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Temporal and bi-directional associations between sleep duration and physical activity/sedentary time in children: An international comparison

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Abstract

The purpose of this multinational and cross-sectional study was to investigate whether nighttime sleep duration was associated with physical activity (PA) and sedentary time (SED) the following day, whether daytime PA/SED were associated with sleep duration the subsequent night, and whether the associations were modified by sex and study sites. Data from 5779 children aged 9–11 years were analyzed. A waist-worn Actigraph GT3X+ accelerometer was used to assess children's 24-h movement behaviours for 7 days, i.e. sleep duration, total SED, light-intensity physical activity (LPA), and moderate- to vigorous-intensity physical activity (MVPA). Multilevel linear regression models were used to account for the repeated measures nested within participants (there were up to 7 sleep → PA/SED and PA/SED → sleep pairings per participant) and schools, and adjusted for covariates. To facilitate interpretation, all sleep and PA/SED variables were standardized. Results showed that the relationship between sleep and PA/SED is bi-directional in this international sample of children. Specifically, for each one standard deviation (SD) unit increase in sleep duration, SED the following day decreased by 0.04 SD units, while LPA and

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Conflict of interest

The authors declare that they have no conflict of interest.

MVPA increased by 0.04 and 0.02 SD units, respectively. Sleep duration decreased by 0.02 SD units and increased by 0.04 SD units for each one SD unit increase in SED and MVPA, respectively. Sleep duration was not affected by changes in LPA. These associations differed across sex and study sites in both directions. However, since the observed effect sizes are subtle, public health initiatives should consider the clinical and practical relevance of these findings.

Keywords

Child health; 24-Hour movements; Within-subject effects; Multilevel modelling; Population health

1. Introduction

Recently, the Canadian 24-Hour Movement Guidelines for Children and Youth provided evidence-informed recommendations for a healthy day, comprising an integration of sleep, physical activity (PA) and sedentary time (SED) (Tremblay et al., 2016). For instance, longer sleep duration is associated with an array of positive health outcomes among school-aged children, such as lower adiposity indicators, better emotional regulation, academic achievement and quality of life/well-being (Chaput et al., 2016). Sufficient PA, including light-intensity physical activity (LPA) and moderate- to vigorous-intensity physical activity (MVPA), is also associated with better mental and physical health outcomes (Janssen and LeBlanc, 2010; Biddle and Asare, 2011; Kwon et al., 2011); while excess SED is associated with unfavorable health indicators (Biddle and Asare, 2011; Carson et al., 2016). However, in recent decades, there has been declines in sleep duration and PA levels, and increases in SED among children worldwide (Matricciani et al., 2012; Dollman et al., 2005; Hallal et al., 2012).

There is a growing interest to determine whether there is a virtuous/vicious cycle between children's nighttime sleep duration and daytime PA/SED in the context of the 24-hour lifestyle recommendations. Thus far, research examining the possible bi-directional connection between sleep duration and PA/SED within the pediatric population has produced inconsistent findings. Studies have reported that nighttime sleep duration positively (Hart et al., 2016), negatively (Sorić et al., 2015; Pesonen et al., 2011), or did not (Ekstedt et al., 2013; Vincent et al., 2017) predict the next day's PA. Similarly, studies have reported that PA/SED during the day positively (Nixon et al., 2008), negatively (Pesonen et al., 2011), or did not (Ekstedt et al., 2013; Vincent et al., 2017; Nixon et al., 2008; Dworak et al., 2008) predict the subsequent night's sleep duration. Reasons for these inconsistency remain unclear. Also, research surrounding the association between sleep duration and SED is limited to only one study (Nixon et al., 2008). More epidemiological inquiry is clearly needed based on the available equivocal evidence.

Furthermore, existing research has been mainly conducted in developed countries (Sorić et al., 2015; Pesonen et al., 2011; Ekstedt et al., 2013; Vincent et al., 2017; Nixon et al., 2008; Nixon et al., 2009), with only one study from a developing country (Sorić et al., 2015). The role of higher-order environmental correlates of children's daily lifestyle behaviours are not well understood due to the limited socio-cultural variability. The present multinational study

is unique in its international diversity and provides an opportunity to determine whether the relationships of interest differ across countries and socio-cultural settings. Such information is key to informing the development of interventions that can be culturally adapted for implementation around the world.

