Int. J. Sport Psychol., 2022; 53: 475-496
doi: 10.7352/IJSP.2022.53.475

# Temporal and bidirectional associations between physical activity and sleep in adolescents

DANIEL FERNÁNDEZ-ARGÜELLES, J.A. CECCHINI ESTRADA, J. FERNANDEZ-RÍO

*University of Oviedo. Oviedo, Principado de Asturias, Spain*

*The purpose of this study was to assess the temporal day-to-day associations between physical activity and sleep in adolescents during a complete week. A total of 236 secondary education students (127 males, 109 females), age range 13-15 years, enrolled in 10 different high schools agreed to participate. They were asked to wear a GT3x accelerometer and complete a diary for a full week (24 hours / seven days). Participants' Body Mass Index and socio-economic status were assessed. Multilevel models were used to test the associations of nighttime sleep (onset, offset, duration and efficiency) and wakefulness movement variables (MVPA, sedentary behavior). MVPA was a significant predictor of sleep duration (B = .004, p < .01) and sleep offset (B = .006, p <.001). Adolescents who were more sedentary during the day fell asleep later (B = .005, p < .001) and woke up later (B = .002, p < .01). Sedentary behavior during the day was inversely related to sleep duration that night (B = -.003, p < .01). Sleep offset was inversely related to MVPA (B = -.064, p < .01) and sedentary behavior (B = -.120, p < .01). Sleep duration was inversely associated with MVPA (B = -.27, p < .05) and sedentary behavior (B = -.41 p < .01) the following day. It seems physical activity could improve adolescents' sleep, while sedentary time could have a negative impact on it. The predictive role of sleep in physical activity is even less conclusive, indicating that the physiological relationship could be influenced by other factors such as time conflicts between individuals' daily activities. More research in this field is needed.*

KEY WORDS: Physical activity; Sedentary behavior; Sleep; Accelerometer; Adolescents; Multilevel analysis.

## Introduction

Physical activity and sleep are both vital factors during adolescence. Among other benefits, they have been related with improvements in body composition, metabolic, skeletal, psychological and cognitive health, as well

---

*Correspondence to: Daniel Fernández Argüelles, Faculty of Teacher Training and Education, Aniceto Sela street, 3305, Asturias, Spain (e-mail: d.fdez.arg@gmail.com)*

as a cardiovascular risk reduction (Cappuccio, D'Elia, Strazzullo & Miller, 2010; Poitras et al., 2016).

Current World Health Organization guidelines for children and adolescents recommend at least 60 minutes of moderate-to-vigorous physical activity (MVPA) per day, considering that more MVPA time results in additional health benefits (World Health Organization, 2020). Moreover, adolescents should practice vigorous aerobic activities and strength exercises at least three times a week. Unfortunately, although there are differences between countries, a large number of adolescents (81%) do not meet these minimum recommendations (Guthold, Stevens, Riley & Bull, 2020).

Sleep is another relevant aspect in adolescents' health. Thus, sleep quality and duration has been related to health variables such as body fat, emotional state and cognitive ability (Fatima, Doi & Mamun, 2015; Shochat, Cohen-Zion & Tzischinsky, 2014). According to the National Sleep Foundation, to avoid possible health risks, adolescents should accumulate between 8 and 10 hours of sleep per night (National Sleep Foundation, 2021). With the beginning of adolescence, a decrease in sleep duration and quality normally occurs due to intrinsic physiological factors that delay the circadian timing, which leads to an increased eveningness preference and sleep-stages modification (Moore & Meltzer, 2008). Furthermore, is necessary to consider other extrinsic factors such as excessive screen time, increased requirements in the academic load at the school, early class time and extracurricular activities (Bartel, Gradisar & Williamson, 2015). Thus, international studies indicate that millions of adolescents have poor sleep, with the resulting damage to their health (Gradisar, Gardner & Dohnt, 2011).

