Bidirectional Day-to-Day Associations of Reported Sleep Duration With Accelerometer Measured Physical Activity and Sedentary Time Among Dutch Adolescents

Bidirectional Day-to-Day Associations of Reported Sleep Duration With Accelerometer Measured Physical Activity and Sedentary Time Among Dutch Adolescents: An Observational Study

Article *in* Journal for the Measurement of Physical Behaviour · December 2020

DOI: 10.1123/jmpb.2020-0010

Nathalie Berninger
Maastricht University

Gregory Knell
University of Texas Health Science Center at Houston

Kelley Pettee Gabriel
University of Alabama at Birmingham

Guy Plasqui
Maastricht University

***Journal for the Measurement of Physical Behaviour*, (Ahead of Print)**
https://doi.org/10.1123/jmpb.2020-0010

Human Kinetics
ORIGINAL RESEARCH

Bidirectional Day-to-Day Associations of Reported Sleep Duration With Accelerometer Measured Physical Activity and Sedentary Time Among Dutch Adolescents: An Observational Study

Nathalie Berninger
Maastricht University

Gregory Knell
The University of Texas Health Science Center (UTHealth) at Houston, and Children's Health Andrews Institute for Orthopedics and Sports Medicine

Kelley Pettee Gabriel
The University of Alabama at Birmingham

Guy Plasqui
Maastricht University

Rik Crutzen and Gill Ten Hoor
Maastricht University

Objectives: To examine the bidirectional association of sleep duration with proportions of time spent in physical behaviors among Dutch adolescents. **Methods**: Adolescents ($n = 294$, 11–15 years) completed sleep diaries and wore an accelerometer (ActiGraph) over 1 week. With linear mixed-effects models, the authors estimated the association of sleep categories (short, optimal, and long) with the following day's proportion in physical behaviors. With generalized linear mixed models with binomial distribution, the authors estimated the association of physical behavior proportions on sleep categories. Physical behavior proportions were operationalized using percentages of wearing time and by applying a compositional approach. All analyses were stratified by gender accounting for differing developmental stages. **Results**: For males (number of observed days: 345, $n = 83$), short as compared with optimal sleep was associated with the following day's proportion spent in sedentary (−2.57%, $p = .03$, 95% confidence interval [CI] [−4.95, −0.19]) and light-intensity activities (1.96%, $p = .02$, 95% CI [0.27, 3.65]), which was not significant in the compositional approach models. Among females (number of observed days: 427, $n = 104$), long sleep was associated with the proportions spent in moderate- to vigorous-intensity physical activity (1.69%, $p < .001$, 95% CI [0.75, 2.64]) and in sedentary behavior (−3.02%, $p < .01$, 95% CI [−5.09, −0.96]), which was replicated by the compositional approach models. None of the associations between daytime activity and sleep were significant (number of obs.: 844, $n = 204$). **Conclusions**: Results indicate partial associations between sleep and the following day's physical behaviors, and no associations between physical behaviors and the following night's sleep.

Keywords: childhood obesity, pediatric health, sedentary behavior

Suboptimal sleep during adolescence is associated with numerous deleterious outcomes, such as poor physical and mental health, behavioral problems, unintentional injuries, and poor academic performance (Adolescent Sleep Working Group, 2014). Short sleep duration during adolescence is associated with obesity (Miller, Kruisbrink, Wallace, Ji, & Cappuccio, 2018) and increases the risk of obesity in adulthood (Landhuis, Poulton, Welch, & Hancox, 2008). The National Sleep Foundation, with endorsement from the European Sleep Research Society, recommends 8–10 hr of sleep per 24-hr cycle (Hirshkowitz et al., 2015) as the optimal sleep duration for adolescents aged 14–17 years, and 9–11 hr of sleep for children aged 6–13 years. However, recent self-report data indicate the mean sleep duration among European teens aged 15–18 years is 7.97 (±1.10) and 7.84 (±1.20) hr for females and males, respectively (Ohayon, Roberts, Zulley, Smirne, & Priest, 2000). Moreover, in a Dutch cohort, approximately 20% of adolescents self-reported sleep disturbances (Verkooijen et al., 2018).

It has been suggested that physical activity, aside from its numerous health benefits, may promote longer and better sleep (Kredlow, Capozzoli, Hearon, Calkins, & Otto, 2015). In addition, sufficient nighttime sleep may promote physical activity the

Berninger and Knell are joint first authors. Berninger and Ten Hoor are with the Department of Work and Social Psychology, Maastricht University, Maastricht, The Netherlands. Knell is with the Department of Epidemiology, Human Genetics, and Environmental Sciences, School of Public Health, The University of Texas Health Science Center (UTHealth) at Houston, Houston, TX, USA; the Center for Pediatric Population Health, School of Public Health, The University of Texas Health Science Center (UTHealth) at Houston, Dallas, TX, USA; and Children's Health Andrews Institute for Orthopedics and Sports Medicine, Children's Health System, Plano, TX, USA. Gabriel is with the Department of Epidemiology, The University of Alabama at Birmingham, Birmingham, AL, USA. Plasqui is with the Department of Human Biology and Movement Sciences, Nutrition and Translational Research in Metabolism, Maastricht University, Maastricht, The Netherlands. Crutzen is with the Department of Health Promotion, CAPHRI, Maastricht University, Maastricht, The Netherlands. Berninger (Nathalie.Berninger@maastrichtuniversity.nl) is corresponding author.

following day due to increased energy (decreased daytime sleepiness) (Chen, Beydoun, & Wang, 2008). The association between sleep and physical activity has been found to be bidirectional in adult populations (Pettee Gabriel et al., 2017), such that optimal sleep duration results in more physical activity/less sedentary time in the subsequent day, and more physical activity during the daytime results in optimal sleep duration that night. However, results so far have been inconsistent (Baron, Reid, & Zee, 2013; Kishida & Elavsky, 2016; Lambiase, Gabriel, Kuller, & Matthews, 2013; Mitchell et al., 2016).

In adolescent populations, analyses on the bidirectional associations between sleep and physical activity have also been mixed owing primarily to differing study designs and analytic methods, and varying physical activity and sleep measures (Krietsch, Armstrong, McCrae, & Janicke, 2016; Master et al., 2019; Ortega et al., 2010; Soric et al., 2015). In addition, these previous adolescent studies have primarily focused only on moderate- to vigorous-intensity physical activity (MVPA) rather than on the range of activity intensities. This ignores the contribution of all behaviors occurring within a finite 24-hr period (sleep, sedentary time, and total physical activity) on health benefit in adolescent populations (Kuzik et al., 2017; Renninger et al., 2020). Furthermore, it is important to understand the codependence of these behaviors (Pronk et al., 2004). Specifically, an alteration to the time spent sleeping will require the displacement of the time spent in some other waking time, energy conserving, or expending behavior, such as sedentary or physical activity behaviors (Chaput, Saunders, & Carson, 2017; Dulloo, Miles-Chan, & Montani, 2017; Tremblay et al., 2017). However, no existing studies that have examined the bidirectional relations of sleep and waking time physical behaviors (i.e., sedentary behavior and physical activity) in adolescent populations have accounted for the compositional nature of the data.

Therefore, the purpose of this study is to examine the bidirectional associations between short and long sleep and the accelerometer-derived proportion of time spent sedentary and physically active (as percentages of total wear time and in relation to the other physical behaviors using a compositional data analysis approach, CoDA) among Dutch adolescents. Given the strong associations between sleep duration and the risk of obesity among adolescents, and the differing developmental stages of males and females during adolescence (Patton & Viner, 2007), we assessed the potential for confounding by age and weight status and we stratified the analyses by gender. In addition, we used categories of sleep duration instead of sleeping time to account for different sleeping recommendations for the two age groups included in this study.

Methods

All materials and supporting documents are available at the Open Science Framework (OSF) repository at https://osf.io/5hpdb/?view_only=0de4df6f0af3462c8b31bba26a151703.