The objective of this study was to examine the temporal and bidirectional associations between sleep duration and PA/SED in children from 12 countries representing a wide range of geographic and social contexts. Specifically, this study examined whether sleep duration the preceding night was associated with total SED/LPA/MVPA accumulated the following day, and whether SED/LPA/MVPA during the day were associated with sleep duration the subsequent night. We hypothesized that longer sleep duration would be temporally and bi-directionally associated with less SED and more LPA/MVPA. Based on the available evidence, we also hypothesized that the associations of interest would differ across sex (Sorić et al., 2015; Pesonen et al., 2011) and study sites (Sorić et al., 2015; Pesonen et al., 2011; Vincent et al., 2017).

2. Methods

2.1. Study design and setting

The International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE) is a cross-sectional, multinational study designed to determine the relationships between lifestyle behaviours and obesity in 12 study sites located in Australia, Brazil, Canada, China, Colombia, Finland, India, Kenya, Portugal, South Africa, UK and USA. These countries represent a wide range of economic development (low to high income) (Katzmarzyk et al., 2013). By design, the within-site samples were not intended to be nationally representative. Rather, the primary sampling frame was urban/suburban schools, which were typically stratified by an indicator of socioeconomic status to maximize variability within sites (Katzmarzyk et al., 2013). A standardized protocol was used to collect data across all sites, and all study personnel underwent rigorous training and certification to ensure the data quality (Katzmarzyk et al., 2013). The Institutional Review Board at the Pennington Biomedical Research Center in Baton Rouge, USA (coordinating center) approved the ISCOLE protocol, and the Ethics Review Boards at each participating institution also approved the local protocol. Written informed consent was obtained from parents or legal guardians, and children before participation in the study. Data were collected during the school year at each study site between September 2011 and December 2013.

2.2. Participants

The sample included 9–11-year-old children from the 12 ISCOLE sites. A total of 7372 children participated in ISCOLE, of which 5779 remained in the present analytical sample. Participants without any valid sleep/PA/SED data were excluded (n = 1214). Participants without covariate information were also excluded, including diet (n = 129), parental education (n = 247), and body mass index (BMI) z-score (n = 3). Participants who were excluded due to missing data consisted of more males, with significantly higher BMI z-scores, but did not differ in age (data not shown). Within the 5779 participants, several nights and days were removed because of insufficient (invalid) data to determine sleep

and/or PA/SED. The final number of pairings were n = 31,019 for the analyses where nighttime sleep duration predicted the subsequent day's PA/SED and n = 31,408 for the analyses where daytime PA/SED predicted the subsequent night's sleep duration.

2.3. Measurements

Sleep duration, SED, LPA and MVPA were all objectively assessed using 24-h accelerometry. An Actigraph GT3X+ accelerometer (ActiGraph LLC, Pensacola, FL, USA) was worn at the waist on an elasticized belt at the right mid-axillary line. Participants were encouraged to wear the accelerometer 24 h per day (removing only for water-based activities) for at least 7 consecutive days, including 2 weekend days. The minimal amount of daytime data considered acceptable for inclusion in the sample was at least 10 h of wake wear time per day. Data were collected at a sampling rate of 80 Hz, downloaded in 1-s epochs with the low frequency extension filter using the ActiLife software version 5.6 or higher (ActiGraph LLC, Pensacola, FL, USA), and later reintegrated to 15-s and 60-s epochs for the different analyses. Nocturnal sleep duration (h/night) was estimated from the accelerometry data using 60-s epochs and a fully automated algorithm for 24-hour waist-worn accelerometers that was developed and validated for ISCOLE (Tudor-locke et al., 2014; Barreira et al., 2015). Sleep data were considered valid if daily total sleep period time was ≥160 min/night and > 90% estimated wear time. After exclusion of total sleep period time and awake non-wear time (any sequence of ≥20 consecutive minutes of 0 activity counts), SED was defined as all movement ≤25 counts per 15-s, LPA between 26 and 573 counts, and MVPA ≥574 counts (Barreira et al., 2015), which is consistent with the widely used Evenson cut-offs (Evenson et al., 2008). Daily values of sleep duration, SED, LPA and MVPA were exported into datasets with multiple observations for each participant (e.g., one row per day), with each participant having up to 7 repeated sleep duration and SED/LPA/MVPA measures.

