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Original article

Adherence to 24-Hour Movement Recommendations and Health Indicators in Early Adolescence: Cross-Sectional and Longitudinal Associations in the Adolescent Brain Cognitive Development Study

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A B S T R A C T

Purpose: Adherence to 24-hour movement guidelines of ≥60 minutes of physical activity, ≤2 hours of screen time, and 9–11 hours of sleep has been shown to benefit cognitive, physical, and psychosocial health in children and young adolescents aged 5–13 years. However, these findings have mostly been based on cross-sectional studies or relatively small samples and the associations between adherence to guidelines and brain structure remain to be evaluated.
Methods: Data from the Adolescent Brain Cognitive Development℠ (ABCD) study of 10,574 early adolescents aged 9–14 years from September 2016 to January 2021 were used to examine whether adherence to 24-hour movement guidelines benefits cognition (general cognitive ability, executive function, and learning/memory assessed by the National Institutes of Health Toolbox neurocognitive battery), body mass index, psychosocial health (internalizing, externalizing, and total problems from the parent-reported Child Behavior Checklist), and magnetic resonance imaging–derived brain morphometric measures at baseline (T1), ∼2 years later (T2), and longitudinally from T1 to T2 (T2-T1). Multivariable linear mixed models were used, with adjustments for sociodemographic confounders. Time elapsed and T1 outcome measures were also controlled for in longitudinal models.
Results: Better cognitive scores, fewer behavioral problems, lower adiposity levels, and greater gray matter volumes were observed in those who met both sleep and screen time recommendations compared to those who met none. Longitudinal follow-up further supports these findings; participants who met both recommendations at T1 and T2 evidenced better outcome measures than those who met none.
Discussion: These findings support consideration of integrated rather than isolated movement recommendations across the day in early adolescence for better cognitive, physical and psychosocial health. Although the associations between physical activity and health indicators were less

IMPLICATIONS AND CONTRIBUTION

In relation to 24-hour movement recommendations for young adolescents, this study found that those with ≤2 hours of screen time and 9–11 hours of sleep evidenced superior cognition, fewer behavioral problems, lower adiposity levels, and greater gray matter volume than those who did not meet any recommendations. However, associations with physical activity were less consistent.

Conflicts of interest: The authors have no conflicts of interest to disclose.
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consistent in this study, the significant findings from sleep and screen time demonstrate the importance of considering movement recommendations in an integrated rather than isolated manner for adolescent health. It is recommended that movement behaviors be simultaneously targeted for better developmental outcomes.

Adequate sleep, regular physical activity, and limited sedentary behavior (including screen time) are well-recognized determinants of healthy development in childhood and adolescence [1–3]. Although often dealt with separately, these modifiable lifestyle factors lie on a continuum of interacting "movement" behaviors [4]. For example, health benefits of regular levels of moderate-to-vigorous physical activity (MVPA) could be attenuated if one engages in excessive screen time and has inadequate sleep [5].

Recognizing this, the World Health Organization and several countries [4,6–8] are shifting away from separate recommendations and moving toward the adoption of 24-hour movement guidelines for overall health and well-being. Based on a set of systematic reviews [9–11] and guidelines first proposed by the Canadian task force in 2016 [4], 24-hour guidelines typically recommend at least 60 minutes of MVPA per day, $\leq$2 hours of recreational screen time per day, and 9–11 hours of sleep per night for those aged 5–13 years.

In support of these guidelines, recent studies have found positive associations between the number of recommendations met and overall health indicators in children and adolescents [12]. Participants who fulfilled more guideline components had lower adiposity levels [13], higher health-related quality of life [14], better psychosocial scores [15], lower risk of depression [16], and superior academic performance [17] as well as global cognition scores [18]. However, findings from combinations of specific movement behaviors have been less consistent across outcome domains, and mostly derived from cross-sectional studies or relatively small samples. Relationships between adherence to 24-hour movement guidelines and brain structure during this critical developmental period also have not been studied. As adolescents undergo significant cortical reorganization and pruning over a protracted period [19], they could be particularly vulnerable to environmental influences and lifestyle habits—both positive and negative [20]—which would then impact sociocognitive development. To answer these questions, we utilized data from a large sample of 10,000+ early adolescents aged 9–11 years from the Adolescent Brain Cognitive Development℠ (ABCD) study, to investigate associations between adherence to movement guidelines from 24-hour movement behavior data (24h-MB) surveying sleep, screen time and physical activity behaviors, and four commonly surveyed health indicators measuring the following: (1) cognition; (2) psychosocial health; (3) body mass index (BMI), and (4) brain morphometric measures, both at baseline and 2 years later.

Materials and Methods

Data source

The ABCD study (http://abcdstudy.org) is the largest longitudinal study on brain development and child health in the United States. It involves 22 nationally distributed research sites (with one site no longer active) and aims to follow 11,878 children from preadolescence into early adulthood. Potential participants were identified through probability sampling of public and private elementary schools estimated to cover over 20% of eligible participants in the US population. Informed consent, assent, and parental permission were obtained prior to all data collections. Further details on recruitment procedures, task design, data collection protocols, and neuroimage processing pipelines are described elsewhere [21,22].

Analyses were conducted on the ABCD 4.0 data release (https://doi.org/10.15154/1523041). After excluding participants who did not provide sociodemographic information for age, sex, highest parental education, family income, and race, 10,574 and 9,273 participants contributed data to 24h-MBs for the baseline (T1) and 2-year follow-up (T2) time points respectively (Table 1). For each of the outcome variables considered, a further number of participants had to be excluded due to missing data and quality checks (Table A1). The main ABCD study was approved by the University of California, San Diego's Institutional Review Board. Our institution received data as part of an agreement (National Institute of Mental Health [NIMH] Data Archive Data Use Certification) signed with the National Institutes of Health (NIH). As only deidentified data were used in these secondary analyses, this study was exempted from a full review by the institutional review board at the National University of Singapore.

