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ORIGINAL ARTICLE

# Temporal relationships between device-derived sedentary behavior, physical activity, and sleep in early childhood

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## Abstract

**Study Objectives:** Understanding the ideal composition of a child's day requires a better understanding of the relations between wake behaviors (sedentary behavior [SB], physical activity [PA]) and sleep. Here, we examine between- and within-person temporal associations between daytime wake behaviors and overnight sleep in early childhood, an important age when healthy behaviors are initiated and 24-hour behaviors are largely determined by caregivers.

**Methods:** Daily, repeated measures of wake behavior and overnight sleep were assessed via wrist-worn actigraphy (mean = 9 days/nights) in 240 children (50.8 ± 9.8 months). Multilevel models with lagged effects were used to examine the temporal associations between wake and overnight sleep measures and adjusted for daily nap duration, age, sex, and socioeconomic status.

**Results:** Between-person associations for sleep outcomes were negative between moderate-to vigorous-intensity PA (MVPA) and total activity for sleep efficiency (SE). Between-person associations for wake outcomes were positive between sleep duration and light PA, and negative between SE and both MVPA and total PA. When children obtained higher SE relative to their individual average, they were more likely to engage in less SB and greater MVPA and total PA the next day.

**Conclusions:** Generally, days with greater activity or sleep were not associated with greater subsequent sleep or PA. Most subsequent behaviors were not influenced by children achieving higher activity or sleep relative to their individual average levels, although higher SE was beneficially associated with next day wake behaviors. Future analyses with young children should consider within-person associations and could investigate lagged effects beyond one day.

## Statement of Significance

Research on the interactive effects of wake behaviors (i.e. sedentary behavior and physical activity) and sleep in early childhood is limited, and temporal analyses that provide important information regarding both between- and within-person associations have not been conducted in children under 6 years of age. These early years are when behavior patterns are developing, and 24-hour behaviors are largely determined by caregivers. In our examination of temporal associations between wake behaviors and sleep in early childhood, most associations were not significant, but when children obtained higher sleep efficiency compared to their average night, they were more active the following day. In addition to between-person analyses, future 24-hour behavior research in young children should also explore within-person associations.

**Key words:** sleep; sedentary behavior; physical activity; temporal; early childhood; intensive longitudinal

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## Introduction

Sedentary behavior (SB), physical activity (PA), and sleep are all health behaviors that significantly contribute to early childhood health. Specifically, minimizing time spent sedentary, participating in adequate levels of PA, and achieving sufficient sleep in childhood have been shown to have beneficial effects on cognitive, mental, and physical health outcomes [1–4]. Relatedly, obtaining recommended levels of PA and sleep while minimizing sedentary activities may also reduce the likelihood of developing adverse health outcomes, such as depression, diabetes, and obesity [2, 4]. A variety of physiological and behavioral pathways connecting these behaviors with such health benefits have been supported [2, 5]. Together, wake behaviors (i.e. SB and PA) and sleep make up the movement continuum and have been coined *24-hour movement behaviors* [6, 7].

U.S. health organizations have developed guidelines for these behaviors that are specific to the early childhood age group (3–5 years). The current Physical Activity Guidelines for Americans recommend that children at this age be physically active throughout the day, but they lack recommendations regarding SB or sleep [8]. The American Academy of Sleep Medicine recommends that, within a 24-hour period, preschoolers sleep 10 to 13 h (including naps) [4]. Early childhood may be an important time for these behaviors, given that sleep is unique at this age (as children transition out of naps) and sleep and PA patterns tend to track through childhood (and even into adulthood) [9–11]. Given that all three behaviors play an important role in health, other nations and the World Health Organization have developed 24-hour movement guidelines that provide recommendations for daily SB, PA, and sleep for various age groups across the lifespan [6, 7, 12–14]. Such holistic recommendations may be beneficial to parents as well as childcare and healthcare providers.

Despite the growing evidence of the connected relations between wake and sleep behaviors, more research is needed on the interactive effects of these health behaviors in early childhood to inform future comprehensive recommendations (i.e. 24-hour guidelines in the United States), policies, and intervention approaches. However, our current understanding of the relations between these behaviors stems primarily from studies conducted in adults [15–18] and children ages 6 years or older [1, 19–21]. Although there is evidence that both acute (e.g. single bouts of structured PA or exercise) and chronic PA (e.g. a PA intervention delivered over multiple sessions) can improve sleep outcomes in adults, recent reviews of pediatric studies have reported that, similar to older children, the relationship between PA and sleep is less conclusive in early childhood [22]. Some collective limitations of prior studies in early childhood are the absence of temporal measures and analyses (i.e. associations were based on aggregated between-person averages for the full wear periods) and the lack of consideration of daytime sleep.

Given that wake and sleep behaviors are temporally linked and share some physiological mechanisms, research groups have begun to promote the exploration of these behaviors through a 24-hour framework [23–25]. As described in by Irish *et al*., [24] the examination of daily between-person and within-person variations may provide greater insight into the interactions of wake and sleep measures. Specifically, analyses of repeated measures can explore the temporal nature of these behaviors (e.g. if individuals participating in greater PA during the day are more likely to sleep longer on subsequent nights, and if participating in greater PA during the day compared to one's average level is associated with their subsequent sleep) and the potential bidirectionality of their associations. Indeed, it is noted by Bolger and Laurenceau [26] that relations of different magnitudes and direction can exist for between-subjects and within-subjects relationships, and therefore, only exploring the averages between individuals can lead to ecological fallacy. In adults, such analyses have elicited applicable information that has added to our understanding of the relations between wake behaviors and sleep, which were previously based solely on reports from behavioral data aggregated over measurement time periods [27]. Some studies have explored temporal relations of wake and sleep behaviors in older children [28–35]. However, similar temporal analyses have not been conducted in children under 6 years of age.