2.4. Covariates

Age, sex, parental education, BMI z-score, unhealthy dietary pattern, daily awake wear time of accelerometer, and type of day (weekday or weekend day) were included as covariates in statistical models. Age was computed from birth and observation dates and sex was self-reported on a questionnaire. Parental education was coded into three categories based on the highest level of education attained by either parent: "did not complete high school", "completed high school or some college", or "completed bachelor's or postgraduate degree". Body mass was measured using a portable Tanita SC-240 Body Composition Analyzer (Arlington Heights, IL) without outer clothing, heavy pocket items, shoes and socks (Katzmarzyk et al., 2013). Height was measured using a Seca 213 portable stadiometer (Hamburg, Germany) without shoes, with the participant's head in the Frankfort plane, fully erect, feet together, and at the end of a deep inhalation (Katzmarzyk et al., 2013). BMI [body mass (kg)/height (m^2)] was calculated, and BMI z-scores were computed using age- and sex-specific reference data from the World Health Organization (De Onis et al., 2007). Computation of the unhealthy dietary pattern scores was explained in detail elsewhere (Mikkilä et al., 2015; Chaput et al., 2015). Most of the strongly loaded food items were common for all 12 countries (Fardet and Boirie, 2014), with positive loadings for fast food, hamburgers, soft drinks, sweets, fried food etc. (Mikkilä et al., 2015; Chaput et al., 2015)

Finally, for each day of observation, awake wear time (minutes per day) was obtained through the accelerometer data reduction process, and “weekend day” was coded as “1” while “week day” as “0”.

2.5. Datasets

To study the relationships of interest, two datasets were created. Each dataset had up to 7 repeated sleep → PA/SED or PA/SED → sleep pairings for each participant; each pairing represented a unique row of observation in the dataset. The first dataset was used to explore the relationship between sleep duration the preceding night (exposure) and SED/LPA/MVPA the following day (outcome). The first row of data for each participant contained sleep duration on day 1 (e.g., 10:00 p.m. on Monday to 7:00 a.m. on Tuesday) and SED/LPA/MVPA on day 2 (e.g., 07:00 a.m. to 10:00 p.m. on Tuesday). The second dataset was used to explore the relationship between daytime SED/LPA/MVPA (exposure) and sleep duration at the subsequent night (outcome). The first row of data for each participant contained SED/LPA/MVPA on day 2 (e.g., 07:00 a.m. to 10:00 p.m. on Tuesday) and sleep duration on day 2 (e.g., 10:00 p.m. on Tuesday to 7:00 a.m. on Wednesday). The sleep → PA/SED or PA/SED → sleep pairing continued for the remaining 6 rows for each participant within each dataset. Covariate data were repeated for all 7 rows for each participant within each dataset, with the exception of awake wear time and type of day, which varied for each row.

2.6. Statistical analysis

Statistical analyses were conducted using SAS version 9.4 (SAS Institute, Cary, NC, USA). Means and standard deviations (SD) of descriptive characteristics were computed by sex and study site. Generalized linear mixed model (PROC GLIMMIX) with a first-order autoregressive matrix (Sorić et al., 2015; Pesonen et al., 2011; Ekstedt et al., 2013) was used to examine the associations of interest and to properly account for the hierarchical nature of the data. Study sites were considered to have fixed effects, schools nested within study sites were viewed as having random effects, and repeated observations of sleep → PA/SED or PA/SED → sleep pairings nested within participants were treated as random effects. The denominator degrees of freedom for statistical tests pertaining to fixed effects were calculated using the Satterthwaite’s approximation (Wang et al., 2011). In analyses testing sleep → PA/SED associations, sleep duration represented the within-person independent variable and SED/LPA/MVPA the within-person dependent variables. In analyses testing PA/SED → sleep associations, SED/LPA/MVPA represented the within-person independent variables and sleep duration the within-person dependent variable. To facilitate interpretation of the bi-directional associations, all sleep duration and PA/SED variables were standardized. Therefore, the coefficients in the regression models represent the change per each SD unit, which allowed us to compare the effect sizes of the associations. Age, sex, highest parental education, BMI z-score, unhealthy dietary pattern score, daily accelerometer awake wear time and type of day were included as covariates in all models. Finally, differences across sex and study sites in the associations were examined using interaction terms; site-by-sex, site-by-sleep or site-by-PA/SED interactions were retained when $p < 0.05$. The level of statistical significance was set at $p < 0.05$.