This sample was drawn from participants in the Focus on Strength (FOS) randomized trial (2014–2016). FOS examined the effects of muscle strengthening exercises on body composition among Dutch adolescents aged 11–15 years (Ten Hoor et al., 2016). Briefly, the FOS study provided strength training exercises to overweight adolescents during school-based physical education, along with motivational sessions (group and individual), to determine the effect on overall physical activity levels over a 1-year period. As part of the study protocol, participants were asked to complete daily sleep diaries while wearing an ActiGraph GT3x (ActiGraph LLC, Pensacola, FL) accelerometer for 1 week at baseline (T0) and after 12 months at follow-up (T1) (Ten Hoor et al., 2016; 2018). In the current study, due to the reduced availability of participants having data at both timeslots, only the baseline data were considered in the analyses. Yet, we conducted all analyses of the current study also with the follow-up data as sensitivity analyses (results retrievable from the OSF directory).

Nine Dutch Schools were recruited via school management. Of the 808 students who were eligible to participate, 34 students declined. Eventually, 774 adolescents (11–15 years old) participated in the study. Following consent from the schools, parents and their children were informed about the intervention and related outcome measurements and told they could refuse participation at any time. The study methods and consent procedure were approved by the ethical review committee of the Faculty of Psychology and Neuroscience, Maastricht University, The Netherlands (ERCPN-05-09-2012A1).

Of the 774 FOS participants, 294 provided sleep diaries and valid accelerometer data the day before and/or after, for at least 4 days.

Data Collection

The student administration of the schools provided the students' gender and date of birth. Anthropometrics were measured using standard procedures (Centers for Disease Control and Prevention, National Center for Health Statistics, and U.S. Department of Health and Human Services, n.d.). Height (SECA 213 stadiometer; Seca GmbH, Hamburg, Germany) and weight (SECA 877 scale; Seca GmbH) were measured without shoes or heavy clothes to the nearest 1 mm and 0.1 kg, respectively. Body mass index was calculated as weight/height squared (in kilogram per meter square) and z scores from age and sex specific reference values (Fredriks, van Buuren, Wit, & Verloove-Vanhorick, 2000). Body composition was assessed by deuterium dilution (Westerterp, Wouters, & van Marken Lichtenbelt, 1995) following the procedure proposed by Schoeller and colleagues (Schoeller et al., 1986). We calculated fat-free mass with age-specific hydration fractions (Timothy, 1989). Compared with underwater weighing, deuterium dilution is a valid method to assess fat mass percentage (van der Kooy et al., 1992; Westerterp et al., 1991).

To assess sedentary behavior and physical activity, students were asked to wear an ActiGraph GT3x for five consecutive days, except during water-based activities such as swimming or taking a shower. As the best position to wear an accelerometer to assess daily physical behaviors is as close to the center of mass as possible, the participants were asked to wear the Actigraph on their lower back (Plasqui, 2017; Plasqui, Bonomi, & Westerterp, 2013; Yngve, Nilsson, Sjostrom, & Ekelund, 2003). Students were told to wear the device for at least one weekend day and, when wearing it during the week, to wear it on schooldays. The accelerometer was attached by an adjustable elastic belt. The ActiLife software (Release version 6.13.3; ActiGraph Corp.) was used to generate activity counts (counts per minute) and, consequently, intensity level categories (sedentary behavior, light, and MVPA). Accelerations were read at a rate of 30 Hz. We reintegrated the data with an output data rate of 15-s epochs because the determination of the counts per minute cutoffs for determining physical behavior levels were done with this data output rate (Banda et al., 2016; Evenson, Catellier, Gill, Ondrak, & McMurray, 2008).

The ActiLife software was used to scan the raw data for wear and nonwear times using the algorithm by Choi and colleagues who considered the vertical axis counts and a minimum nonwear time window of 90 min (Choi, Ward, Schnelle, & Buchowski, 2012). We included data from participants who had worn the accelerometer at least 7 hr per day for a minimum of 4 days. Although higher wear-time cutoff values yield higher reliability of accelerometer data, they result in smaller analyzable sample sizes (Toftager et al., 2013). Therefore, we conducted a separate analysis to determine the highest possible wear-time cutoffs while keeping a maximum of analyzable data points (number of days). Thereby, we created data sets with all possible cutoff values and conducted Wilcoxon signed-rank tests to test for significant differences of participant characteristics (i.e., age, gender, body mass index z score, sleep duration, activity as percentage per wearing day) of those new data sets compared with characteristics of the minimum cutoff of 0 days and 0 hr (see OSF repository). This resulted in establishing 7 hr per day for a minimum of 4-days cutoff as valid, with an estimated reliability of approximately 0.70 (Spearman–Brown coefficient) in adolescents of this age group (Trost, Pate, Freedson, Sallis, & Taylor, 2000).

Daily proportions spent in different intensity levels were calculated using the cutoff points proposed by Evenson and colleagues (Evenson et al., 2008; Trost, Loprinzi, Moore, & Pfeiffer, 2011). Descriptive analyses were performed for both daily time in different intensity levels and proportion of wear time (in percentage). To account for the effect of the time spent wearing the device on physical activity occurring during waking hours, we analyzed the data as proportions of the day spent in each behavior in the multivariable models. This was done by using both proportions in relation to the daily wear time and by using proportions in relation to the other two behaviors, which was done by using a CoDA approach (Chastin, Palarea-Albaladejo, Dontje, & Skelton, 2015).

Sleep actigraphy data were not collected in this sample due to perceived discomfort from the waist-worn ActiGraph during sleep. However, on days that the accelerometer was worn, participants completed sleep and accelerometer wear-time diaries indicating times of the day when they woke up and went to bed, and any other time they put on and took off the accelerometer. The reported clock times in and out of bed were used to estimate sleep duration (minutes per night) (Lambiase et al., 2013; Pettee Gabriel et al., 2017). Reported time in bed from sleep diaries has been shown to be comparable to objective sleep duration measurements (Lockley, Skene, & Arendt, 1999; McCrae et al., 2005; Monk et al., 1994). Categories of sleep duration were used for the mixed-effects models because of differing recommendations per age group (8–10 hr for 14–17 years; 9–11 hr for 9–13.9 years) and because of the fact that sleep diaries are based on self-reports, which cannot measure time-in-bed to minutes precision (Hirshkowitz et al., 2015). Short and long sleep were defined as being shorter and longer than the age-specific optimal recommended sleep duration.

Statistical Analyses

To analyze the bidirectional association of sleep categories and physical activity, two long-format data sets were created with each row representing one day per subject. In the first data set, nighttime sleep duration was combined with the physical behavior that proceeded it in time to examine the association of sleep (i.e., predictor) and the following day's physical behaviors (i.e., outcome). In the second data set, physical behaviors during waking hours were combined with the proceeding night's sleep duration to examine the association of physical activity (i.e., predictor) and the succeeding night's sleep (i.e., outcome).

We performed descriptive univariate analyses and assessed data normality using histograms and QQ plots. Nonnormally distributed variables were reported as medians and interquartile ranges (IQR), normally distributed variables were reported as means and *SD*. Sedentary behavior, light physical activity, and MVPA were presented with compositional geometric means and log-ratio variance, which are "the variances of the logarithms of all pair-wise ratios between parts" (Chastin et al., 2015). We reported categorical variables as absolute numbers and percentages. To assess presumed differences by days of the week in (a) physical activity levels, (b) times in and out of bed, and (c) sleep durations, we performed descriptive analyses stratified by day of the week (e.g., Monday).

To examine the association between sleep duration and physical behavior levels the next day, we used linear mixed-effects models with repeated measures and random intercepts on the individual level, as, for most of the models, random intercept models showed better fit compared with fixed intercept models when applying the Akaike information criterion (Akaike, 1974), and we were interested in the day-to-day associations within participants. As the measurements were autocorrelated, we used an autoregressive covariance structure (see other linear models and overviews of autocorrelations in the OSF directory). To examine the association between daytime physical behavior and sleep categories (e.g., short sleep, optimal sleep, and long sleep), we used generalized linear mixed-effects models with repeated measures, random intercepts on the individual level and a binomial distribution (e.g., optimal sleep vs. long sleep) to estimate the sleep categories, with the optimal sleep duration as the reference category.