Examining temporal relations between wake and sleep behaviors separately in younger children is warranted, given some key differences present in these early years. First, movement opportunities, types of activity engagement, and sleep schedules are strongly caregiver-driven or dictated in young children, more so than in their older counterparts. Second, sleep behaviors across early childhood are unique in that they are distinctive from older children and may even differ between children of the same age (possibly due to maturational development, caregiver practices, and environmental factors) [36, 37]. There is a shift from polyphasic (i.e. multiple daytime and nighttime sleep bouts) to biphasic sleep (i.e. one daytime sleep bout and one nighttime sleep bout) from infancy to toddlerhood, and then another shift in the preschool years to monophasic sleep (i.e. one overnight sleep bout). When these transitions occur varies between children. Interestingly, although napping is frequently a component of total daily sleep in young children and is associated with many health and cognitive outcomes [38], most studies of wake behaviors and sleep in this age group have solely focused on overnight sleep, without accounting for daytime sleep, which could potentially confound the relations between wake behaviors and nighttime sleep.

The purpose of this study was to determine if there are temporal (day-to-day) and bidirectional associations between daytime wake behaviors and overnight sleep. Although temporal relations between wake and sleep behaviors have been generally mixed in preadolescent children, based on evidence in older populations our exploratory hypotheses were that (1) greater total PA, greater time spent in moderate-to vigorous-intensity PA (MVPA), and less SB would be associated with longer sleep duration, earlier sleep mid-point, and greater sleep efficiency (SE) in subsequent nights; and (2) longer overnight sleep duration, earlier overnight sleep mid-point, and greater overnight SE would be associated with greater activity counts, greater time spent in MVPA, and less SB on subsequent days. Additionally, we hypothesized that participating in less SB or greater PA than an individual's average would be beneficially associated with subsequent sleep measures, and obtaining greater sleep, an earlier sleep mid-point, or greater SE than an individuals' average would be beneficially associated with subsequent wake behaviors.

## Methods

### Participants

Participants of this secondary analysis were children attending preschool and childcare centers in western Massachusetts between 2013 and 2019. Eligibility for participation in the parent study (ClinicalTrials.gov ID: NCT03285880) included being between the age of 33 to 71 months, having normal or corrected-to-normal vision and hearing, absence of current or past diagnosis of a sleep disorder or developmental disability, no current use of sleep-affecting or psychotropic medications, and no travel outside of the local time zone within a week prior to the study. Participants with less than three days or three full nights of sufficient accelerometer data (see Actigraphy section), or less than three consecutive wake-to-overnight or overnight-to-wake cycles were excluded from the present study.

## Procedure

All study protocols were approved by the University of Massachusetts Institutional Review Board. Permission and consent were obtained from adult caregivers and preschool teachers and verbal assent was acquired from child participants. At study enrollment, caregivers were given the health and demographics questionnaire to complete any time in the following 16 days. On the first day of the study protocol, children were given an actigraphy monitor to wear on their non-dominant wrist. Children were instructed to wear it continuously for the following 16 days and to press an event marker button corresponding with bed and wake times. During one of the study's preschool visits, research staff measured participating children's height and weight. The aim of the parent study was to examine the effects of napping on memory performance and therefore, during the 16-day study period, two conditions were implemented one week apart between the hours of 12 pm and 4 pm—one afternoon of nap promotion and one afternoon of wake-promotion. Outside of these two afternoons, participants engaged in their typical behaviors and routines.

Caregivers were asked to complete a daily sleep diary and encourage their child to press the event marker button at bed and wake times. Enrolled preschool teachers were also instructed to complete daily nap diaries reporting the sleep of participating children. Caregivers reported on nap and overnight sleep periods at home by recording the time the child was in bed, the time it took the child to fall asleep, and wake time. On days in which the child was at preschool, teachers recorded if children napped and, if so, the time the nap started and ended. On the last day of the study (day 16), questionnaires, sleep diaries, and Actiwatches were collected. Caregivers and childcare centers were monetarily compensated, and children received an age-appropriate book.

## Measures

***Actigraphy.*** SB, PA, and sleep measures were assessed via accelerometry with Actiwatch Spectrum monitors worn on the non-dominant wrist and processed in the Actiware software (Philips Respironics, Bend, OR). The Actiwatch is a water-resistant triaxial accelerometer that has off-wrist detection with a button to mark events in the record. The Actiwatch is considered a valid tool for sleep assessment relative to polysomnography in children [39, 40]. Actiware's default algorithm [41], which has been commonly used in early childhood sleep studies [39, 42], has been compared against epoch-by-epoch data from videosomnography in a validity study in children 28 to 73 months of age and was reported to have an overall agreement of 94%, sensitivity of 97%, and specificity of 24% [43]. Ekblom *et al.* [44] explored the validity of the Actiwatch against indirect calorimetry to assess energy expenditure in preadolescent children (mean age = 8.8 years; $r = 0.90$, $p < .001$) and proposed activity count thresholds for PA intensities. Additionally, reliability of the Actiwatch was tested in a mechanical shaker with intra- and inter-instrument coefficient of variations ranging between 0.72% and 8.4%. Alhassan *et al.* [45] cross-validated these Actiwatch cut points against direct observation as a criterion in preschool children ($r_{sp} = 0.47$, $p < .001$). Direct observation using the Observational System for Recording PA in Children-Preschool tool was used and children's activity was observed during three sessions in childcare. In 15-second epochs, activity levels were coded into five intensity categories (i.e. stationary, limb movement, light, moderate, or vigorous) that were then classified into the same categories used by the Ekblom cut points for comparison.

In the present study, Actiwatches were configured to collect data in 15-second epochs, with a sampling rate of 32 Hz and sensitivity of <.01. Actiwatch data was downloaded in the Actiware software and scored as sleep, wake, or excluded (i.e. if it was designated as off-wrist). Each daily cycle (i.e. wake onset of one day until the wake onset of the subsequent day) was then broken down into rest (or time in bed) and wake intervals. Due to the protocol of the parent study, an experimental condition (i.e. either wake-promotion or nap-promotion) was implemented two afternoons approximately one week apart. Therefore, the full daily cycle (i.e. the same daytime period and subsequent overnight period) of the two experimental days were excluded for each participant from the actigraphy analyses.