24-hour movement behaviors

Self and parental reports were used to extract the amount of time participants spent on each of the three movement behaviors (i.e., sleep, screen time, and physical activity; see Supplementary Methods for details). These responses were then recoded as binary variables, with 1 indicating adherence and 0 indicating nonadherence, to the 24-hour movement recommendations. Participants were subsequently grouped into eight categories of adherence to each combination of 24h-MBs to examine specificity of these MB categories to the different outcome variables investigated (Figure 1).

Cognitive measures

Cognition was assessed with the NIH Toolbox Cognition Battery that comprised seven tasks spanning six cognitive domains: attention, episodic memory, working memory, language, executive function, and processing speed [23]. A crystallized intelligence composite score was computed from the Picture Vocabulary and Oral Reading tasks while a fluid intelligence composite score was computed from the other five tasks (Pattern Comparison, List Sorting Working Memory, Picture Sequence, Flanker, and Dimensional Cart Sort). As two of these tasks—the

Table 1
Demographic, behavioral, and brain volumetric characteristics

	T1 (9–11 years)	T2 (11–14 years)
	Total N = 10,574	Total N = 9,273
	n (%) or mean (SD)	n (%) or mean (SD)
Demographics		
Sex		
Male	5,504 (52.1%)	4,849 (52.2%)
Female	5,070 (48.0%)	4,424 (47.7%)
Age (years)	9.9 (0.6)	12.0 (0.7)
Highest parental education[a]	16.8 (2.6)	16.9 (2.5)
Family income[b]	7.3 (2.4)	7.4 (2.3)
Race		
African-American	1,568 (14.8%)	1,259 (13.6%)
American Indian and Alaska Native	54 (0.5%)	44 (0.05%)
Asian	234 (2.2%)	197 (2.1%)
Pacific Islander	13 (0.1%)	11 (0.1%)
White	6,979 (66.0%)	6,267 (67.6%)
Other	427 (4.0%)	365 (3.9%)
Two or more races	1,299 (12.3%)	1,130 (12.1%)
24-hour movement behaviors		
Sleep duration		
9–11 hours	5,166 (48.8%)	3,012 (32.5%)
8–9 hours	3,866 (36.6%)	4,085 (44.0%)
7–8 hours	1,211 (11.5%)	1,664 (17.9%)
5–7 hours	312 (3.0%)	474 (5.1%)
<5 hours	29 (0.2%)	38 (0.4%)
Weighted screen time (hours/day)	3.7 (3.0)	4.0 (3.2)
Moderate-to-vigorous physical activity (days/week)	3.5 (2.3)	3.8 (2.1)
Percentage meeting sleep guidelines	48.8%	32.5%
Percentage meeting screen time guidelines	35.2%	30.6%
Percentage meeting activity guidelines	16.7%	15.7%
Cognition (NIH Toolbox)		
Fluid intelligence	91.9 (10.6)	93.7 (12.4)
Crystallized intelligence	86.7 (7.0)	91.2 (7.1)
Mean Cognitive Score (5 tasks)	92.3 (6.5)	99.1 (6.9)
Psychosocial health (Child Behavior Checklist)		
Externalizing problems	45.7 (10.3)	44.5 (9.7)
Internalizing problems	48.5 (10.6)	47.8 (10.4)
Total problems	45.9 (11.2)	44.8 (11.2)
Body mass index (kg/m^2)	18.7 (3.9)	20.3 (4.3)
Brain volumes (mm^3)		
Cortical gray matter volume	598,740.3 (56,117.6)	590,379.1 (56,724.2)
Subcortical gray matter volume	60,052.5 (4,874.2)	60,861.6 (4,945.8)
Estimated total intracranial volume	1,494,839 (143,524.6)	1,525,469 (147,482.5)

Highest parental education and family income were measured in ordinal scales.
[a] Highest parental education referred to the highest level of school the parent had completed: 1–12 = Grade 1–12; 13 = High school graduate; 14 = General Educational Development Test (GED) or equivalent; 15 = Some college; 16 = Associate degree: Occupational; 17 = Associate degree: Academic; 18 = Bachelor's degree; 19 = Master's degree; 20 = Professional school degree; and 21 = Doctoral degree.
[b] Family income referred to the total combined family income for the past 12 months before taxes and deductions: 1 = Less than $5,000; 2 = $5,000–$11,999; 3 = $12,000–$15,999; 4 = $16,000–$24,999; 5 = $25,000–$34,999; 6 = $35,000–$49,999; 7 = $50,000–$74,999; 8 = $75,000–$99,999; 9 = $100,000–$199,999; and 10 = $200,000 and greater.

Dimensional Cart Sort and List Sorting Working Memory—were only conducted at T1, a composite fluid intelligence score could not be computed at T2. The remaining five tasks (Picture Vocabulary, Flanker, Picture Sequence, Pattern Comparison, and Oral reading) were instead averaged together for a composite cognition score that could be compared across both time points. Uncorrected standard scores (mean [M] = 100, standard deviation [SD] = 15) were used, which compare the score of the test taker to those in the normative sample (aged 3–85 years).