3. Results

Descriptive characteristics of the sample are shown in Table 1. The average (SD) age was 10.4 (0.6) years and approximately 45.0% of the sample were boys. The average awake wear time was 14.9 (1.5) hours per day. The average sleep duration was 8.8 (1.5) hours per night, below the National Sleep Foundation's recommendation (Hirshkowitz et al., 2015) of 9–11 h of sleep per day for school-aged children (58.9% of kids were below this threshold, data not shown). The average sleep efficiency was 96.2% (1.9%), while wake time after sleep onset of the ISCOLE sample has been reported elsewhere with an average of 0.6 (0.4) minute per night (Tudor-Locke et al., 2015). The average MVPA was 60.0 (33.9) minutes per day; however, 55.9% of the children were below the World Health Organization's recommendation (World Health Organization, 2017) of at least 60 min of MVPA daily (data not shown).

For sleep predicting PA/SED, sleep duration the preceding night was significantly associated with SED, LPA and MVPA the following day (Table 2). Specifically, for each one SD unit increase in sleep duration the preceding night, SED the following day decreased by 0.04 SD units, while LPA and MVPA increased by 0.04 and 0.02 units, respectively. That is, for each 1-hour increase in sleep duration, SED decreased by 3 min, LPA increased by 2 min and MVPA increased by < 1 min (data not shown).

For PA/SED predicting sleep, SED and MVPA were significantly associated with sleep duration the subsequent night, while LPA did not predict sleep duration (Table 3). Specifically, for each one SD unit increase in SED and MVPA, sleep duration decreased by 0.02 SD units and increased by 0.04 units, respectively. That is, for each 1-hour increase in SED and MVPA, sleep duration decreased by 1 min and increased by 6 min, respectively (data not shown).

Results also revealed that bi-directional associations between sleep duration and PA/SED were different across sexes and study sites (Tables 2 and 3). Child's sex moderated the sleep → PA/SED associations (with stronger effects among girls) and the PA/SED → sleep relationships (with stronger LPA → sleep effects in boys and stronger MVPA → sleep effects in girls). Regarding the study site interactions, the sleep → SED/LPA associations were more consistent and stronger in high-income countries (except for UK) when compared with low-and middle-income countries (except for Kenya), while the sleep → MVPA relationship was only observed in Portugal and India. For the other direction, the SED/MVPA → sleep association was more consistent and stronger in low-and middle-income countries (except for Kenya and South Africa), while Canada was the only high-income country that observed a significant and positive PA/SED → sleep association.

4. Discussion

To our knowledge, this study was the first to examine the associations between sleep duration and PA/SED in children from 12 countries in five major geographic regions of the world (Europe, Africa, the Americas, South-East Asia and the Western Pacific). We also used objective tools to measure sleep duration, PA and SED, and the statistical

analyses allowed us to examine the temporal and bi-directional associations between sleep duration and PA/SED. Collectively, our results showed that sleep duration predicted PA/SED the following day, and PA/SED in turn also predicted sleep duration, but not consistent between sexes or countries. Interventions aimed at increasing sleep duration may also help to influence PA and SED in children, and vice versa. Considering the statistically significant small effect sizes, the clinical and practical implications of our findings is however questionable.

On one hand, the sleep duration → PA/SED relationship observed is in line with our hypothesis, such that longer sleep duration the preceding night was associated with lower SED and higher LPA and MVPA the following day. Our results somewhat support the idea that in-adequate sleep could lead to physical inactivity the following day through feelings of sleepiness and tiredness (Carskadon et al., 1981). Our results are also consistent with a randomized crossover trial (Hart et al., 2016), wherein children were slightly more active (4% increase in average activity counts) in the days following a 1.5 hour increase in time in bed versus the days following a 1.5 hour decrease in time in bed. However, in our study, the average activity counts only increased by 0.5% following a 3-hour increase in sleep duration (data not shown). The difference in effect sizes may be due to the difference between experimental and observational studies. That is, when compared to the 3-hour difference in sleep duration in Hart et al.'s experimental trial (Hart et al., 2016), only 13% of our sample had nightly variations of sleep duration ≥3 h (data not shown).