Instead of using overall activity times, we only analyzed proportions of the day (waking hours) spent in sedentary behavior, light activity, and MVPA because shorter days resulted in less available time for these physical behaviors. In addition, physical behaviors were operationalized using the CoDA approach to account for interdependence and multicollinearity of all three activity levels (i.e., less sedentary behavior proportion results in more light activity) (Chastin et al., 2015). First, the durations of the three activity levels were transformed into proportions of the time that the accelerometer was worn on a specific day. Second, the data were transformed by isometric log-ratio transformations (e.g., sedentary behavior proportion) and adjusted for the proportion of the day spent in the other two behaviors (e.g., light physical activity and MVPA), for example, $z\text{SB} = \sqrt{\frac{2}{3}}\ \ln \frac{\text{SB}}{\sqrt{\text{LIPA} \times \text{MVPA}}}$, where SB = sedentary behavior; LIPA = light intensity physical activity; (Chastin et al., 2015). Each of the three physical behaviors (e.g., sedentary behavior [SB]) was once on the first position, with a second variable (e.g., $z\text{LIPA} = \sqrt{\frac{1}{2}}\ \ln \frac{\text{LIPA}}{\text{MVPA}}$) on the second position, providing information on the entire physical behavior composition. The variable that was on the first position in the composition was used to interpret its coefficient (physical behavior composition as predictor), and as outcome variable (physical behavior composition as outcome) (Rasmussen et al., 2018). It provided information on the relative importance of this first part in relation to the other two parts. We did not incorporate the binary outcome of meeting the aerobic physical activity recommendations as the MVPA guidelines (at least 60 min per day) were only met in 33 of the 1620 recorded days across participants.

All tests for statistical significance were two-sided, with an alpha of .05. Data analyses were performed using R (version 3.4.1; RStudio, PBC, Boston, MA). Sensitivity analyses of the data sets without outliers (detected with the Mahalanobis distance; Mahalanobis, 1936) and from the follow-up assessment at 1-year postbaseline (T1) were conducted, and the results can be found in the OSF directory. Covariates were selected using backward elimination where a predictor was retained if the *p* value was <.20. All analyses were controlled for age (locked in the models). For sleep categories predicting physical activity, we ran the analyses separately by gender.

Results

Of the 774 participants, 598 (77.3%) wore the accelerometer and 427 (71.4%) displayed at least 4 days of at least 7 hr of wear time, of which 306 (71.7%) returned valid sleep diaries. We further excluded 12 (3.9%) participants who had missing personal data such as gender or body mass information. This resulted in an analytical sample of 294 (162 females and 132 males) adolescents with a mean age of 12.8 years (IQR = 0.7), a median body mass index *z* score of 0.2 kg/m^2 (IQR = 1.2), and a median fat mass of 25.4% (IQR = 7.8) (Table 1). The known anthropometric characteristics of the original sample did not differ significantly from the sample being analyzed in this study (see OSF directory). General information about the participant characteristics can be retrieved from the FOS effect paper (Ten Hoor et al., 2018).

In the data set of sleep estimating physical behavior the next day, participants' median reported times in bed were consistently between 21:30 and 21:45 across weekdays and between 23:00 and 23:01 on weekends. Participants' median reported times out of bed were between 07:00 and 07:15 during the weekdays, and between 09:00 and 09:30 during weekends. On weekends, participants reported longer sleep durations and shorter accelerometer wear times compared with weekdays. This added up to similar amounts of data on a 24-hr day (see OSF directory). Physical behavior proportions were consistent across the week except on Wednesdays and Thursdays, where participants seemed to accumulate more MVPA, and on Sundays, where they seemed to accumulate less MVPA (Figure 1). In the data set of physical behavior estimating subsequent sleep duration, results were similar (data not shown, but can be found in the OSF directory).

Table 1 Descriptive Characteristics of Participants 2014–2015

	Female	Male	Total
	n = 162	*n* = 132	*N* = 294
Age, mean (*SD*)	12.8 (0.7)	12.9 (0.6)	12.8 (0.7)
Sleep[a]			
Time to bed (hr:min), median (IQR)	22:14 (00:56)	22:08 (00:52)	22:10 (00:55)
Time out of bed (hr:min), median (IQR)	08:06 (00:40)	08:05 (00:54)	08:06 (00:47)
Sleep duration (min/day), median (IQR)	594.4 (50.9)	596.2 (65.9)	595.0 (55.9)
Short sleeper, *n* (%)	16 (9.9)	13 (9.8)	29 (9.9)
Long sleeper, *n* (%)	12 (7.4)	7 (5.3)	19 (6.5)
Optimal sleeper, *n* (%)	134 (82.7)	112 (84.8)	246 (83.7)
Physical activity[b]			
Wear time (min/day), median (IQR)	694.0 (157.2)	712.5 (198.4)	701.2 (181.1)
Sedentary portion[c] (% per day), mean (*SD*)	72.6 (6.4)	72.2 (6.0)	72.4 (6.2)
Sedentary compositional geometric mean, log ratio variance sit–light, sit–MVPA	73.6 (0.1,0.3)	73.2 (0.1, 0.3)	73.4 (0.1, 0.3)
Light portion[c] (% per day), mean (*SD*)	22.8 (4.9)	22.6 (4.6)	22.7 (4.7)
Light activity compositional geometric mean, log ratio variance light–sit, light–MVPA	22.9 (0.1, 0.2)	22.8 (0.1, 0.1)	22.8 (0.1, 0.2)
MVPA portion[c] (% per day), median (IQR)	3.9 (2.6)	4.7 (2.9)	4.3 (3.0)
MVPA activity compositional geometric mean, log ratio variance MVPA–light, MVPA–sit	3.5 (0.2, 0.3)	4.0 (0.1, 0.3)	3.7 (0.2, 0.3)
Meeting guidelines (% per day), median (IQR)	0 (0.2)	0 (0.3)	0 (0.2)
Anthropometrics			
BMI *z* score	0.3 (1.2)	0.1 (1.2)	0.2 (1.2)
Fat mass (%)	27.0 (7.3)	23.1 (7.9)	25.4 (7.8)
Underweight, *n* (%)	4 (2.5)	2 (1.5)	6 (2.0)
Normal weight, *n* (%)	115 (71.0)	101 (76.5)	216 (73.5)
Overweight, *n* (%)	31 (19.1)	19 (14.4)	50 (17.0)
Obese, *n* (%)	12 (7.4)	10 (7.6)	22 (7.5)

Note. BMI = body mass index; IQR = interquartile range; % per day = proportion of the day; MVPA = moderate- to vigorous-intensity physical activity; sit light = log (sitting percentage/light percentage).
[a]Reported time in bed at night and the time out of bed the following morning were used to estimate the total time in bed. Short sleep defined as those nights with <8/9 hr reported time in bed. Long sleep defined as those nights with >10/11 hr reported time in bed. Optimal sleep is defined as those nights with 8–10/9–11 hr reported time in bed. [b]Estimates of sedentary and physical activity behaviors are estimated via accelerometry. Sedentary intensity defined as 0–100 counts. Light intensity defined as 101–2,295 counts. Accumulated MVPA defined as ≥2,296 counts. Meeting guidelines defined as the proportion of days accumulating at least 60 min of MVPA. [c]The percentage of the day is the estimated proportion of waking minutes spent in each activity level.