Psychosocial health measures

Parental reports of problem behaviors over the past 6 months were collected using the Child Behavior Checklist for ages 6–18 years [24,25]. Composite scores summarizing internalizing problems (those directed toward "self," e.g., from anxiety, depression, and social withdrawal scales), externalizing problems (those directed toward "others," e.g., from rule-breaking and aggressive behavior scales), as well as an overall composite for total problems were extracted. Raw scores were converted to norm-referenced T-scores (M = 50, SD = 10), with higher scores indicating greater levels of emotional and behavioral problems. Clinically significant elevations are typically denoted by T-scores ≥65.

Body mass index

Participants' height and weight were objectively measured up to three times and averaged to obtain BMI scores using the formula weight (kg)/height (m^2). Extreme values of <11 or >36 kg/m^2 were excluded as possible data entry errors/outliers (∼1% of data). Values were then converted to z-scores (zBMI)

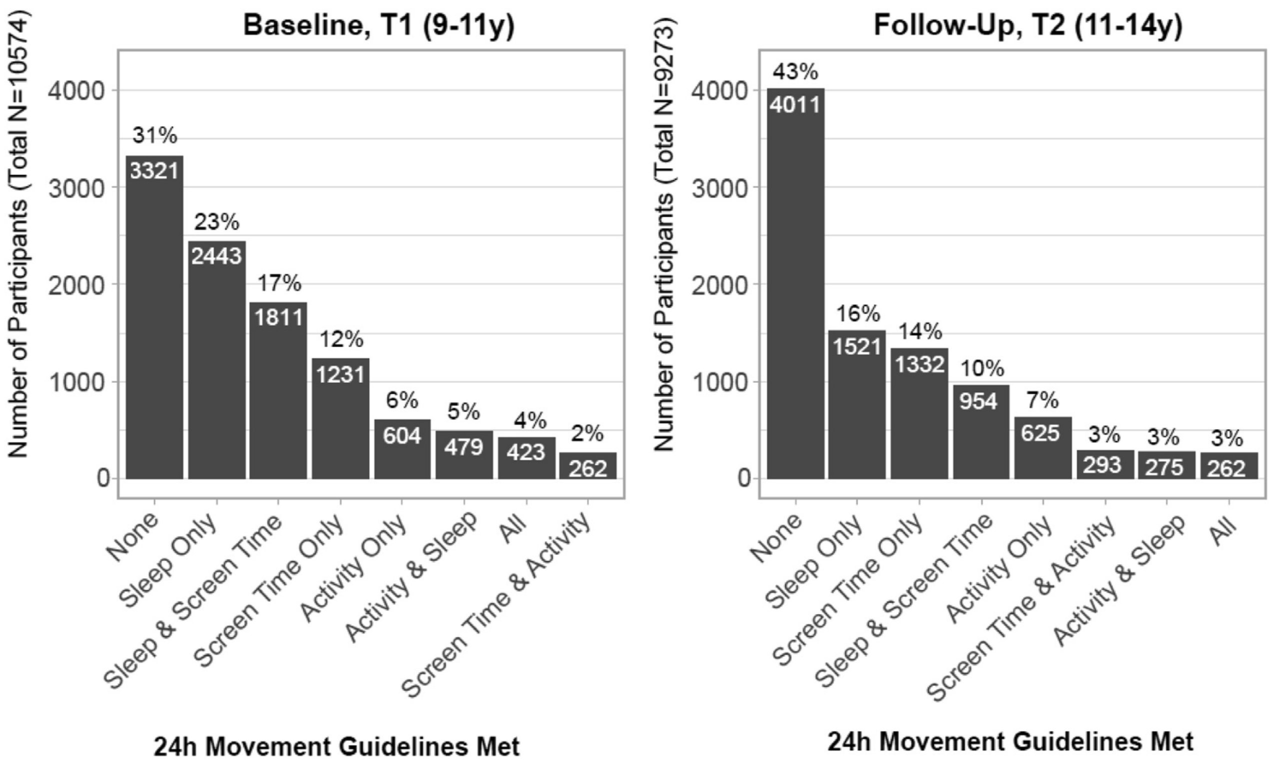

Figure 1. Number of participants meeting 24-hour movement guidelines at baseline (T1) and follow-up (T2).

using the World Health Organization's Child Growth Standards with the R package "zscorer" [26].

Brain morphometric measures

Scanning parameters, preprocessing, and analytical pipelines are described in separate papers [22,27]. Structural brain images were processed using FreeSurfer 7.1.1 (https://surfer.nmr.mgh.harvard.edu) to obtain measures of estimated total intracranial volume and total cortical and subcortical gray matter volumes (GMVs). Only participants whose structural data passed quality review checks by the ABCD study team were included in the final analysis.

Statistical analysis

Cross-sectional analyses were conducted for both T1 and T2 separately. Associations between adherence to each 24h-MB combination category (compared to a reference group meeting no recommendations) and outcome variables for cognition, psychosocial health, zBMI, and GMVs were investigated using linear mixed effects models, controlled for age, sex, highest parental education, household income, and race. GMV models additionally controlled for estimated total intracranial volume measures. As the ABCD study includes siblings, families nested within site were additionally modeled as a random effect. Unstandardized regression coefficients (b) are reported to indicate difference between the mean of outcomes measured in each 24h-MB group and the mean of the reference group that did not meet any recommendations, keeping all other variables constant.