***Sleep variables.*** Epochs were designated as sleep episodes using a combination of sleep diaries and marked events (e.g. the onset of sleep opportunities). First, as noted above, time in bed (or rest) episodes were identified. If sleep diary entries or event markers were unavailable, the first three consecutive minutes of sleep were used to define sleep onset, and the last five consecutive minutes of sleep defined sleep offset for sleep episodes. Actiware's algorithm was applied to both nap and overnight rest intervals to calculate estimated sleep and wake epochs within these intervals. Epochs classified as wake within a rest interval contributed to sleep related metrics such as sleep onset latency and wake after sleep onset, and were not included in daytime wake behavior calculations. The data were then processed in SPSS (Version 25.0, IBM Corp., Armonk, NY). Only overnight periods with complete actigraphy data (i.e. "full" nights were defined as overnight rest intervals that had no excluded intervals, scored as such by the algorithm) were included in the present study. No participants had notable wake periods during the overnight intervals (i.e. two or more distinct overnight sleep bouts). Sleep variables included nap sleep duration (min), nap time in bed (min), nighttime sleep duration (min), nighttime time in bed (min), total (i.e. 24-hour) time in bed (min), total sleep duration (min), sleep mid-point (decimalized time of the mid-point between overnight sleep onset and wake onset), and nighttime SE (sleep duration divided by time in bed, expressed as a percentage).

***Daytime wake variables.*** Intervals identified as wake during the day were further processed to calculate SB and PA measures. Although a recent review of accelerometry measurement practices recommends 600 min of wake wear time [46], a large proportion of our sample napped for 60 to 120 min each day and, therefore, only days with a minimum wear time of 480 min were processed for SB and PA variables. Activity counts/min represented total activity, which was determined by summing the daytime interval activity counts divided by the waking wear time for that day. Daytime wake epochs were also classified into SB and PA intensity level categories using the Ekblom *et al.* [44] cut points (i.e. sedentary ≤ 79, light intensity PA = 80 to 261, MVPA ≥ 262). The wake behaviors in this study consisted of total activity (i.e. activity counts/min) and percent time in SB, in light PA, and in MVPA.

***Health and demographics questionnaires.*** Adult caregivers completed an in-house questionnaire that included assessments of child demographic information, health, and sleep behaviors, which was used to confirm eligibility criteria and characterize the sample (i.e. child's age, sex, socioeconomic status, race, and ethnicity). A composite socioeconomic score (range: 0 to 7, with a higher score indicating higher socioeconomic status) was calculated from caregiver-reported household income, employment status, and highest level of education [47]. Additionally, caregivers completed the Child Sleep Habits Questionnaire, which provided information regarding their child's habitual sleep, routines, and the presence of any sleep disturbance [48, 49].

***Other covariates.*** Date of birth, date of measurement, body weight, and height were used to calculate a body mass index (BMI) score, which was converted to percentile using the Center for Disease Control's calculations for children and then categorized accordingly (i.e. underweight ≤ 5th percentile, healthy = 5th to 84th percentile, overweight = 85th to 94th percentile, and obese = 95th percentile or greater) [50].

### Data analysis

To examine the temporal associations between daytime wake behaviors and overnight sleep measures, we used multilevel models with lagged effects in Stata (Version 16.0, StataCorp LLC, College Station, TX) and an autoregressive (1) error covariance structure. Two-level models were run to examine each daytime wake behavior-overnight sleep temporal association ($n$ = 24 models). Within-person variables (level-1) were centered at the person mean, and between-person variables (level-2) were centered at the sample mean for ease of interpretation. Given that, to our knowledge, this is the first temporal analysis of wake and sleep behaviors in early childhood and that many participants did not have consecutive wake and sleep measures for multiple days in a row, we opted to explore a lag of a single period in our models (i.e. how today's activity is related to tonight's sleep, and how tonight's sleep is related to tomorrow's activity).

First, we examined the temporal associations with daytime wake behaviors as the predictor variables and overnight sleep measures as the dependent variables. We fit 12 models to examine three overnight sleep outcomes (sleep duration, sleep mid-point, and SE) where each of the four wake behaviors (SB, light PA, MVPA, and total activity) were entered as predictors. In addition to the wake behaviors, we included day (between-person) daily nap duration (within-person, continuous), and the previous night's sleep outcome measure (within-person, continuous) as time variant predictors. In these models, daily wake behavior and nap duration measures temporally preceded daily overnight sleep measures (i.e. wake and nap measures were the lagged variables). All models were also adjusted for the following time invariant variables: age (between-person, continuous), sex (categorical), and socioeconomic status (between-person, continuous).

Next, we examined the temporal associations with overnight sleep measures as the predictor variables. We fit 12 models to examine four daytime wake behavior outcomes (SB, light PA, MVPA, and total activity) where each of the three overnight sleep measures were entered as predictors (sleep duration, sleep mid-point, and SE). In addition to the overnight sleep measures, we included day (between-person), daily nap duration (within-person, continuous), and the previous day's wake behavior outcome measure (within-person, continuous) as time variant predictors. In these models, daily overnight sleep measures temporally preceded the daily wake behavior and nap duration measures (i.e. sleep measures were the lagged variables). All models were also adjusted for the following time invariant variables: age (between-person, continuous), sex (categorical), and socioeconomic status (between-person, continuous).