Traditionally, among other treatments, sleep experts have prescribed physical activity to improve nighttime sleep, for instance to reduce insomnia symptoms (Moore & Meltzer, 2008). Several hypotheses have tried to explain how physical activity improves sleep. First, physiological processes (e.g., better thermoregulation) would promote an easier sleep onset, an earlier circadian phase and an increase in the slow-wave stage of sleep (Brand et al., 2010a; Youngstedt, 2005). Second, physical activity seems to have psychological benefits such as the reduction of depression and anxiety, and improvements in self-steem and well-being (Biddle, Ciaccioni, Thomas & Vergeer, 2019; McMahon et al., 2017). Hence, an adolescent who have practiced physical activity, would experience a subjective sensation of well-being, which would promote a better sleep; this would result in a shorter sleep onset and the feeling of having rested better. In other words, physical activity impact in sleep would have a psychological explanation. Third and last, according to the time displacement concept in sociology, sleep and physical activity are framed within a 24 hours schedule full of demands (e.g., academics, social, family), which force adolescents to make decisions about the time to invest in each one, based on their personal priorities (Sharif, Wills & Sargent, 2010). Considering this hypothesis, adolescents may prefer to spend their time in social popular activities like playing video games, using their mobile phone or having a drink with their friends rather than doing physical activity or sleep.

Regarding sleep-physical activity directionality, the main hypothesis is based in the restorative capacity that sleep has on the body (Kline, 2014). Therefore, a subject who has slept in sufficient quantity and quality would feel more rested and potentially prepared to move more the next day.

Previous research has tried to clarify the relationships between physical activity and sleep. Unfortunately, most existing studies are cross-sectional and use questionnaires to assess them. In recent years, several systematic reviews have been published on this topic. Antczak et al. (2020) found in children a weak association between vigorous physical activity and sleep. Another review in university students concluded that physical activity was associated with better sleep quality but less sleep duration (Memon et al., 2021). Lastly, another review in adolescents seem to indicate that physical activity, regardless if it is measured by objective or subjective methods, has a positive effect on subjective and objective sleep (Lang et al., 2016). In all these reviews, authors encourage further research with objective measures due to the lack of studies on this regard. Recent researches with temporal day-to-day designs with accelerometers have found the positive effect of physical activity on sleep (Lin et al., 2018, Master et al, 2019). Furthermore, experimental studies also support a causal relationship. For instance, an intervention carried out in adolescents for 3 weeks in a row running for 30 minutes in the morning every day significantly improved sleep subjectively and objectively (electroencephalogram recordings) (Kalak et al., 2012). Nevertheless, there are studies that have not found the physical activity positive effect on sleep (Kim, Umeda, Lochbaum & Sloan, 2020; Knebel et al., 2020).

Regarding the predictive role of sleep in physical activity, research is also scarce and the results contradictory. For instance, considering studies that have used objective measures: Mead, Baron, Sorby and Irish (2019) found that a healthier sleep was associated with less physical activity levels the next day, using Fitbit. On the contrary, Verloigne, Van Oeckel, Brondeel and Poppe (2021) found that a longer sleep was associated with more movement during the following day. A recent systematic review with meta-analysis in children and adolescents concluded that more sleep duration improved physical activity and decreased sedentary behavior the next day (Huang, Ho, Tremblay & Wong, 2021). Lastly, another recent systematic review did not find any association between sleep and physical activity, although it was conducted in university students (Memon et al., 2021).

It should be borne in mind that most of the previous studies only considered MVPA, since in the present study we added sedentary behavior. Similarly, we we have considered as sleep variable not only sleep duration (e.g., sleep onset, sleep efficiency). Moreover, it is necessary to consider that studies with 24 hours actigraphy with temporal analysis in this field are still scarce. Finally, like few studies before, we included within- and between-person analysis in the statistical models. This allowed us knowing the day-to-day changes (temporal relationship) of each subject in their physical activity and sleep parameters as well as at the entire sample level.