Next, longitudinal analyses with linear mixed effects models were conducted to look at associations with changes from T1 to T2 (i.e., T2-T1) for each of the outcome variables considered, controlled for sociodemographic variables at T1 included in the cross-sectional analyses, outcomes at T1, and time elapsed between T1 and T2 assessments. Analyses were conducted first by comparing groups that met specific 24h-MB categories at both T1 and T2 with the group that did not meet any recommendations. As adherence to both sleep and screen time recommendations at both T1 and T2 most consistently showed favorable outcomes compared to the group that met no recommendations, we followed up this finding by also comparing groups that only met the sleep and screen time combination at *either* T1 or T2, compared to the rest of the sample.

p-values were corrected for multiple comparisons using the Benjamini-Hochberg procedure to control the false discovery rate (FDR) at 0.05 [28]. This correction was carried out separately for T1, T2, and T2-T1 (# outcomes × seven 24h-MB categories). Results are reported with and without this correction.

Post hoc analyses

To follow-up on significant associations between adherence to each 24h-MB category and cortical GMV, we further inspected relationships by lobar region (frontal, parietal, temporal, occipital) following delineations in https://surfer.nmr.mgh.harvard.edu/fswiki/CorticalParcellation.

To follow-up on unexpected findings between adherence to physical activity recommendations and the following—(1) composite cognition scores, (2) externalizing behaviors, and (3) cortical GMV—we modeled frequency of MVPA per week as a

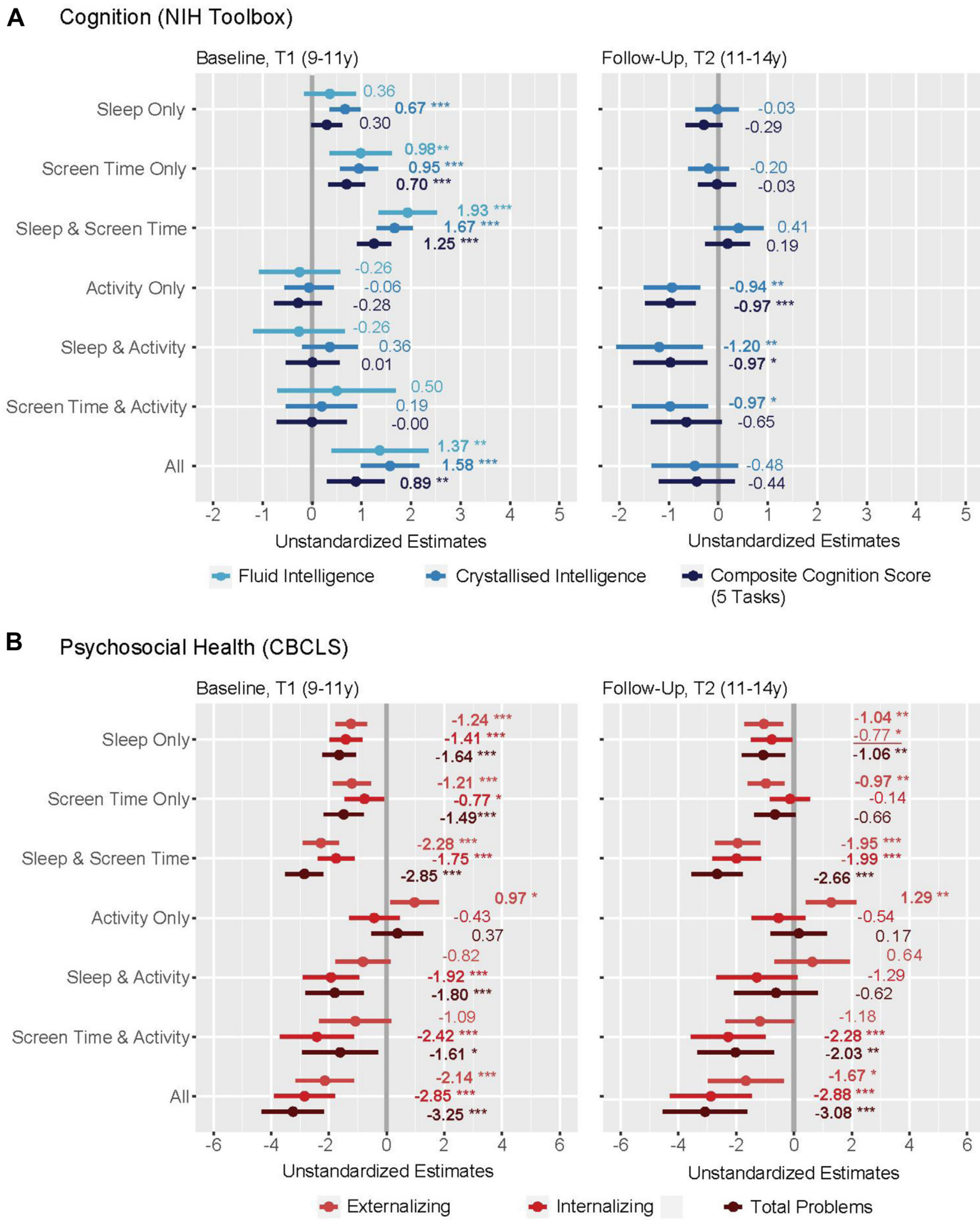

Figure 2. Cross-sectional associations between adherence to 24-hour movement behaviors and (A) cognitive scores, (B) psychosocial health scores, (C) zBMI, and (D) GMVs. Plots show unstandardized estimates of regression coefficients from multilevel models for baseline (T1; left panel) and follow-up (T2; right panel) time points, respectively. Error bars indicate 95% confidence intervals while asterisks denote level of significance, uncorrected (***$p < .001$, **$p < .01$, *$p < .05$). Significant p-values ($p < .05$) that survive multiple comparisons corrections are denoted in bold font, while those that do not are underlined. The gray reference line refers to the group that did not meet any recommendations. All models were controlled for age, sex, highest level of education (parent), race, family income, and estimated total intracranial volume (GMV models only). Families nested within site were additionally modeled as a random effect.