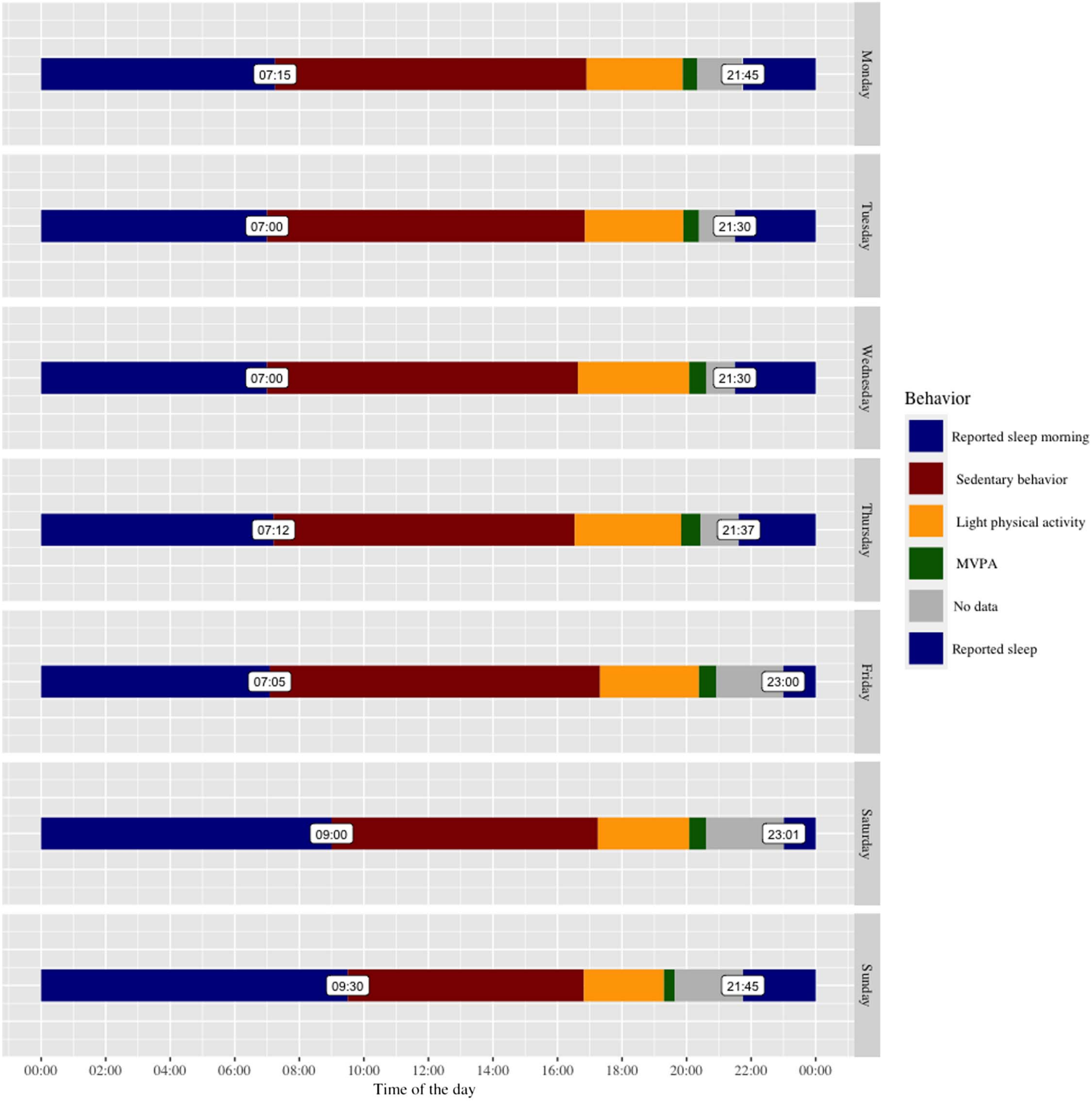

Figure 1 — Daily summary estimates reflecting reported time in bed predicting physical activity and sedentary behavior the next day. MVPA = moderate- to vigorous-intensity physical activity.

Sleep Category Predicting Sedentary Behavior and Physical Activity the Next Day

The results of the linear mixed-effects models with repeated measures for sleep category estimating physical activity and sedentary behavior are depicted in Table 2. Among female adolescents, long sleep was associated with a significantly smaller proportion of waking-minutes sedentary the following day (−3.02%, $SE = 1.05$, $p < .01$, 95% confidence interval [CI] [−5.09 to −0.96]) and a significantly greater proportion of waking minutes in MVPA the following day (1.69%, $SE = 0.48$, $p < .001$, 95% CI [0.75 to 2.64]). Among male adolescents, short sleep was associated with a significantly smaller proportion of waking minutes the following day spent in sedentary behaviors (−2.57%, $SE = 1.21$, $p = .03$, 95% CI [−4.95 to −0.19]) and a significantly greater proportion of waking minutes the following day spent in light physical activity (1.96%,

Table 2 Linear Mixed-Effects Models With Repeated Measures for Sleep Category Predicting Physical Activity and Sedentary Behavior the Following Day

	Sedentary behavior				Light physical activity				MVPA			
Sleep duration[a]	β	*SE*	*p*	95% CI	β	*SE*	*p*	95% CI	β	*SE*	*p*	95% CI
Physical activity portions (% per day)[b]												
Females (number of obs.: 427, *n* = 104)												
Short sleep	−0.28	0.99	.78	[−2.23, 1.68]	0.37	0.77	.63	[−1.15, 1.88]	−0.12	0.45	.79	[−0.99, 0.76]
Long sleep	−3.02	1.05	<.01	[−5.09, −0.96]	1.25	0.81	.12	[−0.34, 2.84]	1.69	0.48	<.001	[0.75, 2.64]
Intercept	57.08	15.62	<.001	[26.35, 87.81]	34.97	12.36	<.01	[10.65, 59.28]	7.99	5.38	.14	[−2.58, 18.57]
Males (number of obs.: 345, *n* = 83)												
Short sleep	−2.57	1.21	.03	[−4.95, −0.19]	1.96	0.86	.02	[0.27, 3.65]	0.60	0.55	.28	[−0.48, 1.67]
Long sleep	0.93	1.32	.48	[−1.66, 3.53]	−0.38	0.94	.69	[−2.23, 1.47]	−0.54	0.59	.36	[−1.71, 0.62]
Intercept	77.60	15.42	<.001	[47.23, 107.97]	19.30	11.73	.10	[−3.80, 42.39]	3.11	6.04	.61	[−8.77, 15.00]
Compositional data analysis												
Females (number of obs.: 427, *n* = 104)												
Short sleep	−0.01	0.05	.83	[−0.12, 0.09]	0.03	0.03	.42	[−0.04, 0.10]	−0.02	0.07	.77	[−0. 16, 0.11]
Long sleep	−0.15	0.06	<.01	[−0.26, −0.04]	−0.03	0.04	.46	[−0.10, 0.04]	0.18	0.07	.01	[0.04, 0.32]
Intercept	0.81	0.76	.29	[−0.68, 2.31]	0.30	0.45	.51	[−0.59, 1.19]	−1.12	0.87	.20	[−2.83, 0.59]
Males (number of obs.: 345, *n* = 83)												
Short sleep	−0.11	0.07	.10	[−0.25, 0.02]	0.03	0.04	.45	[−0.05, 0.11]	0.09	0.09	.33	[−0.09, 0.26]
Long sleep	0.09	0.07	.23	[−0.06, 0.23]	0.02	0.04	.71	[−0.07, 0.10]	−0.12	0.09	.20	[−0.31, 0.06]
Intercept	2.02	0.83	.02	[0.38, 3.65]	0.40	0.43	.35	[−0.44, 1.24]	−2.39	0.95	.01	[−4.27, −0.51]

Note. % per day = proportion of the day; CI = confidence interval; MVPA = moderate-to-vigorous intensity physical activity; obs. = observed days.
[a]Reported time in bed at night and the time out of bed the following morning were used to estimate the total time in bed. Short sleep defined as those nights with <8/9 hr reported time in bed. Long sleep defined as those nights with >10/11 hr reported time in bed. The referent group is defined as those nights with 8–10/9–11 hr reported time in bed. [b]Estimates of sedentary and physical activity behaviors are estimated via accelerometry. Sedentary intensity defined as 0–100 counts. Light intensity defined as 101–2,295 counts. Accumulated MVPA defined as ≥2,296 counts.