On the other hand, we observed positive SED/MVPA → sleep duration associations, which is also in line with our hypothesis. Our results somewhat contradict Dworak et al.'s experimental study, where the authors observed no association between moderate- and vigorous-intensity physical exercise and sleep duration among children (Dworak et al., 2008). Given the small effect sizes, our findings could result from a sufficient power to detect a statistically significant association in large sample of children. Nevertheless, our findings are in line with the results from the extensive laboratory studies conducted among adult populations. As summarized in a recent meta-analysis, the adult literature indicates that PA has small but beneficial acute effects on sleep duration (Kredlow et al., 2015). Also, our SED → sleep duration result is somewhat consistent with an observational study conducted by Nixon et al., wherein more SED predicted shorter sleep duration (< 9 h) in a sample of 7-year-old children (Nixon et al., 2008).

However, our findings of the favorable sleep duration → PA/SED and SED/MVPA → sleep duration relationships contradict most of the other observational studies that used a similar study design and objective measurements in pediatric populations (Pesonen et al., 2011; Ekstedt et al., 2013; Vincent et al., 2017; Nixon et al., 2009). For instance, while Ekstedt et al. (2013) and Vincent et al. (2017) found non-significant associations, Sorić et al. (2015) and Pesonen et al. (2011) observed negative findings. Reasons for this inconsistency remain unclear but can include unmeasured modifying factors, such as externally set schedules that pre-empt bodily-driven need for sleep/PA/SED. With regard to the null association, daytime PA may be more dependent on motivation and scheduled time for activity than on sleep per se (Ekstedt et al., 2013). Regarding the negative association, children who have shorter sleep durations might also be more physically active during the day due to their inherent activity

level, which manifests itself during both night and day, in both directions (Pesonen et al., 2011). Difference in these results may also be caused by discrepancies between average sleep duration and PA levels between study samples (Vincent et al., 2017), which was addressed in the present study. Another possible explanation would be the fact that there are only a certain number of hours in a day, and sleeping longer produces an overall time deficit, thereby reducing time in other activities, and vice versa (Olds et al., 2012).

For interaction terms, in line with the literature, we found sex differences with stronger associations observed mostly among girls (Sorić et al., 2015; Pesonen et al., 2011). Although the mechanism is unclear and has never been discussed in previous studies, one possible explanation we postulate is the floor and ceiling effects in sleep research (Youngstedt, 2003). That is, for instance, MVPA might benefit more for girls because they have shorter sleep duration (8.0 h) than boys (9.4 h), and vice versa. Consistent with our hypothesis, we also observed different associations across study sites. More consistent and stronger sleep duration → PA/SED associations were observed in high-income countries, and SED/MVPA → sleep duration relationships in low- and middle-income countries. This discrepancy highlights the need for a better understanding of the relationships before generalizing findings, and emphasizes that interventions that have shown success in one country may not necessarily be replicated in another setting.

Findings from this study have several important public health implications. First, we observed that over 50% of the children did not meet the sleep or PA recommendations. Given the health importance of these behaviours among children, future initiatives targeting the improvement of sleep and PA, and decreasing of SED, are needed. Second, since we observed positive sleep duration → PA/SED and SED/MVPA → sleep duration relationships, it is likely that a positive side effect of interventions aimed at increasing sleep duration would have a concurrent positive effect on PA and SED levels, and vice versa. Again, these effects might resemble null findings in public health practice, since there is only minute-change of the respondent behaviour after hour-change of the predictors. Third, given the observed interaction terms, our study results imply that pooling data from different sexes and socio-cultural contexts may not be the optimal strategy while investigating the associations of interest.

An important strength of this study is the large multinational sample of children from low- to high-income countries across several regions of the world. Highly standardized measurement protocol, the use of objective measurements whenever possible, and a rigorous quality control program also ensure high-quality data across all sites (Katzmarzyk et al., 2013). However, our results need to be interpreted in light of the following limitations. First, waist-worn accelerometers have been shown to overestimate sleep duration compared with wrist-worn devices (Hjorth et al., 2012). This non-differential misclassification might have diluted the associations of interest. Accelerometers may also be limited in their ability to properly distinguish between sleep and waking states, as they are based on movement detection. However, the use of one single device is less cumbersome for children and still provides valid proxy measurements of both sleep and PA/SED (Hjorth et al., 2012; Tudor-Locke et al., 2015). Second, the present study focused on sleep duration only and other sleep characteristics such as sleep quality would be relevant to investigate in future studies.