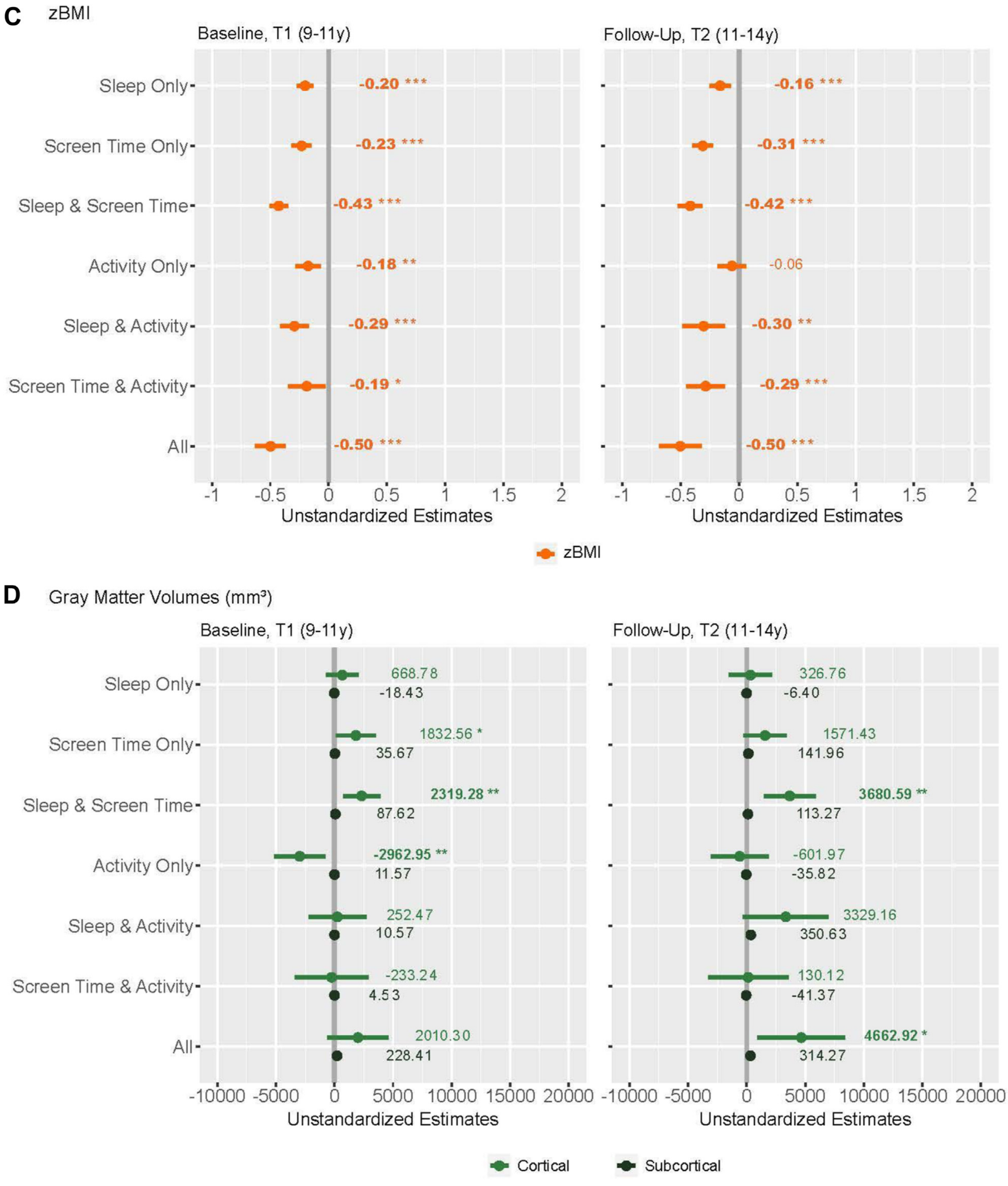

Figure 2. Continued.