Taking into account the aforementioned, the main objective of this research was to assess the temporal day-to-day associations between wakefulness movement variables (MVPA, sedentary behavior) and sleep (onset, offset, duration, efficiency) in adolescents using accelerometers during a complete week.

## Materials and Methods

### Study Design

A simple (one group), micro-longitudinal, ex post facto research design was used to study the bidirectional relationships between physical activity and sedentary behavior in relation to sleep for a week. Physical activity and sedentary behavior during the day were examined in relation to sleep quality and quantity during the following night. Then, these sleep variables and their relation to physical activity and sedentary behavior the following day were also examined.

The study followed the principles of the Declaration of Helsinki (World Medical Association, 2013), and it was approved by the researchers' State Research Ethics Committee (135/18). The whole project was explained to both families and students, and parents/tutors signed an informed written consent prior to enter the study. Complete confidentiality and anonymity was granted. Finally, they were informed that participation was voluntary and that they could leave the study at any time.

### Participants

A total of 249 Secondary Education students, age range 13-15 years, enrolled in 10 different high schools in a northern Spain city agreed to participate. Non-probabilistic, convenience and volunteer sampling was used (Peat, Mellis, Williams & Xuan, 2020). Finally, 236 students (127 males, 109 females), age range 12-15 years (M = 13.28, SD = .55), provided valid data. Table 1 shows the participants' sociodemographic and personal characteristics.

TABLE I
*Participant's characteristics and descriptive statistic*

| | Frequency | Percentage |
|---|---|---|
| **Gender** | | |
| Males | 127 | 53.8 |
| Females | 109 | 46.2 |
| **Age** | | |
| 12 | 5 | 2.1 |
| 13 | 167 | 70.8 |
| 14 | 57 | 24.2 |
| 15 | 7 | 3.0 |
| **BMI** | | |
| Underweight | 11 | 4.7 |
| Normal weight | 144 | 61.1 |
| Overweight | 61 | 25.6 |
| Obesity | 21 | 8.8 |
| **Socioeconomic status** | | |
| Low | 57 | 24.2 |
| Medium | 114 | 48.3 |
| High | 65 | 27.5 |
| *Actigraphy variables* | | |
| Sleep onset (time, hrs:min) | 11:18 PM (1:09) | |
| Sleep offset (time, hrs:min) | 7:42 AM (1:17) | |
| Sleep duration (min) | 472.33 (74.11) | |
| Sleep efficiency (percentage) | 91.27% (3.57%) | |
| MVPA (min) | 58.17 (29.88) | |
| Sedentaiy behavior (min) | 610.93 (83.91) | |

## MEASURES

### *Actigraphy measures*

Participants wore ActiGraph GT3x accelerometers (ActiGraph™, Fort Walton Beach, FL, USA) on the waist along 7 complete days, except on water activities (bathing, swimming) but they were asked to move them to the wrist of their non-dominant hand during sleep at night. Adolescents were instructed on how to handle the accelerometer and how to complete a diary in which they recorded the times they turned off the lights to go to sleep at night, the times they woke up and the times they had removed the accelerometer. Data were collected at a sampling rate of 30 Hz with the standard frequency extension and downloaded in 1-s epochs. Actigraphy data analysis was conducted with Actilife v.6. (ActiGraph, Pensacola, FL, USA).

Regarding sleep data, it was re-integrated in 60-s epoch and scored using Sadeh's algorithm (Sadeh, Sharkey & Carskadon, 1994). Accelerometers has showed good correlations with the gold standard measure for sleep: polysomnography (Full et al., 2018). Sleep onset and offset were selected by two blinded scorers based on visual inspection (Beltran-Valls et al., 2019). Diary's data was used (when it was provided by the participants) to help identify and confirm sleep onset and offset. Sleep duration was calculated as the main sleep between sleep onset and offset, and sleep efficiency was calculated as the percentage of time asleep (total time in bed divided by sleep duration) (Full et al., 2018). A valid sleep night required ≥160 min of sleep duration. Only subjects with ≥3 nights, including at least one during the weekend, were included in the sample (Kracht et al., 2020).