Given the ceiling effect (Youngstedt, 2003) observed for sleep efficiency in ISCOLE, it was not possible to use this variable for analysis. Future studies should examine this aspect in samples of individuals having larger inter-individual variability in sleep quality/efficiency. Third, ISCOLE was not designed to provide nationally representative data and therefore the degree to which the results are generalizable to the studied countries are not known. Fourth, residual confounding by unmeasured variables is always a possibility in observational studies. Moreover, the present study only considered the acute effect between sleep duration and PA/SED within 24 h. It is possible that these behaviours could impact each other within a longer exposure time window. Finally, although we investigated the relationships temporally, temporality on its own does not equate to causality.

5. Conclusions

The current study provides evidence that nocturnal sleep duration is temporally and bi-directionally associated with daytime PA/SED in children from around the world, generally in a positive (health promoting) fashion. It is important to acknowledge, however, that the magnitude of the association is questionable for clinical and practical relevance. In addition to sex differences, discrepancies in the reported relationships between study sites suggest that the geographic area in the world and socio-cultural variability are important factors to consider in future research and public health interventions. More work is needed to confirm the limited research results in low- and middle-income countries, and to further elucidate the mixed findings observed. Further studies are also needed to better investigate the relationships between various sleep characteristics (including sleep quality) and PA/SED.

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Table 1

Descriptive characteristics of participants ($n = 5779$).

	Participants (*n*, % boys)	Age (years)	Wake wear time (h/day)	Sleep duration (h/night)	Sleep efficiency (%)	SED (h/day)	LPA (h/day)	MVPA (min/day)
All sites	5779 (45.0)	10.4 (0.6)	14.9 (1.5)	8.8 (1.5)	96.2 (1.9)	8.6 (1.7)	5.3 (1.2)	60.0 (33.9)
Stratified by sex								
Boys	2601 (100.0)	10.5 (0.6)	14.9 (1.5)	9.4 (1.5)	96.0 (1.9)	8.4 (1.7)	5.4 (1.2)	69.3 (37.1)
Girls	3178 (0.0)	10.4 (0.6)	14.8 (1.5)	8.0 (1.5)	96.3 (1.8)	8.7 (1.6)	5.2 (1.2)	52.3 (28.8)
Stratified by country (site)								
High-income countries								
Australia (Adelaide)	433 (46.7)	10.8 (0.5)	14.3 (1.4)	9.4 (1.3)	95.4 (1.9)	8.0 (1.5)	5.2 (1.1)	66.3 (34.8)
Canada (Ottawa)	496 (40.9)	10.5 (0.4)	14.6 (1.4)	9.1 (1.4)	96.2 (1.8)	8.6 (1.5)	5.1 (1.1)	56.0 (28.4)
Finland (Helsinki, Espoo and Vantaa)	433 (45.3)	10.5 (0.4)	14.9 (1.5)	8.5 (1.6)	96.9 (1.4)	8.8 (1.7)	4.9 (1.0)	69.4 (37.8)
Portugal (Porto)	563 (41.6)	10.5 (0.3)	15.2 (1.4)	8.3 (1.5)	97.2 (1.3)	9.3 (1.5)	5.0 (1.1)	52.3 (30.4)
UK (Bath and North East Somerset)	374 (42.8)	10.9 (0.5)	14.2 (1.4)	9.4 (1.3)	95.7 (1.9)	8.3 (1.5)	4.8 (1.0)	65.2 (33.5)
USA (Baton Rouge)	421 (40.4)	10.0 (0.6)	14.8 (1.6)	8.9 (1.6)	96.1 (1.8)	8.7 (1.7)	5.3 (1.1)	51.6 (28.6)
Low- and middle-income countries								
Brazil (Sao Paulo)	435 (48.5)	10.5 (0.5)	15.1 (1.6)	8.6 (1.7)	95.6 (1.9)	8.4 (1.7)	5.7 (1.2)	59.4 (36.5)
China (Tianjin)	460 (51.7)	9.9 (0.5)	15.1 (1.3)	8.8 (1.2)	96.5 (1.9)	9.4 (1.6)	4.9 (1.2)	45.2 (23.1)
Colombia (Bogota)	820 (49.2)	10.5 (0.6)	15.0 (1.6)	8.8 (1.7)	95.9 (1.9)	8.3 (1.7)	5.6 (1.2)	68.2 (35.8)
India (Bangalore)	526 (45.1)	10.5 (0.5)	15.1 (1.4)	8.6 (1.4)	96.6 (1.7)	8.6 (1.5)	5.7 (1.2)	48.8 (26.6)
Kenya (Nairobi)	453 (45.5)	10.3 (0.7)	15.2 (1.5)	8.6 (1.4)	95.9 (2.0)	8.3 (1.7)	5.7 (1.1)	73.6 (40.7)
South Africa (Cape Town)	365 (38.6)	10.3 (0.7)	14.6 (1.50	9.2 (1.4)	96.1 (2.0)	8.1 (1.7)	5.4 (1.2)	63.1 (33.8)