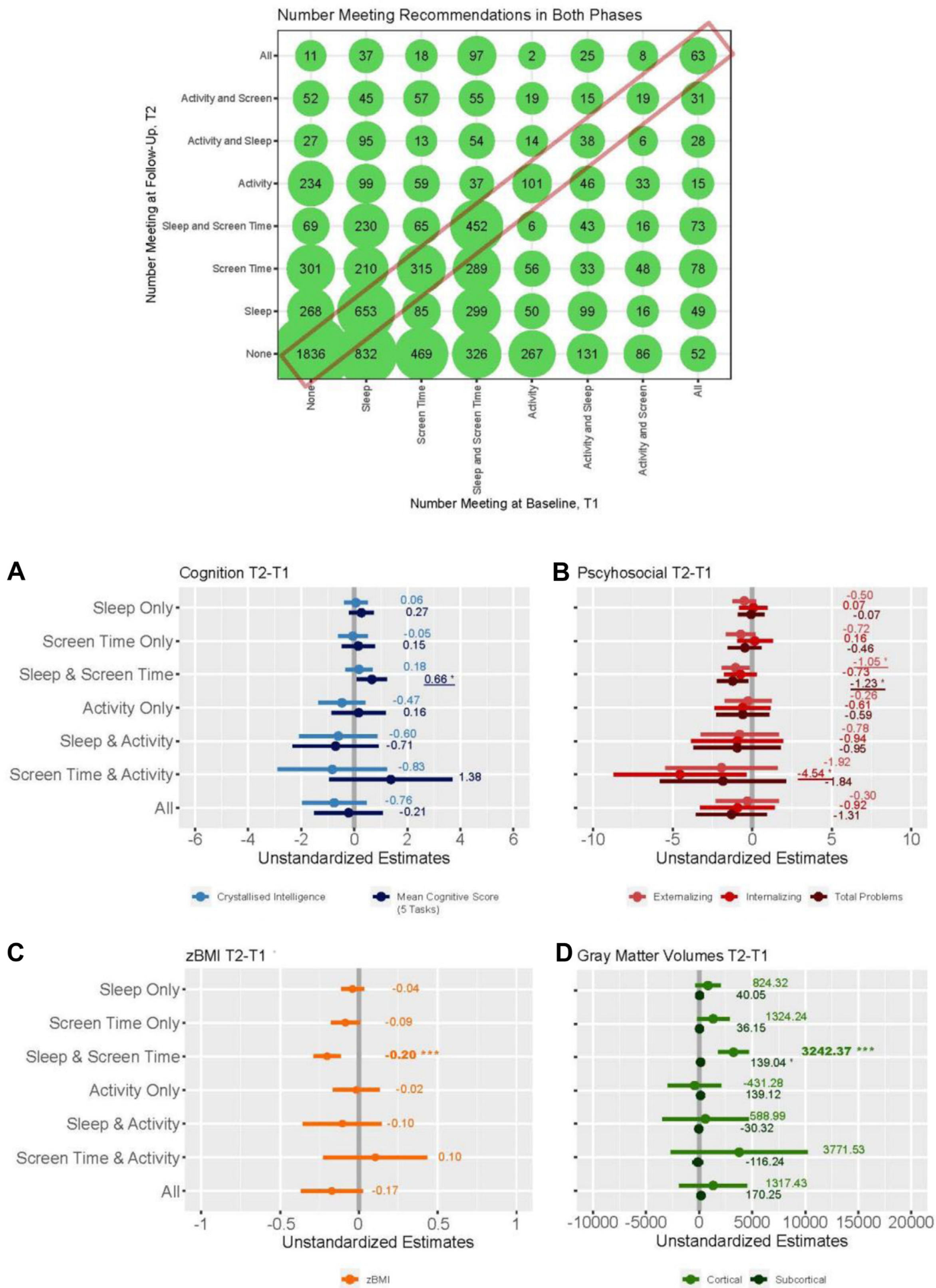

Figure 3. Top panel: Balloon plot showing frequencies of participants meeting combinations of 24-hour recommendations at baseline (T1) and follow-up (T2). Bottom panel: Longitudinal (T2-T1) associations between adherence to 24-hour movement behaviors at both time points (i.e., groups indicated in the red rectangle) and (A) cognitive scores, (B) psychosocial health scores, (C) zBMI, and (D) GMVs. Plots show unstandardized estimates of regression coefficients from multilevel models. The gray reference line refers to the group that did not meet any recommendations. Error bars indicate 95% confidence intervals while asterisks denote level of significance, uncorrected (***$p < .001$, ** $p < .01$, *$p < .05$). Significant p-values ($p < .05$) that survive multiple comparison corrections are denoted in bold font, while those that do not are underlined. All models were controlled for age, sex, highest level of education (parent), race, family income, estimated total intracranial volume (GMV models only), as well as time elapsed between baseline and follow-up and baseline measures of all dependent variables. Families nested within site were additionally modeled as a random effect.

categorical variable, with 0 days per week as the reference value in both T1 and T2, and additionally controlled for whether sleep and screen time recommendations were met (0/1 indicator variable) in addition to the other sociodemographic covariates used in the previous analyses.

All analyses were conducted using R version 4.1.0.

Results

Sample characteristics of the 10,574 (M ± SD = 9.9 ± 0.6 years, 52% male) and 9,273 (M ± SD = 12.0 ± 0.7 years, 52% male) participants who provided demographic and 24h-MB data at T1 and T2 respectively are provided in Table 1. At T1, almost half of the sample (49%) met sleep guidelines of 9–11 hours/night, 35% met screen time guidelines of $\leq$2 hours/day, and 17% met MVPA guidelines of $\geq$60 minutes/day. Only 4% of participants met all three 24-hour movement recommendations, while of concern, 31% did not meet any (Figure 1). At T2, the proportion of those who met sleep guidelines dropped to about a third (32%) of the sample, while the proportion meeting screen time guidelines reduced slightly (31%) and those who met MVPA guidelines remained relatively stable (16%). Notably, of the 9,255 participants who provided 24h-MB data both at T1 and T2, only <1% met all three guidelines both at T1 and T2, while 20% did not meet any.

Cross-sectional analyses

24-hour movement behaviors and cognition. At T1, compared to participants who did not meet any recommendations, those who met screen time only, sleep and screen time, or all three recommendations evidenced superior fluid intelligence, crystallized intelligence, and composite cognition scores, with adherence to sleep and screen time recommendations showing the greatest benefit (b = 1.93, p < .001, $p_{\text{FDR-corr}}$ < .001; Figure 2A). At T2 however, these benefits were not significant in any group (p > .11). Unexpectedly, those who met activity only (b = −0.94, p = .001, $p_{\text{FDR-corr}}$ = .005), sleep and activity (b = −1.20, p = .007, $p_{\text{FDR-corr}}$ = .019), and screen time and activity (b = −0.97, p = .013, $p_{\text{FDR-corr}}$ = .03) recommendations instead showed poorer crystallized intelligence scores compared to those who did not meet any recommendations.