Given that the within-person predictor variables were centered at the person mean, a positive coefficient value indicated a score that was greater than the individual's aggregated (i.e. cross-day) score. As the between-person predictor variables were centered at the sample mean, a positive coefficient value was indicative of a score that was higher than the aggregated mean of other participants. For interpretation purposes, we classified significant associations as "beneficial" if there were estimated increases in sleep duration, SE, or any PA measure, or decreases in SB or sleep mid-point. Significant associations in the opposite direction were described as "unfavorable." Finally, remaining nonsignificant associations were labeled as "neutral." Our initial significance threshold was set as $p < .05$. To account for multiple comparisons, we used a Bonferroni correction and divided this value by the number of outcomes ($k = 7$), setting the significance value at $p < .007$. Although three of our variables were slightly skewed (total activity, MVPA, and SE), log-transformations of these measures did not alter the diagnostics of the models and therefore these variables were kept non-transformed. Additionally, other linear mixed model assumptions (e.g. linearity, constant variance) were met.

## Results

### Descriptive statistics

A total of 287 children met the initial wear-time criteria for the current study. However, 45 children were missing at least one covariate measure and two did not have at least two consecutive wake-to-overnight or overnight-to-wake actigraphy measurement periods. As a result, data for 240 participants were included in the present analyses (Figure 1). Participants excluded due to missing covariate data did not differ in wake or sleep behaviors from those that had complete covariate data. Descriptive characteristics for the study sample are presented in Table 1. The sample was 49.2% female, the average socioeconomic status score was 4.5 ± 2.0 (from a 0 to 7 range), and the average BMI percentile was 63.3 (i.e. within the healthy weight status category). The majority of children were identified as White by their caregivers, and 27.4% were identified as Hispanic.

The average wear period for daytime wake behavior actigraphy measurement was 9.7 days (7.1 weekdays and 2.6 weekend days), with an average daily wear time of 722.4 ± 63.1 min. Participants spent approximately 42% of daytime wake in SB, 43% in light PA, and 15% in MVPA. The average daily activity counts/minute among participants was 564.8 ± 107. Participants napped an average of 5.4 days/week (4.6 on weekdays and 0.8 on weekends), with an average nap duration of 51.3 ± 35.9 min. The average number of nights of actigraphy-measured sleep was 9.0 nights (6.3 weekday nights and 2.7 weekend nights). At night, participants slept an average of 570.0 ± 41.0 min (i.e. 9.5 h), had a sleep mid-point of 2.2 ± 0.7 (i.e. approximately 2:10 am), and had a SE of 88.3 ± 3.5%. The large variability around the person mean-centered averages for wake and sleep measures may suggest that overall there was some inconsistency in behaviors between days within the children in this sample.

### Temporal associations of daytime wake behaviors predicting subsequent (same night) sleep

The multilevel mixed model coefficient estimates and associated standard errors are presented for the between- and within-person associations of daytime wake behaviors and sleep measures of the subsequent night in Table 2.

*SB*. There were no significant associations among between- or within-person SB and any of the overnight sleep measures.

***Light PA.*** There were no significant associations between light PA and any of the overnight sleep measures.

***Moderate-to-vigorous PA.*** Children that averaged greater time in MVPA during the day had lower SE on subsequent nights. Specifically, increasing MVPA during wake by 1% was associated with a .12% decrease in SE on subsequent nights (95% CI, −.2 to −.12). There were no significant associations between within-person MVPA and SE. Additionally, there were no significant associations between MVPA and sleep duration or mid-point.

*Total activity.* Participants with higher total activity during the day had lower SE on the following night but the within-person association was not significant for this sleep metric. Increasing total activity by one count/minute was associated with a .006% decrease in SE (95% CI, −.01 to −.002). There were no other significant associations for total PA.