$SE = 0.86$, $p = .02$, 95% CI [0.27 to 3.65]), compared with those with optimal sleep.

Results from the CoDA models were similar for females. CoDA models indicated that long sleep was significantly negatively associated with the proportion of time spent in sedentary behavior compared with light activity and MVPA (−0.15, $SE = 0.06$, $p < .01$, 95% CI [−0.26 to −0.04]), and with the proportion of time spent in MVPA compared with sedentary behavior and light activity (0.18, $SE = 0.07$, $p = .01$, 95% CI [0.04 to 0.32]; Figure 2a). Similar associations were not found among males in the CoDA models (Figure 2b).

Physical Activity and Sedentary Behavior Predicting Sleep Duration That Night

The generalized linear mixed-effects models with repeated measures to determine the association between daytime physical activity and nighttime sleep are presented in Table 3. Neither the results of the CoDA analyses nor the results of the analyses using physical activity portions revealed significant effects.

Discussion

This study examined the associations between daytime physical behaviors with categories of sleep duration the following night and nighttime sleep with the following day's physical behaviors. Results from the first research question indicate that nighttime sleep was partially related to the following day's physical behaviors among this cohort of Dutch adolescents. Among females, long nighttime sleep was significantly associated with more time spent in the following day's health-benefiting MVPA and less time spent in sedentary behavior. Short sleep was not associated with next days' physical behaviors among females. These associations were found both with the proportions and with the CoDA analyses. For males, short nighttime sleep was associated with a smaller and higher proportion of time the following spent sedentary and in light-intensity activities, respectively. However, this association was only found when applying proportions not when applying CoDA analyses. The reason is that sedentary behavior was only replaced by light activity and not by both light activity and MVPA, which would have yielded more equal distributions of the three behaviors and, therefore, lower sedentary behavior and higher light activity CoDA values. Long sleep was not associated with next days' physical behaviors among males. There were no significant findings when estimating the association between daytime physical behavior and the following night's sleep.

Previous studies on the association of sleep and physical activity among adolescents have found the strongest and most consistent associations between nighttime sleep and the following day's physical behaviors (Krietsch et al., 2016; Master et al., 2019; Ortega et al., 2010; Soric et al., 2015). However, the results are mixed. Ortega et al. (2010) found that males who reported a shorter sleep duration had lower odds of engaging in any intensity of physical activity the following day (Ortega et al., 2010). Similarly, Master et al. (2019) found significant associations with sleep duration and MVPA, however, in different directions. They found that a longer sleep duration, rather than a shorter sleep duration, resulted in less MVPA the following day (Master et al., 2019). Whereas, Soric et al. (2015) and Krietsch et al. (2016) found that

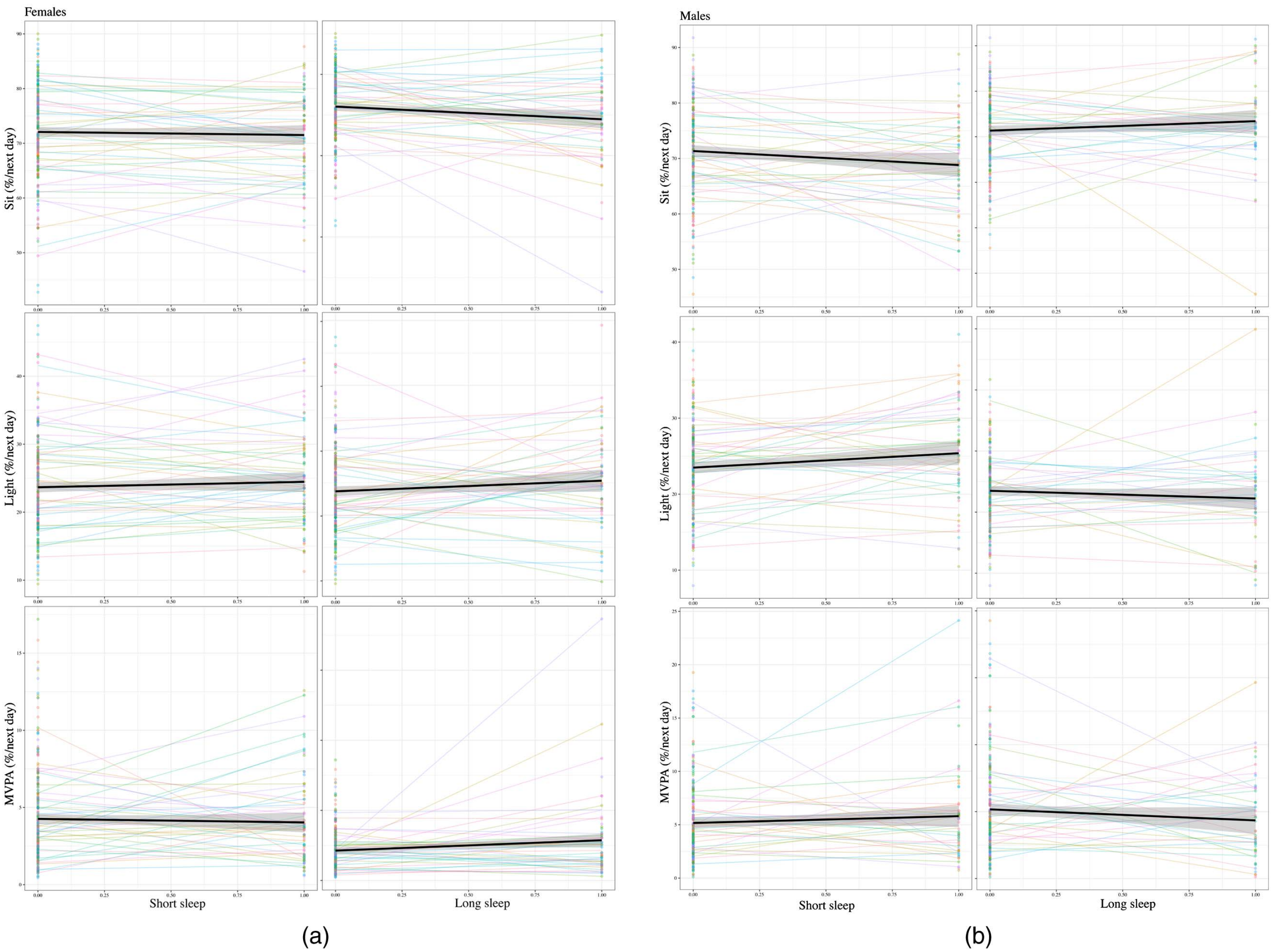

Figure 2 — (a) Model-predicted influence of short and long sleep on the portion of physical activity the next day among females: Spaghetti plot of average (thick) and subject-specific (thin) regression lines. (b) Model-predicted influence of short and long sleep on the portion of physical activity the next day among males: Spaghetti plot of average (thick) and subject-specific (thin) regression lines.

total sleep time was unrelated to the following day's MVPA, but more time in bed and sleep onset (the timing of when the subject went to bed), respectively, were significantly associated with the following day's MVPA (Krietsch et al., 2016; Soric et al., 2015). Previous studies' associations are most consistently statistically significant when investigating relationships within subjects (across multiple days); however, these studies did not account for the compositional nature of the 24-hr activity data. In addition, other discrepancies in results could be attributed to a number of factors, including the varying methods to measure physical behaviors and sleep (Soric et al., 2015), and differing analytic methods to control for the potentially confounding effects of gender and age. Of the other studies on the bidirectional associations between sleep and physical behaviors among adolescents (Krietsch et al., 2016; Master et al., 2019; Ortega et al., 2010; Soric et al., 2015), only Soric et al. and Ortega et al. analyzed the data within gender strata. Soric et al. found that the lower estimated total daily energy expenditure resulting from a longer sleep duration differed between genders. Ortega et al. found that in both males and females, morning tiredness (but not necessarily sleep time) was associated with significantly lower odds of leisure-time physical activity the following day. Furthermore, short sleep duration was associated with the time spent watching television in males, but not females. These findings, and the current study's differing findings by gender, indicate the importance of stratified analyses by gender on this topic in future research. However, taking the collective findings from this and previous studies, among adolescent populations, there seems to be no consistent support for associations between nighttime sleep and the following day's physical behavior in adolescents.