24-hour movement behaviors and psychosocial health. At T1, participants who met most combinations of 24h-MBs evidenced lower internalizing and total problems compared to participants who did not meet any recommendations (Figure 2B). However, participants who only met activity recommendations evidenced greater levels of externalizing problems (b = 0.97, p = .02, $p_{\text{FDR-corr}}$ = .04). These associations were largely mirrored at T2, with the exception of those meeting sleep and activity and screen time only recommendations no longer showing lower levels of internalizing and total problems compared to the group that did not meet any recommendations.

24-hour movement behaviors and standardized BMI (zBMI) measures. At both T1 and T2, participants who met most combinations of 24h-MBs showed lower adiposity levels than those who did not meet any recommendations, with the exception of the group that only met activity recommendations at T2 (p = .33; Figure 2C).

24-hour movement behaviors and gray matter volumes. Compared to participants who did not meet any recommendations, only those who met both sleep and screen time recommendations alone consistently showed greater total cortical GMVs at both T1 (b = 2,319.28 mm^3, p = .004, $p_{\text{FDR-corr}}$ = .009) and T2 (b = 3,680.59 mm^3, p = .001, $p_{\text{FDR-corr}}$ = .005) (Figure 2D). Follow-up analyses show that these relationships were significant in the frontal (T1: b = 876.68 mm^3, p = .02; T2: b = 1,449.00 mm^3, p = .005) and temporal lobe regions (T1: b = 644.11 mm^3, p = .004; T2: b = 903.47 mm^3, p = .003) at both time points (Figure A1). Those who only met activity recommendations at T1 evidenced smaller GMVs than those who did not meet any (b = −2,962.95 mm^3, p = .008, $p_{\text{FDR-corr}}$ = .02) but this relationship was no longer significant at T2 (p = .63).

Longitudinal analyses

Considering groups of participants who met the same combinations of 24h-MBs at both T1 and T2 (Figure 3), it was clear that only the group that met sleep and screen time recommendations at both T1 and T2 showed improvements across time (T2-T1) on all health indicators surveyed. They showed the greatest increase in composite cognition score (b = 0.66, p = .02, $p_{\text{FDR-corr}}$ = .21), decrease in externalizing (b = −1.05, p = .02, $p_{\text{FDR-corr}}$ = .18) and total problems (b = −1.23, p = .01, $p_{\text{FDR-corr}}$ = .18), decrease in zBMI (b = −0.20, p < .001, $p_{\text{FDR-corr}}$ < .001), and increase in total cortical (b = 3,242.37 mm^3, p < .001, $p_{\text{FDR-corr}}$ < .001) and subcortical (b = 139.04 mm^3, p = .01, $p_{\text{FDR-corr}}$ = .18) volumes compared to the group that did not meet any recommendations, although only zBMI and total cortical change remained significant after FDR correction.

Follow-up analyses on groups that only met sleep and screen time recommendations at either T1 or T2 suggested that for zBMI and GMV measures, early adherence (T1) to recommendations still benefitted T2-T1 measures (zBMI: b = −0.07, p = .04; GMV: b_{cortical} = 1,312.04 mm^3, p = .001 and $b_{\text{subcortical}}$ = 100.15 mm^3, p = .002) (Figure A2). This suggests that some effects span a longer timescale. In contrast, for psychosocial health, T2 adherence to recommendations was related to improved T2-T1 outcomes ($b_{\text{externalizing}}$ = −0.73, p = .04; $b_{\text{internalizing}}$ = −0.89, p = .03; b_{total} = −0.94, p = .03), suggesting a more immediate effect. For cognition, only those who met sleep and screen time recommendations at both time points evidenced improvements (b = 0.5, p = .045) compared to the rest of the sample.

Post hoc analyses

When frequency of physical activity per week was coded as an interval variable (0–7 days), nonlinear relationships between frequency of physical activity per week and composite cognition, cortical GMV, and externalizing behaviors were found (Figure A3), whereby better health outcomes were associated with moderate levels of weekly physical activity.

Discussion

In this study, we found that young adolescents aged 9–11 years who slept 9–11 hours *and* kept to $\leq$2 hours of recreational screen time a day demonstrated higher cognitive scores, better psychosocial health, lower adiposity levels, and greater cortical GMVs than those who did not meet any recommendations. Approximately 2 years later, most of these associations persisted, although the association with cognition was not significant. Considering longitudinal changes, only those who met sleep and screen time recommendations at both time points again evidenced improvements across time on all health indicators than the group that did not meet any recommendations, even after controlling for baseline metrics.

Although meeting either sleep or screen time recommendations alone was also beneficial for certain aspects of cognition, the effect was the largest when both recommendations were met. Sleep and screen time are closely linked and an increase in screen time particularly before bedtime is known to negatively impact subsequent sleep [29]. This is affected by delaying bedtimes, increasing sleep onset latency, awakenings after sleep onset and sleep disturbance severity, and reducing total sleep time, although we did not have information about timing of screen use here. Proposed mechanisms include displacement of time that would have been spent sleeping, delayed melatonin secretion due to evening light exposure, and increased presleep arousal levels [30]. The $\leq$2-hour screen time recommendation has also recently been debated, suggesting that what matters most is whether screen "consumes" other areas of life, such as adequate sleep [31], which could be why these movement behaviors need to be considered holistically.

Considering psychosocial health scores, those who met combinations including sleep and screen time also tended to show fewer internalizing, externalizing, and total problem scores compared to those who did not. Adequate sleep has been shown to be important for emotional regulation and mental well-being and has been linked to fewer behavioral problems in school-aged children [9,32], while high levels of recreational screen time ($>$2 hours/day) have been associated with greater externalizing problems and psychological distress which could be linked to the content of screen use [32].