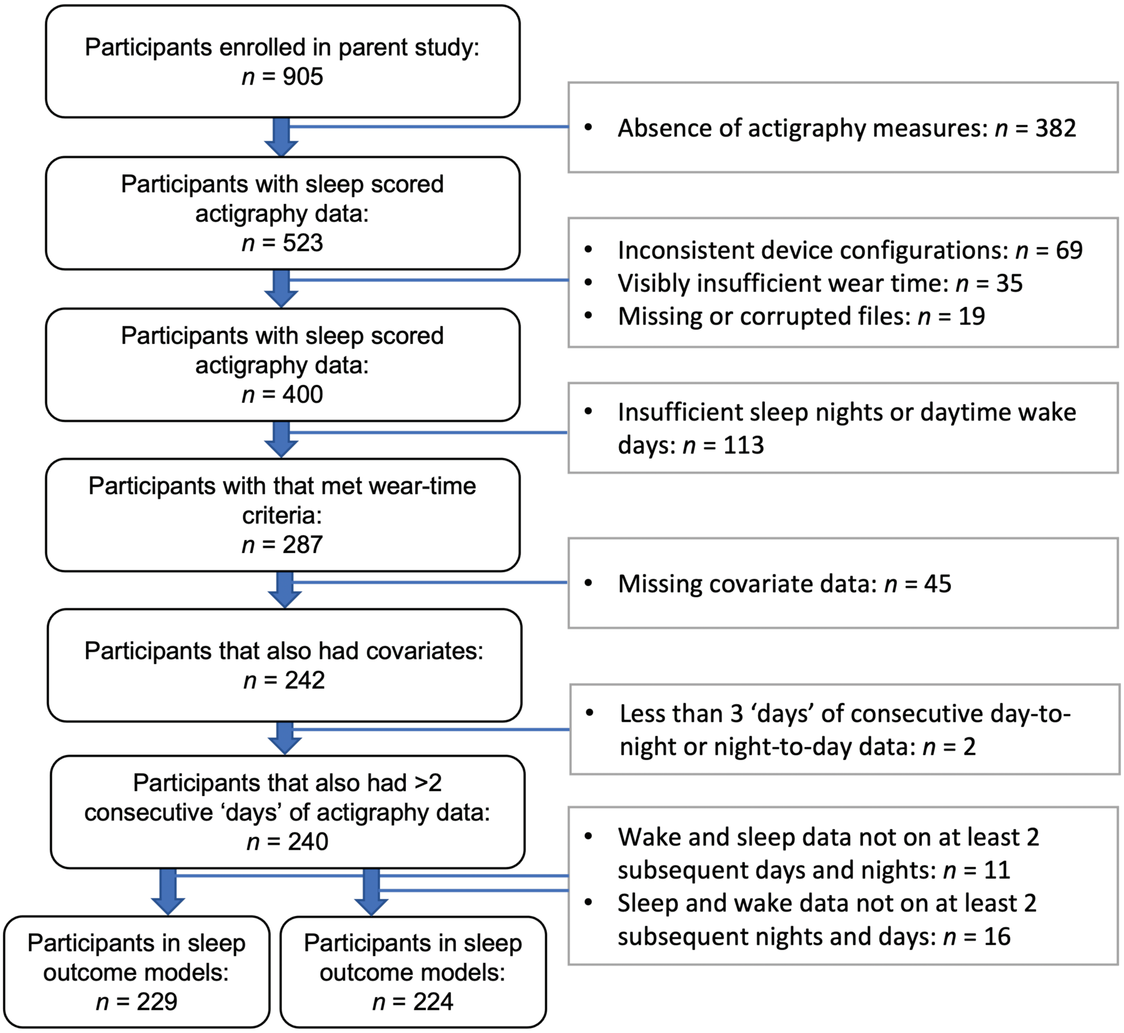

**Figure 1.** Participant flow diagram.

**Table 1.** Descriptive characteristics of the study sample ($n$ = 240)

| Variables | Mean (*SD*) or *n* (%) |
|---|---|
| *Sample characteristics* | |
| Age (months) | 50.8 (9.8) |
| Sex (female) | 118 (49.2) |
| Socioeconomic status (score, range = 0 to 7) | 4.5 (2.0) |
| Body mass index category | |
| Healthy | 152 (66.7) |
| Underweight | 15 (6.6) |
| Overweight | 32 (14.0) |
| Obese | 29 (12.7) |
| Race | |
| White | 155 (67.1) |
| Black/African American | 21 (9.1) |
| Asian | 10 (4.3) |
| Native Hawaiian/Pacific Islander | 2 (0.8) |
| Two or more racial groups | 26 (11.3) |
| Other | 17 (7.4) |
| Hispanic (yes) | 65 (27.4) |
| Nap duration (min) | 51.3 (35.8) |
| Nap duration (within-person mean centered) | −.00000016 (41.48) |
| *Overnight sleep measures* | |
| Sleep duration (minutes) | 570.0 (41.0) |
| Sleep duration (within-person mean centered) | −.00000069 (49.64) |
| Sleep mid-point (decimalized time) | 2.2 (0.7) |
| Sleep mid-point (within-person mean centered) | .0000000048 (0.52) |
| Sleep efficiency (%) | 88.3 (3.5) |
| Sleep efficiency (within-person mean centered) | −.0000000088 (4.27) |
| *Wake behavior measures* | |
| Sedentary behavior (%) | 41.9 (7.7) |
| Sedentary behavior (within-person mean centered) | −.00000013(7.93) |
| Light physical activity (%) | 42.8 (4.8) |
| Light physical activity (within-person mean centered) | .000000021 (5.42) |
| MVPA (%) | 15.3 (5.3) |
| MVPA (within-person mean centered) | .000000013 (4.20) |
| Total activity (activity counts/min) | 564.8 (107.0) |
| Total activity (within-person mean centered) | −.00000024 (95.07) |

Percentages of wake behaviors are expressed as percentage of device wear time.
MVPA, moderate- to vigorous-intensity physical activity.

### Temporal associations of sleep predicting subsequent (next day) daytime wake behaviors

The multilevel mixed model coefficient estimates and associated standard errors are presented for the between- and within-person associations of sleep measures and wake behaviors of the following day in Table 3.

*Sleep duration.* Children with longer sleep duration were more likely to participate in more light PAs on subsequent days. A one-minute increase in sleep duration was associated with a .02% increase in light PA (95% CI, .007 to .02). There were no other significant associations between sleep duration and daytime wake behaviors.

***Sleep mid-point.*** There were no significant temporal associations for between- or within-person sleep mid-point and any wake behaviors.

***SE.*** Children that had higher SE across nights were more likely to participate in less next day MVPA (95% CI: −.48 to −.15) and total activity (95% CI: −9.9 to −3.06). Specifically, a 1% increase in SE was associated with next day decreases of .31% and 6.5 counts/minute for MVPA and total activity, respectively. Conversely, when children obtained a higher SE relative to their individual average, this was positively associated with next day MVPA (95% CI, .16 to .51) and total activity (95% CI: 3.4 to 10.7). A 1% increase in SE was associated with an increased MVPA of .33% and an increase in total activity of 7.05 counts/minute. Additionally, when children obtained a higher SE compared to their personal average night, they were more likely to be less sedentary the next day. A 1% increase in SE was associated with a reduction in next day SB of .39% (95% CI: −.68 to −.11). A significant association was not observed for between-person SE and SB, and SE did not have any significant temporal associations with next day light PA.

### *Bidirectionality of temporal associations*

A summary of the temporal associations for all between- and within-person predictors are presented in Figure 2 (associations for between-person predictors are presented in panel a and within-person predictors are presented in panel B). An association was considered bidirectional if both temporal associations were significant for each overnight sleep and wake measure (e.g. if the wake behavior measure was significantly associated with a subsequent sleep measure, and if that same sleep measure was significantly associated with the same subsequent activity measure). The only bidirectional was for between-person associations with SE and total activity and considered unfavorable (i.e., children with higher SE were more likely to have less next day activity, and children with less total activity were more likely to have lower SE on subsequent nights).