Abbreviations: SED, total sedentary time; LPA, light-intensity physical activity; MVPA, moderate- to vigorous-intensity physical activity. Data are shown as mean (standard deviation) unless otherwise specified.

Table 2

Associations between nighttime sleep duration and physical activity/sedentary time the following day (n = 5779 participants and 31,019 pairings).

	SED			LPA			MVPA		
	β	**95% CI**	***p*-Value**	**β**	**95% CI**	***p*-Value**	**β**	**95% CI**	***p*-Value**
All sites[a]	− 0.039	(− 0.047, − 0.030)	< 0.001	0.044	(0.035, 0.054)	< 0.001	0.020	(0.010, 0.030)	< 0.001
Stratified by sex[b]									
Boys	− 0.025	(− 0.039, − 0.012)	< 0.001	0.028	(0.014, 0.043)	< 0.001	0.015	(− 0.003, 0.034)	0.096
Girls	− 0.046	(− 0.058, − 0.035)	< 0.001	0.053	(0.041, 0.066)	< 0.001	0.025	(0.013, 0.037)	< 0.001
Stratified by country (site)[c]									
High-income countries									
Australia (Adelaide)	− 0.049	(− 0.082, − 0.016)	0.004	0.056	(0.022, 0.091)	0.002	0.030	(− 0.013, 0.073)	0.172
Canada (Ottawa)	− 0.052	(− 0.082, − 0.023)	< 0.001	0.060	(0.028, 0.093)	< 0.001	0.029	(− 0.006, 0.063)	0.105
Finland (Helsinki, Espoo and Vantaa)	− 0.037	(− 0.070, − 0.005)	0.024	0.047	(0.015, 0.080)	0.005	0.009	(− 0.037, 0.055)	0.690
Portugal (Porto)	− 0.085	(− 0.113, − 0.057)	< 0.001	0.101	(0.071, 0.131)	< 0.001	0.038	(0.004, 0.071)	0.028
UK (Bath and North East Somerset)	0.010	(− 0.028, 0.047)	0.612	− 0.003	(− 0.042, 0.036)	0.861	− 0.020	(− 0.072, 0.031)	0.435
USA (Baton Rouge)	− 0.035	(− 0.065, − 0.004)	0.026	0.036	(0.002, 0.070)	0.037	0.027	(− 0.007, 0.060)	0.116
Low- and middle-income countries									
Brazil (Sao Paulo)	− 0.013	(− 0.043, 0.016)	0.374	0.025	(− 0.008, 0.058)	0.140	− 0.013	(− 0.049, 0.023)	0.480
China (Tianjin)	0.008	(− 0.028, 0.044)	0.648	0.001	(− 0.040, 0.042)	0.967	− 0.025	(− 0.058, 0.009)	0.152
Colombia (Bogota)	− 0.007	(− 0.030, 0.016)	0.564	0.022	(− 0.003, 0.046)	0.083	− 0.024	(− 0.054, 0.005)	0.106
India (Bangalore)	− 0.027	(− 0.058, 0.003)	0.080	0.020	(− 0.016, 0.056)	0.274	0.037	(0.007, 0.066)	0.014
Kenya (Nairobi)	− 0.065	(− 0.102, − 0.029)	< 0.001	0.074	(0.034, 0.114)	< 0.001	0.037	(− 0.010, 0.083)	0.121
South Africa (Cape Town)	− 0.024	(− 0.056, 0.008)	0.149	0.024	(− 0.012, 0.060)	0.185	0.020	(− 0.020, 0.060)	0.331

Abbreviations: CI, confidence interval; SED, total sedentary time; LPA, light-intensity physical activity; MVPA, moderate- to vigorous-intensity physical activity.