Interestingly, in a previous study among adults, longer nighttime sleep was associated with less sedentary behavior, and shorter nighttime sleep was associated with more light-intensity physical activity (Pettee Gabriel et al., 2017). This closely aligns with the current study's findings for females (longer nighttime sleep was associated with less sedentary behavior) and males (shorter nighttime sleep was associated with more light-intensity physical activity), respectively. As the previous study's authors noted, this may

Table 3 Generalized Linear Mixed-Effects Models With Repeated Measures for Physical Activity and Sedentary Behaviors Predicting Sleep Category That Night

	Short sleep[b]				Long sleep[b]			
Physical activity[a]	β	*SE*	*p*	95% CI	β	*SE*	*p*	95% CI
Females (number of obs.: 475, *n* = 116)								
Physical activity portions								
Sedentary portion (% per day)	−0.00	0.02	.99	[−0.04, 0.04]	−0.01	0.02	.52	[−0.04, 0.02]
Intercept	−10.72	4.54	.02	[−20.17, −1.92]	−2.62	3.90	.50	[−10.44, 5.18]
Light portion (% per day)	0.02	0.02	.42	[−0.03, 0.07]	0.00	0.02	.93	[−0.04, 0.05]
Intercept	−11.32	4.41	.01	[−20.51, −2.74]	−3.53	3. 70	.34	[−10.94, 3.89]
MVPA portion (% per day)	−0.07	0.05	.16	[−0.18, 0.02]	0.05	0.04	.19	[−0.03, 0.12]
Intercept	−10.70	4.41	.02	[−19.88, −2.11]	−3.45	0.04	.35	[−10.89, 3.99]
Compositional data analysis								
Sedentary behavior	−0.41	0.49	.40	[−1.39, 0.56]	−0.03	0.47	.95	[−0.94, 0.90]
Light physical activity	0.92	0.63	.14	[−0.30, 2.19]	−0.36	0.59	.55	[−1.56, 0.80]
MVPA	−0.51	0.31	.10	[−1.14, 0.09]	0.39	0.30	.20	[−0.19, 0.99]
Intercept	−11.44	4.43	<.01	[−20.67, −2.86]	−2.67	3.80	0.48	[−10.26, 4.98]
Males (number of obs.: 369, *n* = 88)								
Physical activity portions								
Sedentary portion (% per day)	0.00	0.02	.86	[−0.04, 0.05]	0.04	0.02	.07	[−0.00, 0.09]
Intercept	−14.87	5.03	<.01	[−25.79, −5.43]	−7.99	6.23	.20	[−20.88, 4.65]
Light portion (% per day)	−0.01	0.03	.81	[−0.07, 0.05]	−0.06	0.03	.07	[−0.13, 0.00]
Intercept	−14.48	4.77	<.01	[−24.77, −5.38]	−3.51	0.03	.56	[−15.92, 8.89]
MVPA portion (% per day)	0.00	0.04	.99	[−0.09, 0.08]	−0.06	0.06	.25	[−0.18, 0.04]
Intercept	−14.59	4.74	<.01	[−24.83, −5.57]	−4.44	6.03	.46	[−16.90, 7.93]
Compositional data analysis								
Sedentary behavior	0.18	0.56	.75	[−0.91, 1.29]	1.15	0.62	.06	[−0.07, 2.41]
Light physical activity	−0.43	0.71	.55	[−1.83, 0.98]	−0.88	0.79	.27	[−2.46, 0.70]
MVPA	0.25	0.34	.47	[−0.42, 0.93]	−0.27	0.38	.48	[−1.04, 0.47]
Intercept	−14.48	4.79	<.01	[−14.87, −5.42]	−6.42	6.04	.29	[−18.94, 5.89]

Note. % per day = proportion of the day; CI = confidence interval; MVPA = moderate- to vigorous-intensity physical activity; obs. = observed days.
[a]Estimates of sedentary and physical activity behaviors are estimated via accelerometry. Sedentary intensity defined as 0–100 counts. Light intensity defined as 101–2,295 counts. Accumulated MVPA defined as ≥2,296 counts. [b]Reported time in bed at night and the time out of bed the following morning were used to estimate the total time in bed. Short sleep defined as those nights with <8/9 hr reported time in bed. Long sleep defined as those nights with >10/11 hr reported time in bed. The referent group is defined as those nights with 8–10/9–11 hr reported time in bed.

indicate that physical activity levels are more dependent upon the time available in the day, which is the direct result of the time spent sleeping. However, the data in this previous study were not analyzed as the total proportion of the data, but rather as an estimate of total minutes (Pettee Gabriel et al., 2017), while in the current study, proportions of the days as well as a compositional data approach were used. Therefore, the findings may be due to other external forces, such as fixed schedules or parental/school schedules, which was confirmed by the fact that females were more active and less sedentary on weekends, while males were more active and less sedentary during the week (especially on Tuesdays and Wednesdays; see descriptive data in the OSF directory). However, the allocation of time spent physically active being dependent upon external forces among adolescents may be explored further using randomized trials, which control for planned versus unplanned physical activity.

The strengths of this study include the use of accelerometry among a highly compliant cohort of adolescents. Aside from removing self-reporting error with this device-based assessment of physical behavior, accelerometry also detects movement and nonmovement across the full spectrum of intensities, including sedentary and light-intensity physical activity. This allowed the evaluation of sleep, as it relates to activities beyond MVPA, to encompass the full 24-hr activity cycle. This represents a paradigm shift in the field toward an integrated model that incorporates both sleep and waking behaviors to optimize health, rather than focusing on a single behavior (Rosenberger et al., 2019). Despite these strengths, this study has limitations that should be noted. First, the generalizability of these results is limited by the sample's homogenous characteristics (age, race/ethnicity, socioeconomic status). However, the results of this study generally align with other studies' findings and the homogenous sample provides increased internal validity in light of the relatively small sample size. Second, although actigraphy measured waking behaviors, it did not measure sleep duration, but rather, we relied upon a proxy estimate based on self-reported time to bed and time out of bed. However, self-reported time in/out of bed from sleep diaries has been shown to be comparable to objective sleep duration measurements (Lockley et al., 1999; McCrae et al., 2005; Monk et al., 1994). We were able to confirm in additional analyses (not reported, but retrievable in the OSF directory) the reported times in bed and time spent in waking behaviors generally summed to a full day. In addition, results from previous studies using sleep actigraphy among adolescents (Master et al., 2019) generally align with the current study's findings.

These findings provide an important addition to the literature aiming to understand the possible bidirectional associations of sleep and physical activity among children and adolescents. Adolescents undergo significant developmental changes that are known to impact these important health behaviors, and socially are subject to nondiscretionary activities that may impact their time spent in health promoting or compromising behaviors. Furthermore, the impact of daytime schedules on physical activity and nighttime sleep metrics (e.g., sleep duration, sleep quality, sleep onset, sleep latency) should be considered. This will allow us to understand whether physical activity impacts sleep in ways that may not appear by measuring the time in bed. Other confounding factors such as pubertal status, socioeconomic status, and school start times might be worth considering in future research and with more available data. Although experimental designs will allow for the causal relations between these behaviors to be explored and will provide for greater variability in the variables of interest, the feasibility of such designs is questionable. Therefore, future research may strive to take advantage of natural experimental designs. Overall, these results suggest that promoting best sleep practices (Hirshkowitz et al., 2015) may have a positive impact on daytime physical activity behaviors.

Acknowledgments

The data in this project were from the Focus on Strength study, sponsored by the Netherlands Organisation for Health Research and Development (ZonMw. Grant no. 525001004). Support for manuscript preparation came to Dr. Knell through a postdoctoral fellowship at the University of Texas School of Public Health Cancer Education and Career Development Program—National Cancer Institute/National Institutes of Health Grant T32 CA57712. The authors declare there is no conflict of interest.