For adiposity levels measured by zBMI scores, most combinations of adherence to recommendations (with the exception of activity at T2) resulted in lower BMI levels compared to those who met none. Sufficient sleep together with a proper diet and adequate levels of physical activity are known to regulate hormones related to growth, maturation, and energy homeostasis, while insufficient levels could lead to energy imbalance and obesity [33]. As higher BMI has been associated with poorer cognitive function across the life span [34] as well as a range of long-term health issues [35], BMI levels need to be monitored throughout childhood and adolescence, and intervened appropriately.

Brain structural findings revealed that it was again the combination of sleep and screen time recommendations which consistently yielded greater GMVs compared to the group that met none, both cross-sectionally and longitudinally. Gray matter densities typically increase from birth before reaching a peak at around the onset of puberty, before declining throughout adolescence and early adulthood [19,36,37] - suggestive of pruning or reorganization for efficient neural processing. This could suggest premature GMV decreases in young adolescents who do not consistently meet optimal movement recommendations. These cross-sectional differences tended to occur in the frontal and temporal regions—areas that mature later and could be most vulnerable to insults during this period—while longitudinal differences were more widespread across the brain. Although prior neuroimaging work has focused separately on associations between 24h-MB components (e.g., sleep [38] or screen time [39]) and brain structure, these findings suggest that these movement behaviors need to be simultaneously targeted for better developmental outcomes.

Intriguingly, combinations including adherence to activity recommendations appeared to have nonsignificant or even detrimental effects on some of the health indicators surveyed here (unless they were combined with adherence to both sleep and screen time recommendations). For cognition and GMV, this could seem contradictory to many cross-sectional studies which show a positive association between physical fitness and academic success [40], likely through a facilitation of neuroplasticity on certain brain structures and consequently cognitive function. Considering that this group also exhibited more externalizing problems at both T1 and T2, this could suggest a coping mechanism in young adolescents with behavioral disorders who are also more likely to be hyperactive, or that their parents themselves encourage physical activity as a means to dealing with behavioral issues [15]. Children with higher symptom attention-deficit/hyperactivity-disorder severity have been shown to exhibit poorer cognition and smaller GMV in widespread regions [41]. There is also a possibility that these children could be involved in sports with high training and time demands, leaving less time for academic activities. In addition, post hoc analyses at T1 showed a beneficial relationship between meeting physical activity recommendations for moderate levels of physical activity (e.g., 1–6 days/week compared to 0 days/week but not at 7 days for cognition) suggesting that this benefit could have been accruing with lesser days of adherence. This finding supports recent guideline updates which explicitly state that children and adolescents can accumulate physical activity through "an average of 60 minutes per day of MVPA per day and not necessarily on all 7 days of the week" [42].

Our study clearly highlights the contributions of 24h-MBs to cognitive, mental, and physical health in a very large sample and from both cross-sectional and longitudinal perspectives. However, there are some limitations to consider. Self-report measures can be inaccurate, and future work utilizing objective data with mobile and wearable technologies will enable an unbiased, real-time, and unobtrusive measurement of movement behaviors with high temporal resolution. For example, as only intense levels of physical activity are those typically linked to favorable health outcomes [43], the use of accelerometers/mobile technology could help quantify physical activity objectively to examine the effect of duration, type, and intensity of activity on various health indicators. Second, we did not have information on daytime activities during the rest of the 24-hour day that could additionally impact on outcomes observed, for example, whether certain groups engaged more in educational activities that would benefit cognition and GMV development. Third, adoption of healthy amounts of 24h-MBs could reflect greater parental awareness and supervision. Parents who closely regulate these behaviors in their children are more likely to seek out enriching activities, provide proper nutrition, and spend more time with them. Finally, due to COVID-19 restrictions beginning March 2020, some participants completed remote assessments using a variety of devices for T2, which could have influenced the nature of some tasks. The pandemic itself also worsened adherence to 24-hour movement recommendations [44] due to restrictions in outdoor movement and could have independently affected these health indicators [45]. Of note, 2,517 of 9,273 participants' data were collected post March 11, 2020, that is, when COVID-19 was declared a pandemic, and movement restrictions began to increase. Nonetheless, separate sensitivity analyses controlling for T2 data collection dates (i.e., pre vs. post March 11) yielded similar overall conclusions (Figure A4). Finally, as the onset of puberty could influence the trajectory of outcomes apart from age, we conducted sensitivity analyses controlling for pubertal development status, with overall similar results (Figure A5).

Conclusions and future work

In conclusion, young adolescents aged 9–11 years who met 24-hour movement recommendations of both sleep and screen time consistently demonstrated better cognition, psychosocial health, lower levels of adiposity, and greater GMVs than those who did not meet these recommendations. These associations persisted in longitudinal analyses 2 years later suggesting the importance of maintaining these behaviors for overall health and well-being. Positive associations between moderate amounts of weekly physical activity and health outcome measures also suggest a need for further refinements into its optimal amount. Finally, these guidelines would be strengthened by introduction of appropriate public policies that would encourage adoption, rather than only health promotion at an individual level. For example, delaying school start times and regulating late night extra-curricular activities would create an environment that would enable many more adolescents to obtain adequate sleep [46].

Data Statement

The ABCD data repository grows and changes over time. The ABCD data used in this report came from the Curated Annual Release 4.0, also defined in NDA Study 1223 (https://doi.org/10.15154/1522595). All deidentified participant data are available upon request from the NIMH Data Archive (https://nda.nih.gov/abcd).

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Supplementary Data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jadohealth.2022.10.019.

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