[a]Adjusted for age, sex, body mass index z-score, parental education, unhealthy dietary pattern score, daily accelerometer awake wear time, type of day, and study site.

[b]Adjusted for age, body mass index z-score, parental education, unhealthy dietary pattern score, daily accelerometer awake wear time, type of day and study site.

[c]Adjusted for age, sex, body mass index z-score, parental education, unhealthy dietary pattern score, daily accelerometer awake wear time and type of day.

Table 3

Associations between daytime physical activity/sedentary time and sleep duration that night (n = 5779 participants and 31,408 pairings).

	SED			LPA			MVPA		
	β	**95% CI**	***p*-Value**	**β**	**95% CI**	***p*-Value**	**β**	**95% CI**	***p*-Value**
All sites[a]	− 0.023	(− 0.036, − 0.009)	0.001	0.005	(− 0.007, 0.017)	0.414	0.040	(0.028, 0.052)	< 0.001
Stratified by sex[b]									
Boys	− 0.025	(− 0.045, − 0.006)	0.009	0.009	(− 0.009, 0.026)	0.327	0.033	(0.018, 0.048)	< 0.001
Girls	− 0.021	(− 0.039, − 0.002)	0.033	0.001	(− 0.015, 0.018)	0.863	0.053	(0.035, 0.071)	< 0.001
Stratified by country (site)[c]									
High-income countries									
Australia (Adelaide)	0.018	(− 0.024, 0.060)	0.401	− 0.033	(− 0.071, 0.006)	0.094	0.019	(− 0.015, 0.053)	0.274
Canada (Ottawa)	− 0.063	(− 0.108, − 0.018)	0.006	0.050	(0.011, 0.089)	0.013	0.041	(0.000, 0.081)	0.049
Finland (Helsinki, Espoo and Vantaa)	0.010	(− 0.049, 0.068)	0.748	− 0.009	(− 0.064, 0.047)	0.758	− 0.004	(− 0.047, 0.038)	0.834
Portugal (Porto)	0.004	(− 0.042, 0.051)	0.850	− 0.022	(− 0.061, 0.018)	0.279	0.041	(− 0.001, 0.083)	0.057
UK (Bath and North East Somerset)	0.048	(− 0.001, 0.095)	0.048	− 0.046	(− 0.089, − 0.004)	0.034	− 0.014	(− 0.051, 0.023)	0.448
USA (Baton Rouge)	− 0.024	(− 0.081, 0.032)	0.392	0.008	(− 0.040, 0.056)	0.739	0.044	(− 0.009, 0.096)	0.102
Low- and middle-income countries									
Brazil (Sao Paulo)	− 0.080	(− 0.131, − 0.028)	0.003	0.053	(0.007, 0.099)	0.023	0.069	(0.025, 0.114)	0.002
China (Tianjin)	− 0.028	(− 0.063, 0.007)	0.112	0.007	(− 0.022, 0.036)	0.652	0.086	(0.046, 0.127)	< 0.001
Colombia (Bogota)	− 0.058	(− 0.098, − 0.017)	0.006	0.031	(− 0.006, 0.068)	0.104	0.061	(0.028, 0.094)	< 0.001
India (Bangalore)	− 0.032	(− 0.074, 0.011)	0.144	0.007	(− 0.029, 0.042)	0.715	0.086	(0.040, 0.131)	< 0.001
Kenya (Nairobi)	0.005	(− 0.044, 0.055)	0.829	− 0.023	(− 0.067, 0.020)	0.286	0.029	(− 0.009, 0.067)	0.134
South Africa (Cape Town)	0.020	(− 0.028, 0.067)	0.415	− 0.039	(− 0.081, 0.003)	0.068	0.030	(− 0.009, 0.070)	0.134

Abbreviations: CI, confidence interval; SED, total sedentary time; LPA, light-intensity physical activity; MVPA, moderate- to vigorous-intensity physical activity.

[a]Adjusted for age, sex, body mass index z-score, parental education, unhealthy dietary pattern score, daily accelerometer awake wear time, type of day, and study site.

[b]Adjusted for age, body mass index z-score, parental education, unhealthy dietary pattern score, daily accelerometer awake wear time, type of day and study site.

[c]Adjusted for age, sex, body mass index z-score, parental education, unhealthy dietary pattern score, daily accelerometer awake wear time and type of day.