Regarding physical activity data, sleep night and non-wear time were excluded from the analysis using Actilife v.6. (ActiGraph, Pensacola, FL, USA). Choi's algorithm (Choi, Liu, Matthews & Buchowski, 2011) and diary information was used to exclude non-wear time. This procedure guaranteed that physical activity and sedentary behavior were obtained from awake and wear time only. Physical activity data was categorized in MVPA and sedentary time with Evenson's cut points (Evenson, Catellier, Gill, Ondrak & McMurray, 2008), which have shown to be a valid and reliable measure in youth (Trost, Loprinzi, Moore & Pfeiffer, 2011). To be included in the analyses, participants were required to wear the accelerometer for ≥10 hours per day and have at least ≥4 valid days (one of them on weekends) (Colley, Gorber & Tremblay, 2010).

## *Anthropometry*

Participants' anthropometric measures were obtained during the physical education class, following recommendations of The International Society for the Advancement of Kinanthropometry (Marfell-Jones, Stewart & de Ridder, 2012). To assess participants' weight (kg), a digital professional *Tanita RD-545* (Tanita Corporation, Tokyo, Japan) was used. It has a precision of 50 gm between 0-100 kg, and 100 gm between 100-200 kg. To assess participants' height, a portable stadiometer *SECA 213* (SECA Ltd., Hamburg, Germany) with a ± 1 mm precision was used (range 20-205 cm). Duplicate measurements were taken and when there was a discrepancy over .5 cm or .5 kg, a third measurement was taken; then, the closest two were averaged. BMI was calculated based on the weight (kg)/height$^2$ (m) formula (Garrow & Webster, 1985). The cut-off points were those established by the IOTF (Cole & Lobstein, 2012).

## *Socioeconomic Status (SES)*

It was assessed using the Family Affluence Scale II-revised, developed in the Health Behaviour in School-Aged Children study (HBSC) (Currie et al., 2014). It includes six simple questions: car, van or truck ownership (No = 0; One = 1; Two or more = 3), having one's own bedroom (No = 0; Yes = 1), number of computers, including laptops and tables, but no video game consoles and smartphones (None = 0; One = 1; Two = 2; Three or more = 3), family holidays abroad in the past year (Never = 0; Once = 1; Twice = 2; Three or more times = 3).

Dishwater ownership (No = 0; Yes = 1) and number of bathrooms, considering this as a room with bath/shower or both (None = 0; One = 1; Two = 2; Three or more =3). Participants' scores were added and results were categorized in three levels: low = 0-6; medium = 7-9; high = 10-13. The questionnaire has been validated in different European countries (Torsheim et al., 2016).

### Statistical Analyses

Multilevel models of repeated measures with two levels were used: the level 1 model with repeated measures at different time points (over a week) allowed to assess changes within-participants, whereas level 2 model allowed to assess differences between-participants. These analyses helped to assess the temporal associations between physical activity and sedentary behavior in relation to nighttime sleep variables. Moreover, the two-level data, within and between-participants, allowed the construction of models that grouped daily sleep observations in relation with next day physical activity and sedentary behavior and vice versa.

A first-order autoregressive error covariance structure was used in the models to prevent correlations of consecutive sleep and physical activity measures to be stronger than non-consecutive measures. Several sleep variables (sleep onset, sleep offset, sleep duration and sleep efficiency) were used to wakefulness movement variables (MVPA and sedentary behavior). The opposite procedure was also conducted: MVPA and sedentary behavior were used as sleep variables predictors.

Within-person variables focused on the person's mean, so positive values indicated higher scores than the person´s average. Regarding between-person variables, they focused on the sample means, so positive values indicated higher scores than other sample subjects.

Covariates were included in all models (gender, age, BMI and SES). Restricted cubic spline were adjusted to assess the linearity of the relationship between night sleep and physical activity. Three striations were generated using knots at the 20th, 40th, 60th, and 80th percentiles to produce a smooth fitted curve.