References

Adolescent Sleep Working Group. (2014). School start times for adolescents. *Pediatrics, 134*(3), 642–649. doi:10.1542/peds.2014-1697

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control, 19*(6), 716–723. doi:10.1109/TAC.1974.1100705

Banda, J.A., Haydel, K.F., Davila, T., Desai, M., Bryson, S., Haskell, W.L., … Robinson, T.N. (2016). Effects of varying epoch lengths, wear time algorithms, and activity cut-points on estimates of child sedentary behavior and physical activity from accelerometer data. *PLoS One, 11*(3), e0150534–e0150534. PubMed ID: 26938240 doi:10.1371/journal.pone.0150534

Baron, K.G., Reid, K.J., & Zee, P.C. (2013). Exercise to improve sleep in insomnia: Exploration of the bidirectional effects. *Journal of Clinical Sleep Medicine, 9*(8), 819–824. PubMed ID: 23946713 doi:10.5664/jcsm.2930

Centers for Disease Control and Prevention, National Center for Health Statistics, and U.S. Department of Health and Human Services. (n.d.). NHANES: Body composition procedures manual. Retrieved from http://www.cdc.gov/nchs/data/nhanes/nhanes_05_06/BC.pdf

Chaput, J.-P., Saunders, T., & Carson, V. (2017). Interactions between sleep, movement and other non-movement behaviours in the pathogenesis of childhood obesity. *Obesity Reviews, 18,* 7–14. PubMed ID: 28164448 doi:10.1111/obr.12508

Chastin, S.F., Palarea-Albaladejo, J., Dontje, M.L., & Skelton, D.A. (2015). Combined effects of time spent in physical activity, sedentary behaviors and sleep on obesity and cardio-metabolic health markers: A novel compositional data analysis approach. *PLoS One, 10*(10), e0139984. PubMed ID: 26461112 doi:10.1371/journal.pone.0139984

Chen, X., Beydoun, M.A., & Wang, Y. (2008). Is sleep duration associated with childhood obesity? A systematic review and meta-analysis. *Obesity, 16*(2), 265–274. PubMed ID: 18239632 doi:10.1038/oby.2007.63

Choi, L., Ward, S.C., Schnelle, J.F., & Buchowski, M.S. (2012). Assessment of wear/nonwear time classification algorithms for triaxial accelerometer. *Medicine & Science in Sports & Exercise, 44*(10), 2009. PubMed ID: 22525772 doi:10.1249/MSS.0b013e318258cb36

Dulloo, A.G., Miles-Chan, J.L., & Montani, J.P. (2017). Nutrition, movement and sleep behaviours: Their interactions in pathways to obesity and cardiometabolic diseases. *Obesity Reviews, 18*(Suppl. 1), 3–6. doi:10.1111/obr.12513

Evenson, K.R., Catellier, D.J., Gill, K., Ondrak, K.S., & McMurray, R.G. (2008). Calibration of two objective measures of physical activity for children. *Journal of Sports Sciences, 26*(14), 1557–1565. PubMed ID: 18949660 doi:10.1080/02640410802334196

Fredriks, A.M., van Buuren, S., Wit, J.M., & Verloove-Vanhorick, S.P. (2000). Body index measurements in 1996-7 compared with 1980. *Archives of Disease in Childhood, 82*(2), 107–112. PubMed ID: 10648362 doi:10.1136/adc.82.2.107

Hirshkowitz, M., Whiton, K., Albert, S.M., Alessi, C., Bruni, O., DonCarlos, L., … Adams Hillard, P.J. (2015). National Sleep Foundation's sleep time duration recommendations: Methodology and results summary. *Sleep Health, 1*(1), 40–43. PubMed ID: 29073412 doi:10.1016/j.sleh.2014.12.010

Kishida, M., & Elavsky, S. (2016). An intensive longitudinal examination of daily physical activity and sleep in midlife women. *Sleep Health, 2*(1), 42–48. PubMed ID: 29073452 doi:10.1016/j.sleh.2015.12.001

Kredlow, M.A., Capozzoli, M.C., Hearon, B.A., Calkins, A.W., & Otto, M.W. (2015). The effects of physical activity on sleep: A meta-analytic review. *Journal of Behavioral Medicine, 38*(3), 427–449. PubMed ID: 25596964 doi:10.1007/s10865-015-9617-6

Krietsch, K.N., Armstrong, B., McCrae, C.S., & Janicke, D.M. (2016). Temporal associations between sleep and physical activity among overweight/obese youth. *Journal of Pediatric Psychology, 41*(6), 680–691. PubMed ID: 26801238 doi:10.1093/jpepsy/jsv167

Kuzik, N., Carson, V., Andersen, L.B., Sardinha, L.B., Grøntved, A., Hansen, B.H., … Ekelund, U. (2017). Physical activity and sedentary time associations with metabolic health across weight statuses in children and adolescents. *Obesity, 25*(10), 1762–1769. PubMed ID: 28782888 doi:10.1002/oby.21952

Lambiase, M.J., Gabriel, K.P., Kuller, L.H., & Matthews, K.A. (2013). Temporal relationships between physical activity and sleep in older women. *Medicine & Science in Sports & Exercise, 45*(12), 2362–2368. PubMed ID: 23739529 doi:10.1249/MSS.0b013e31829e4cea

Landhuis, C.E., Poulton, R., Welch, D., & Hancox, R.J. (2008). Childhood sleep time and long-term risk for obesity: A 32-year prospective birth cohort study. *Pediatrics, 122*(5), 955–960. PubMed ID: 18977973 doi:10.1542/peds.2007-3521

Lockley, S.W., Skene, D.J., & Arendt, J. (1999). Comparison between subjective and actigraphic measurement of sleep and sleep rhythms. *Journal of Sleep Research, 8*(3), 175–183. PubMed ID: 10476003 doi:10.1046/j.1365-2869.1999.00155.x

Mahalanobis, P.C. (1936). *On the generalized distance in statistics*. National Institute of Science of India.

Master, L., Nye, R.T., Lee, S., Nahmod, N.G., Mariani, S., Hale, L., & Buxton, O.M. (2019). Bidirectional, daily temporal associations between sleep and physical activity in adolescents. *Scientific Reports, 9*(1), 7732. PubMed ID: 31118441 doi:10.1038/s41598-019-44059-9

McCrae, C.S., Rowe, M.A., Tierney, C.G., Dautovich, N.D., Definis, A.L., & McNamara, J.P. (2005). Sleep complaints, subjective and objective sleep patterns, health, psychological adjustment, and daytime functioning in community-dwelling older adults. *The Journals of Gerontology, Series B: Psychological Sciences & Social Sciences, 60*(4), P182–P189. doi:10.1093/geronb/60.4.P182

Miller, M.A., Kruisbrink, M., Wallace, J., Ji, C., & Cappuccio, F.P. (2018). Sleep duration and incidence of obesity in infants, children, and adolescents: A systematic review and meta-analysis of prospective studies. *Sleep, 41*(4), 1–19. doi:10.1093/sleep/zsy018

Mitchell, J.A., Godbole, S., Moran, K., Murray, K., James, P., Laden, F., … Glanz, K. (2016). No evidence of reciprocal associations between daily sleep and physical activity. *Medicine & Science in Sports & Exercise, 48*(10), 1950–1956. PubMed ID: 27285490 doi:10.1249/MSS.0000000000001000

Monk, T.H., Reynolds, C.F., III, Kupfer, D.J., Buysse, D.J., Coble, P.A., Hayes, A.J., … Ritenour, A.M. (1994). The Pittsburgh sleep diary. *Journal of Sleep Research, 3*(2), 111–120. PubMed ID: 10607115 doi:10.1111/j.1365-2869.1994.tb00114.x