## Discussion

The aim of this study was to understand the immediate and bidirectional effects of sleep on subsequent waking behaviors and waking behaviors on subsequent sleep. Our temporal analysis of daily repeated measures examined both between- and within-person behaviors. In addition to examining associations of average behaviors across participants, this allowed us to also explore associations between wake and sleep measures when participants differed from their own individual averages. Most wake behaviors (i.e. SB, MVPA, and total activity) were not predictive of the subsequent night's sleep. However, children with higher SE were more likely to participate in less overall activity and MVPA the next day. Across participants, overnight sleep duration and mid-point were generally not predictive of the next day's wake behaviors, although longer sleep duration was associated with more light PA. Unfavorable relations were observed for between-person SE with both next-day MVPA and total activity. Within-person predictors were not consistent with associations observed for the between-person predictors and presented some beneficial relations, although only for SE. When children had higher SE than their typical night, they were more likely to have increased time spent in MVPA and total activity and less time sedentary the following day. It is important to note that the effect sizes for the significant temporal associations

**Table 2.** Results from multilevel models of physical activity predicting subsequent sleep

| | Sleep duration | | Sleep mid-point | | Sleep efficiency | |
|---|---|---|---|---|---|---|
| | Coef. (*SE*) | *P* | Coef. (*SE*) | *P* | Coef. (*SE*) | *P* |
| *Sedentary behavior* | | | | | | |
| Intercept | 573.06 (2.3) | — | 2.2 (0.04) | — | 88.6 (.2) | — |
| Between-person | .02 (.31) | .953 | .0007 (.005) | .896 | .06 (.03) | .034 |
| Within-person | –.37 (.40) | .370 | –.0006 (.006) | .926 | –.03 (.03) | .474 |
| *Light physical activity* | | | | | | |
| Intercept | 573.23 (2.7) | — | 2.2 (0.04) | — | 88.6 (.2) | — |
| Between-person | 1.01 (.5) | .041 | –.02 (.009) | .079 | –.02 (.05) | .665 |
| Within-person | –.82 (.6) | .185 | .009 (.001) | .354 | –.03 (.06) | .604 |
| *Moderate- to-vigorous-physical activity* | | | | | | |
| Intercept | 572.73 (2.8) | — | 2.2 (0.04) | — | 88.6 (.2) | — |
| Between-person | –.97 (.4) | .028 | .01 (.008) | .165 | **–.12 (.04)** | **.004** |
| Within-person | 1.7 (.6) | .008 | –.002 (.009) | .820 | .09 (.06) | .113 |
| *Total activity* | | | | | | |
| Intercept | 572.8 (2.3) | — | 2.2 (0.04) | — | 88.6 (.21) | — |
| Between-person | –.04 (.02) | .104 | .0004 (.0004) | .381 | **–.006 (.002)** | **.003** |
| Within-person | .07 (.03) | .032 | –.00004 (.0005) | .932 | .004 (.003) | .185 |

Coefficient estimates (Coef.) and standard error (SE) of multilevel mixed models adjusted for daily nap duration, previous night of sleep outcome measure, age, sex, and socioeconomic status are presented for the between- and within-person associations of wake behaviors and sleep measures of the subsequent night. Statistically significant associations (*P* < .007) are noted in bold text.

**Table 3.** Results from multilevel models of nighttime sleep predicting next-day wake behaviors

| | Sedentary behavior | | Light physical activity | | Moderate-to-vigorous-physical activity | | Total activity | |
|---|---|---|---|---|---|---|---|---|
| | Coef. (*SE*) | *P* | Coef. (*SE*) | *P* | Coef. (*SE*) | *P* | Coef. (*SE*) | *P* |
| *Sleep duration* | | | | | | | | |
| Intercept | 42.2 (.45) | — | 42.5 (.27) | — | 15.2 (.3) | — | 563.26 (5.9) | — |
| Between-person | –.01 (.01) | .331 | **.02 (.008)** | **.004** | –.009 (.008) | .248 | –.14 (.2) | .397 |
| Within-person | –.006 (.01) | .643 | –.019 (.01) | .021 | .01 (.009) | .148 | .22(.2) | .202 |
| *Sleep mid-point* | | | | | | | | |
| Intercept | 42.3 (.5) | — | 42.4 (.31) | — | 15.2 (.3) | — | 562.2 (6.5) | — |
| Between-person | .55 (.75) | .461 | –1.0 (.5) | .025 | .47(.5) | .317 | 3.6 (9.7) | .713 |
| Within-person | –.24 (1.0) | .812 | .62 (.6) | .332 | –.32 (.6) | .604 | -4.7 (12.9) | .718 |
| *Sleep efficiency* | | | | | | | | |
| Intercept | 42.2 (.4) | — | 42.5 (.28) | — | 15.2 (.3) | — | 563.7 (5.8) | — |
| Between-person | .36 (.13) | .007 | –.04 (.09) | .633 | **–.31 (.09)** | **<.001** | **–6.5 (1.7)** | **<.001** |
| Within-person | **–.39 (.14)** | **.006** | .05 (.09) | .556 | **.33 (.09)** | **<.001** | **7.05 (1.9)** | **<.001** |

Coefficient estimates (Coef.) and standard error (SE) of multilevel mixed models adjusted for daily nap duration, previous day of wake behavior outcome measure, age, sex, and socioeconomic status are presented for the between- and within-person associations of sleep measures and wake behaviors of the following day. Statistically significant associations (*P* < .007) are noted in bold text.

were small and therefore may not reflect clinically meaningful changes in theses outcomes.

## Between-person wake behaviors predicting sleep outcomes

Overall, our results suggest that young children who engage in greater levels of PA during the day do not necessarily obtain longer sleep that night. Prior studies in older children have been mixed. One study in 8- to 10-year-old children reported null associations between SB and MVPA with subsequent sleep duration and unfavorable associations for light PA and subsequent sleep duration [32]. However, a recent study in preadolescents (mean age = 12.2 years) described unfavorable associations between in-school and after-school MVPA and subsequent sleep duration [51]. It is possible that prior discrepancies are due to methodological differences as some studies used wrist-based actigraphy, whereas others had devices placed on the hip.