## Results

### Descriptive Results

Table I describes the participant›s basic characteristics. Approximately half (46.2%) were girls. Most were 13 years old. More than half had normal weight (61.1%). Regarding the sleep variables, sleep onset was at 11:18 pm, sleep offset at 7:42 am, sleep duration was 472.33 minutes (7:52, hours:minutes), and sleep efficiency was 91.3%. During daytime, adolescents averaged of 58.17 minutes in MVPA and 610.93 minutes in sedentary behavior. Half of the participants showed a medium SES, one quarter high SES and the other quarter low SES.

## Daytime Physical Activity As a Predictor of Subsequent Night Sleep

Table II shows the results of a series of multilevel models that examined the associations of daytime MVPA and sedentary behavior with nighttime sleep variables.

*MVPA.* Physical activity within-person and between-person was not significantly associated with sleep onset. Within-person: MVPA was a significant predictor of sleep offset (B = .006, $p < .001$) and sleep duration (B = .004, $p < .01$). In days with more MVPA minutes than their individual average, the adolescents got up later and slept more those nights. An increase on

Table II
*Multilevel models analyzing daytime MVPA and sedentary behavior as predictors of night sleep variables*

| | **Sleep onset** | | **Sleep offset** | | **Sleep duration (min)** | | **Sleep efficiency (%)** | |
|---|---|---|---|---|---|---|---|---|
| Parameter | B | SE | B | SE | B | SE | B | SE |
| Intercept | 3.68 | 1.31 | 5.85 | .97 | 9.21 | 1.22 | 91.25 | 2.70 |
| Gender | .16 | .09 | .14 | .07 | -.01 | .09 | .14 | .20 |
| Age | .05 | .10 | .07 | .07 | .08 | .09 | .62** | .20 |
| BMI | .12 | .07 | -04 | .05 | -.20 | .06 | -.56*** | .14 |
| SES | .15 | .06 | .05 | .05 | -.09 | .06 | -03 | .14 |
| Daytime MVPA minutes (within-person) | .001 | .00 | .006*** | .00 | .004** | .00 | -.001 | .00 |
| Daytime MVPA minutes (between-person) | .003 | .00 | -.001 | .00 | -.005* | .00 | .017** | .00 |
| | **Sleep onset** | | **Sleep offset** | | **Sleep duration (min)** | | **Sleep efficiency (%)** | |
| Parameter | B | SE | B | SE | B | SE | B | SE |
| Intercept | -5.79 | 1.25 | 5.18 | 1.07 | 10.29 | 1.08 | 93.53 | 2.80 |
| Gender | -.15 | .09 | .11 | .08 | .28** | .08 | .63** | .20 |
| Age | .13 | .09 | .19* | .07 | .08 | .07 | .06 | .20 |
| BMI | .13* | .06 | -.07 | .05 | -.23*** | .05 | -.49** | .14 |
| SES | .09 | .06 | .04 | .05 | -.017 | .05 | -.04 | .14 |
| Daytime sedentary minutes (within-person) | .005*** | .00 | .002*** | .00 | -.003*** | .00 | .0005 | .00 |
| Daytime sedentary minutes (between-person) | .005*** | .00 | .0004 | .00 | -.004*** | .00 | .002 | .00 |

The results were adjusted for covariates. Analysis included within and between-person level. BMI=Body Mass Index, SES=Socioeconomic Status, MVPA=Moderate to Vigorous Physical Activity. *p<.05, **p<.01, ***p<.00

an hour per day of MVPA was associated with an additional 14 minutes of sleep duration. MVPA within-person was not a significant predictor of sleep efficiency. Between-person: those who participated in more MVPA showed shorter sleep duration and decreased sleep efficiency.