Ohayon, M.M., Roberts, R.E., Zulley, J., Smirne, S., & Priest, R.G. (2000). Prevalence and patterns of problematic sleep among older adolescents. *Journal of the American Academy of Child and Adolescent Psychiatry, 39*(12), 1549–1556. PubMed ID: 11128333 doi:10.1097/00004583-200012000-00019

Ortega, F.B., Chillon, P., Ruiz, J.R., Delgado, M., Albers, U., Alvarez-Granda, J.L., … Castillo, M.J. (2010). Sleep patterns in Spanish adolescents: Associations with TV watching and leisure-time physical activity. *European Journal of Applied Physiology, 110*(3), 563–573. PubMed ID: 20556419 doi:10.1007/s00421-010-1536-1

Patton, G.C., & Viner, R. (2007). Pubertal transitions in health. *The Lancet, 369*(9567), 1130–1139. doi:10.1016/S0140-6736(07)60366-3

Pettee Gabriel, K., Sternfeld, B., Shiroma, E.J., Perez, A., Cheung, J., & Lee, I.M. (2017). Bidirectional associations of accelerometer-determined sedentary behavior and physical activity with reported time in bed: Women's Health Study. *Sleep Health, 3*(1), 49–55. doi:10.1016/j.sleh.2016.10.001

Plasqui, G. (2017). Smart approaches for assessing free-living energy expenditure following identification of types of physical activity. *Obesity Reviews, 18*(Suppl. 1), 50–55. doi:10.1111/obr.12506

Plasqui, G., Bonomi, A.G., & Westerterp, K.R. (2013). Daily physical activity assessment with accelerometers: New insights and validation studies. *Obesity Reviews, 14*(6), 451–462. PubMed ID: 23398786 doi:10.1111/obr.12021

Pronk, N.P., Anderson, L.H., Crain, A.L., Martinson, B.C., O'Connor, P.J., Sherwood, N.E., & Whitebird, R.R. (2004). Meeting recommendations for multiple healthy lifestyle factors. Prevalence, clustering, and predictors among adolescent, adult, and senior health plan members. *American Journal of Preventive Medicine, 27*(2), 25–33. doi:10.1016/j.amepre.2004.04.022

Rasmussen, C.L., Palarea-Albaladejo, J., Bauman, A., Gupta, N., Nabe-Nielsen, K., Birk Jørgensen, M., & Holtermann, A. (2018). Does physically demanding work hinder a physically active lifestyle in low socioeconomic workers? A compositional data analysis based on accelerometer data. *International Journal of Environmental Research and Public Health, 15*(7), 1306. doi:10.3390/ijerph15071306

Renninger, M., Hansen, B.H., Steene-Johannessen, J., Kriemler, S., Froberg, K., Northstone, K., … Ekelund, U. (2020). Associations between accelerometry measured physical activity and sedentary time and the metabolic syndrome: A meta-analysis of more than 6000 children and adolescents. *Pediatric Obesity, 15*(1), e12578. PubMed ID: 31709781 doi:10.1111/ijpo.12578

Rosenberger, M.E., Fulton, J.E., Buman, M.P., Troiano, R.P., Grandner, M.A., Buchner, D.M., & Haskell, W.L. (2019). The 24-hour activity cycle: A new paradigm for physical activity. *Medicine & Science in Sports & Exercise, 51*(3), 454–464. PubMed ID: 30339658 doi:10.1249/MSS.0000000000001811

Schoeller, D.A., Ravussin, E., Schutz, Y., Acheson, K.J., Baertschi, P., & Jequier, E. (1986). Energy expenditure by doubly labeled water: Validation in humans and proposed calculation. *American Journal of Physiology, 250*(5, Pt. 2), R823–R830. PubMed ID: 3085521 doi:10.1152/ajpregu.1986.250.5.r823

Soric, M., Starc, G., Borer, K.T., Jurak, G., Kovac, M., Strel, J., & Misigoj-Durakovic, M. (2015). Associations of objectively assessed sleep and physical activity in 11-year old children. *Annals of Human Biology, 42*(1), 31–37. PubMed ID: 25007958 doi:10.3109/03014460.2014.928367

Ten Hoor, G.A., Kok, G., Rutten, G.M., Ruiter, R.A.C., Kremers, S.P.J., Schols, A.M.J.W., & Plasqui, G. (2016). The Dutch 'Focus on Strength' intervention study protocol: Programme design and production, implementation and evaluation plan. *BMC Public Health, 16*(1), 496. doi:10.1186/s12889-016-3150-6

Ten Hoor, G.A., Rutten, G.M., Van Breukelen, G.J.P., Kok, G., Ruiter, R.A.C., Meijer, K., … Schols, A.M.J.W. (2018). Strength exercises during physical education classes in secondary schools improve body composition: A cluster randomized controlled trial. *International Journal of Behavioral Nutrition and Physical Activity, 15*(1), 92. doi:10.1186/s12966-018-0727-8

Timothy, G.L. (1989). Assessment of body composition in children. *Pediatric Exercise Science, 1*(1), 19–30. doi:10.1123/pes.1.1.19

Toftager, M., Kristensen, P.L., Oliver, M., Duncan, S., Christiansen, L.B., Boyle, E., … Troelsen, J. (2013). Accelerometer data reduction in adolescents: Effects on sample retention and bias. *International Journal of Behavioral Nutrition and Physical Activity, 10*(1), 140. doi:10.1186/1479-5868-10-140

Tremblay, M.S., Chaput, J.-P., Adamo, K.B., Aubert, S., Barnes, J.D., Choquette, L., … Gray, C.E. (2017). Canadian 24-hour movement guidelines for the early years (0–4 years): An integration of physical activity, sedentary behaviour, and sleep. *BMC Public Health, 17*-(Suppl. 5), 874. doi:10.1186/s12889-017-4859-6

Trost, S.G., Loprinzi, P.D., Moore, R., & Pfeiffer, K.A. (2011). Comparison of accelerometer cut points for predicting activity intensity in youth. *Medicine & Science in Sports & Exercise, 43*(7), 1360–1368. PubMed ID: 21131873 doi:10.1249/MSS.0b013e318206476e

Trost, S.G., Pate, R.R., Freedson, P.S., Sallis, J.F., & Taylor, W.C. (2000). Using objective physical activity measures with youth: How many days of monitoring are needed? *Medicine & Science in Sports & Exercise, 32*(2), 426–431. PubMed ID: 10694127 doi:10.1097/00005768-200002000-00025

van der Kooy, K., Leenen, R., Deurenberg, P., Seidell, J.C., Westerterp, K.R., & Hautvast, J.G. (1992). Changes in fat-free mass in obese subjects after weight loss: A comparison of body composition measures. *International Journal of Obesity and Related Metabolic Disorders, 16*(9), 675–683.

Verkooijen, S., de Vos, N., Bakker-Camu, B.J.W., Branje, S.J.T., Kahn, R.S., Ophoff, R.A., … Boks, M.P.M. (2018). Sleep disturbances, psychosocial difficulties, and health risk behavior in 16,781 Dutch adolescents. *Academic Pediatrics, 18*(6), 655–661. PubMed ID: 29530583 doi:10.1016/j.acap.2018.03.003

Westerterp, K.R., Meijer, G.A., Saris, W.H., Soeters, P.B., Winants, Y., & ten Hoor, F. (1991). Physical activity and sleeping metabolic rate. *Medicine & Science in Sports & Exercise, 23*(2), 166–170. PubMed ID: 2017012

Westerterp, K.R., Wouters, L., & van Marken Lichtenbelt, W.D. (1995). The Maastricht protocol for the measurement of body composition and energy expenditure with labeled water. *Obesity Research, 3*(Suppl. 1), 49–57. doi:10.1002/j.1550-8528.1995.tb00007.x

Yngve, A., Nilsson, A., Sjostrom, M., & Ekelund, U. (2003). Effect of monitor placement and of activity setting on the MTI accelerometer output. *Medicine & Science in Sports & Exercise, 35*(2), 320–326. PubMed ID: 12569223 doi:10.1249/01.MSS.0000048829.75758.A0