The lack of significant associations for between-person wake behaviors with sleep duration in the present study may be related to a difference in potential pathways in children compared to adults, as well as the consideration that wake behaviors and sleep duration are constrained to a 24-hour period. A number of biological mechanisms have been proposed to describe how both acute bouts and chronic participation in PA can affect sleep factors in adolescents and adults (e.g. changes in body temperature, circadian phasing, immune function, metabolic factors, and mood) [15, 17, 52, 53]. Given that childhood is a time of substantial physiological development, some of the mechanisms that have been proposed in adults may not be relevant in children. However, it should be noted that the above mechanisms have been based on studies in adults with more diverse sleep health (e.g. greater ranges in sleep metrics, such as sleep

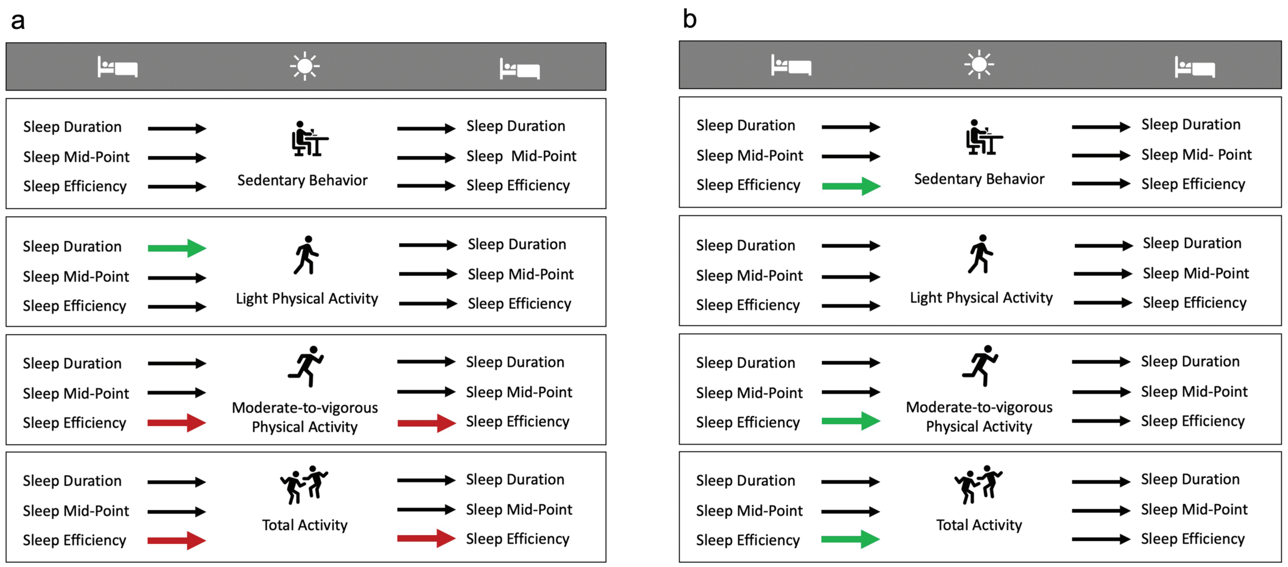

**Figure 2.** Summary of the temporal associations for (A) between- and (B) within-person daytime wake and overnight sleep measures. Arrows on the left side of each panel represent the temporal associations between sleep measures and next day wake behaviors. Arrows on the right side of each panel represent the temporal association between wake behaviors and subsequent sleep. Green arrows indicate a beneficial significant association and red arrows indicate an unfavorable significant association ($p < .007$). Black arrows represent a null (or neutral) association. Variables with two red or green arrows on the same row within the same panel represent a bidirectional relationship.

duration and efficiency, and inclusion of those with diagnosed sleep disorders) and variability in wake behavior patterns. Thus, wake behaviors may have less influence on sleep in our early childhood sample, given the health inclusion criteria and that sleep disturbances are less prevalent at this age. Additionally, the wake behaviors examined here (proportion of time spent in SB, light PA, and MVPA) and sleep duration make up a composition of behaviors for a 24-hour cycle. Therefore, they are co-dependent—meaning that an increase in one behavior will be at the expense of one or more of the remaining behaviors. Our null associations may not be surprising, particularly for SB, as along with sleep duration these two components consist of a large proportion of time.

Our hypotheses regarding between-person wake behaviors predicting sleep mid-point were not met. Sleep mid-point, which denotes the time at which a sleep bout occurs, can reflect both trait-like factors [54] and state-like factors, such as variations in weather [55]. Although temporal studies in older children have not included sleep mid-point, studies examining relations between wake behaviors and other sleep timing measures (e.g. bed and wake time) have reported some beneficial relations [28, 56]. It is possible that our findings differ from these other youth temporal studies because, relative to the preadolescent and adolescent participants in the other studies, our preschool population participates in daytime activities and routines that are guided by adult caregivers. The higher level of adult caregiver authority over both daytime routines and sleep schedules (i.e. consistent overnight bedtime and wake time schedules) in young children could potentially contribute to the overall lack of beneficial significant associations in the present study [57].

We observed significant, unfavorable associations for between-person MVPA and total PA with SE. These unexpected associations between wake behaviors and SE are in line with a study in preadolescents that found higher between-person MVPA was associated with more interrupted sleep the following night [28]. Our findings are also comparable with a recent study where compositional data analysis of 24-hour behaviors was used to examine relations and theoretical time reallocations on estimates of sleep quality in preschoolers [58]. Although temporal associations were not examined, when aggregated stationary time (i.e., SB) was theoretically increased by 30 min at the expense of MVPA, there was an estimated increase in SE rather than the expected decrease in SE. Although it is not clear why greater MVPA levels would be related to less SE, given that this type of activity increases sympathetic nervous system activity (e.g. increasing core temperature and adrenaline), which may not be conducive to sleep transitions, the timing of MVPA may be an important factor to consider [15]. It is possible that higher amounts of activity prior to bedtime could increase arousal in children, which may result in more fragmented sleep. However, Pesonen *et al.* [33] found that sleep measures did not differ with the timing of high MVPA (i.e. the day versus evening), yet high levels of MVPA did result in shortened sleep latency in preadolescents.

