
inhibition	0.009	0.006	-0.028	0.057
updating	0.061	-0.027	0.025	-0.053
maintenance	0.071	-0.022	-0.068	-0.062
detection	0.006	0.028	0.052	-0.071
monitoring	0.020	0.002	-0.090	0.032
focus	-0.012	0.007	-0.037	0.003
attention	0.109	0.033	0.017	-0.140
perception	0.020	-0.015	0.041	-0.103
Social Cognition & Communication				
face recognition	0.102	-0.119	0.012	-0.160
facial expression	-0.021	0.001	0.044	-0.017
mentalizing	0.085	0.069	-0.104	-0.081
empathy	-0.044	0.079	-0.053	0.067
communication	-0.001	0.050	-0.041	-0.007
interaction	0.027	-0.014	-0.036	0.004
discrimination	0.013	-0.029	0.033	-0.082
competition	0.028	-0.011	-0.013	-0.045
inference	0.051	0.092	-0.067	-0.013
judgment	0.076	0.098	-0.088	-0.090
intention	0.079	0.058	-0.043	-0.084
belief	0.003	0.046	-0.064	-0.018
interpersonal	0.003	0.054	-0.033	0.016
social interaction	0.016	0.012	-0.039	-0.014
social cognitive	0.042	0.050	-0.077	-0.071

Supplementary Table 10. Standardized Path Coefficients from CLPM Analysis Between Activity Engagement and Mental Health Symptoms

Supplementary Table 10 is provided in a separate Excel file (Sheet 4) due to length exceeding one page.

Description: Standardized path coefficients from cross-lagged panel model (CLPM) analyses testing bidirectional temporal associations between activity engagement and mental health symptoms.

Supplementary Table 11. ***P*** **values and FDR-corrected** ***P*** **values from CLPM Analysis Between Activity Engagement and Mental Health Symptoms**

Supplementary Table 11 is provided in a separate Excel file (Sheet 5) due to length exceeding one page.

Description: Raw and false discovery rate (FDR)-adjusted p-values from cross-lagged panel model (CLPM) analyses testing bidirectional associations between activity engagement and mental health symptoms, highlighting significant temporal associations after multiple comparisons adjustment (FDR-corrected $P < .05$).

Supplementary Table 12. Standardized Estimate effects and *P* values in Mediation Analysis

Independent / dependent variables	Total effect		Direct effect		Indirect effect		% Mediated
	Estimate (95% CI)	*P* value	Estimate (95% CI)	*P* value	Estimate (95% CI)	*P* value	Percentage
Physical social							
Withdrawn and depressed	-0.077 (-0.102, -0.053)	**<0.001**	-0.077 (-0.101, -0.052)	**<0.001**	-0.001 (-0.002, 0.001)	0.300	1.0%
Social problems	-0.056 (-0.081, -0.031)	**<0.001**	-0.054 (-0.079, -0.029)	**<0.001**	-0.002 (-0.004, -0.000)	**0.004**	3.8%
Digital social							
Rule-breaking behaviors	0.075 (0.045, 0.105)	**<0.001**	0.072 (0.042, 0.102)	**<0.001**	0.003 (0.001, 0.005)	**<0.001**	3.7%
Digital non-social							
Rule-breaking behaviors	0.084 (0.058, 0.110)	**<0.001**	0.080 (0.055, 0.106)	**<0.001**	0.004 (0.002, 0.006)	**<0.001**	4.7%
Social problems	0.050 (0.023, 0.078)	**<0.001**	0.048 (0.020, 0.076)	**0.002**	0.003 (0.000, 0.005)	**0.006**	5.0%
Thought problems	0.064 (0.037, 0.090)	**<0.001**	0.063 (0.036, 0.090)	**<0.001**	0.001 (-0.001, 0.002)	0.460	1.0%
Attention problems	0.087 (0.060, 0.115)	**<0.001**	0.083 (0.056, 0.111)	**<0.001**	0.004 (0.002, 0.006)	**<0.001**	4.5%
Mental health problem total score	0.072 (0.045, 0.099)	**<0.001**	0.069 (0.042, 0.096)	**<0.001**	0.003 (0.001, 0.005)	**<0.001**	4.2%

***Note*:** Results with *P*<.05 are highlighted in **bold**.