### Within-person wake behaviors predicting sleep outcomes

In the current study, children participating in more activity compared to their typical day was not predictive of sleep outcomes. Other studies examining sleep duration and SE have been mixed [28, 31, 33, 35]. Differences among findings could at least partially be attributed to variations in samples and methodology (e.g. types of accelerometers, monitor placement, and data processing). In the current study, increases in slow wave sleep or improvements in mood (which has been linked to better sleep duration and quality) following PA may contribute to increased sleep duration [15]. Such biological pathways have not been established in children and warrant further investigation.

While our within-person wake behavior and sleep mid-point associations were null, another study that considered sleep timing described that greater time spent in MVPA and total activity and less SB compared to one's average was associated with a later sleep onset and offset [28]. This difference, and our lack of significant findings, could perhaps be related to less daily variability in PA levels within individuals at this age. However, the hypothesis that young children have more consistent individual, day-to-day routines compared to older children or adolescents is something that could be further explored by examining within-person variability of wake behaviors longitudinally.

### Between-person sleep predicting wake behavior outcomes

Children with longer duration, an earlier sleep mid-point, or greater SE did not engage in less SB on succeeding days. Previous youth temporal studies have reported heterogenous between-person associations. For example, one study reported that 12-year-old students with higher SE spent less time sedentary after school the next day [51]. However, this study segmented out the day for wake behaviors, which may contribute to our different findings (in addition to the different ages of the two samples). Furthermore, it is possible that time spent sedentary may not be as sensitive to beneficial influences of sleep at this young age. Specifically, SBs in young children are largely influenced by environmental factors, such as access to screen time and opportunities to be physically active [59].

In the present study, only sleep duration was significantly associated (beneficially) with the next day's level of light PA. While light PA has not often been considered in temporal analysis studies in children, one other study found that sleep duration predicted a decrease in the next day's level of light PA [32]. The positive association with light PA observed in the present study could be related to less daytime sleepiness in children receiving sufficient sleep, which in turn could result in having sufficient energy and alertness for greater general body movements of lower intensities throughout the day.

Our finding that children with greater average SE participated in less MVPA and total activity on subsequent days is in contrast with other youth temporal studies [28, 30, 34, 51]. Although it is unexpected that higher SE would be related to lower MVPA and total activity and that sleep duration or timing would not be associated with greater activity levels, it is possible that, as previously proposed, some daytime behaviors may generally be less sensitive to sleep influences at this age, given that they are largely influenced by the environmental factors.

### Within-person sleep predicting wake behavior outcomes

While the literature in children has again been mixed for temporal within-person associations for wake behavior outcomes, here we observed that when young children had higher SE relative to their typical individual night, this was beneficially associated with most wake measures. Consistent with one of our hypotheses, when children achieved higher SE than their typical individual night, they were more likely to participate in less SB, more MVPA, and more total activity the next day. The MVPA finding appears to be novel in comparison to other similar studies [34, 35]. It is possible that high SE the previous night could lead to greater activity the next day because the child is more rested and therefore has less daytime sleepiness, and positive benefits of sleep quality on affect could translate to an increased willingness or motivation to engage in more movement.

Our hypothesis that achieving better sleep would decrease sedentary time and increase time spent in light intensity PA the next day was based on explanations proposed in adults. Specifically, improvements in sleep quality could aid in supporting higher activity levels (which would in turn reduce time spent sedentary) as a result of greater alertness, less sleepiness, improvements in mood, lower perceived level of exertion, and better heat tolerance [15]. Although such factors could serve as potential mechanisms in children, the current study does not support these relations and further research may be warranted.

### Strength and limitations

Some important strengths of this study include the use of objective (i.e. device-based) measurements of sleep and wake behaviors, the large sample size, and the inclusion of daytime sleep in our models. However, some limitations should be considered. First, our data stemmed from a parent study that included two experimental days and although data was excluded for the 24-hour period following each of those conditions, behaviors could have theoretically had an influence on subsequent behaviors beyond that. However, these two conditions (nap-promotion and wake-promotion) are not unusual behaviors for this age group, and we do not anticipate that there was a lagged effect beyond 24 h. Although we examined bidirectionality, a traditional longitudinal design or chronic experimental study could more accurately explore such effects. Additionally, we only examined the lagged effect of half of a 24-hour cycle, and it is possible that effects of wake or sleep behaviors may carry over or become evident after longer periods. As with any observational study, there is always the risk of residual confounding and some unmeasured factors (e.g. environmental and genetic) could influence both wake and sleep measures. Our use of beneficial and unfavorable classifications may in some cases be an oversimplification of the observed associations, particularly as each behavior occurs within a finite period of time (i.e. 24 h). Finally, although sleep measures of the current sample are comparable, PA levels were slightly higher than observed in other North American early childhood studies [60, 61]. Such differences may be related to our inclusion criteria (i.e. healthy sleepers without diagnosed sleep or developmental disorders) as well as differences in the type of accelerometer, and therefore our generalizability may be limited.

## Conclusions

These findings demonstrate some evidence of temporal associations between wake behaviors and sleep measures in early childhood, although the bidirectional nature was not supported. Generally, days with higher levels of activity or sleep were not associated with greater subsequent sleep or PA, and some beneficial associations were observed for wake behaviors when participants obtained greater SE compared to their individual average. However, most of these associations were null and effect sizes were generally small. The difference in inter-versus intraindividual relations that we observed suggests that future analyses with young children should consider within-person associations in addition to the commonly used method of examining aggregated behaviors between participants. Other potential future directions may include investigating lagged effects beyond 1 day as some recent papers in older children have begun [51], engaging more advanced analysis methods, such as dynamic structural equation models with 24-hour behaviors [62], examining the timing of PA intensity bouts, and utilizing a more diverse sample of young children to include those diagnosed with developmental or sleep disorders.

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