Figure 1 shows the results of the restricted cubic splines. An increasing slope in the association between daytime MVPA and sleep offset can be observed. It begins to be significant after 100 minutes of daily MVPA (OR = 1.45, 95% CI = 1.07, 1.97), and continues to grow until 180 minutes of daily MVPA (OR = 2.29, 95% CI = 1.37, 3.82).

*Sedentary behavior.* Within-person: adolescents who were more sedentary during the day fell asleep later (B = .005, $p < .01$) and woke up later (B = .002, $p < .01$). An additional sedentary hour over their average during the day meant a delayed sleep onset (18 min) and sleep offset (7 min). Furthermore, sedentary behavior during the day was inversely related to sleep duration that night (B = -.003, $p < .01$). This means that on the days when adolescents were more sedentary than their average, they slept less that night. Specifically, an additional hour in sedentary behavior was associated with an 11-min sleep duration reduction. Lastly, there was no relationship between sedentary behavior and sleep efficiency. Between-person: There was an emp-

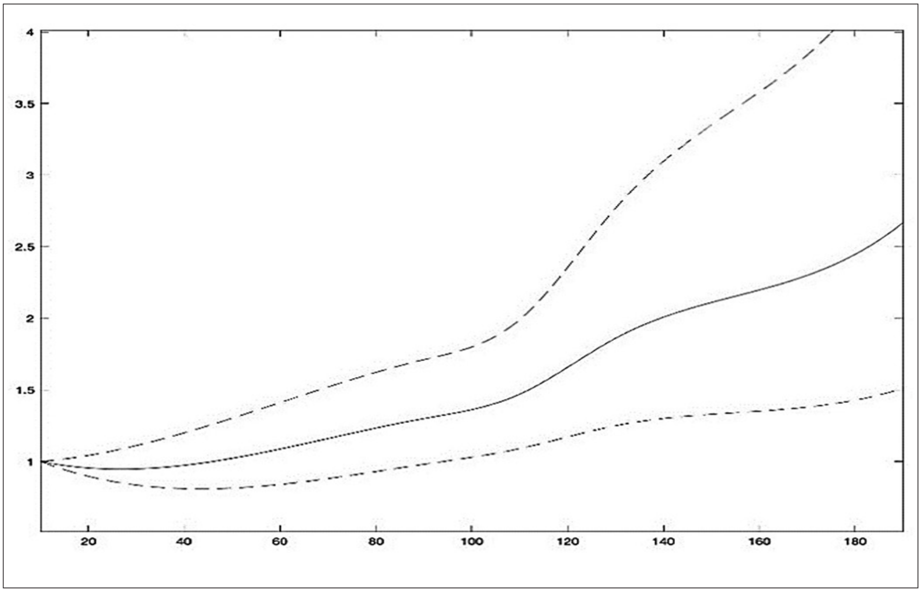


Fig. 1. - MVPA minutes were modeled by restricted cubic splines using a mixed linear repeated measures model, adjusted for age, sex, BMI, SES, and MVPA.

ty space here. Now it is all right. sedentary behavior in relation to sleep onset and sleep duration. Those who spent more time in sedentary behavior than the sample mean had a later sleep onset (B = .005, $p < .01$) and shorter sleep duration (B = -.004, $p < .01$).

Figure 2 shows how sedentary daily hours were inversely associated to sleep duration. There is a significant slope until 11 hours of daily sedentary behavior (OR = .46, 95% CI = .36, .58) that flattens between 11 and 12 hours, and falls again until 14 hours (OR = .22, 95% CI = .17, .29).

## Nighttime Sleep As a Predictor of Physical Activity The Following Day

Table III shows the results of a series of multilevel models that examined the associations of nighttime sleep variables with daytime MVPA and sedentary behavior.

*Sleep onset*. Within-person: sleep onset was inversely related to MVPA (B = -.067, $p < .01$), which means that if the adolescent began to sleep earlier than his/her average; more MVPA was performed the next day and vice versa. Those days when the adolescents began to sleep later, they increased their sedentary behavior the next day (B = .41, $p < .01$). Between-person: there

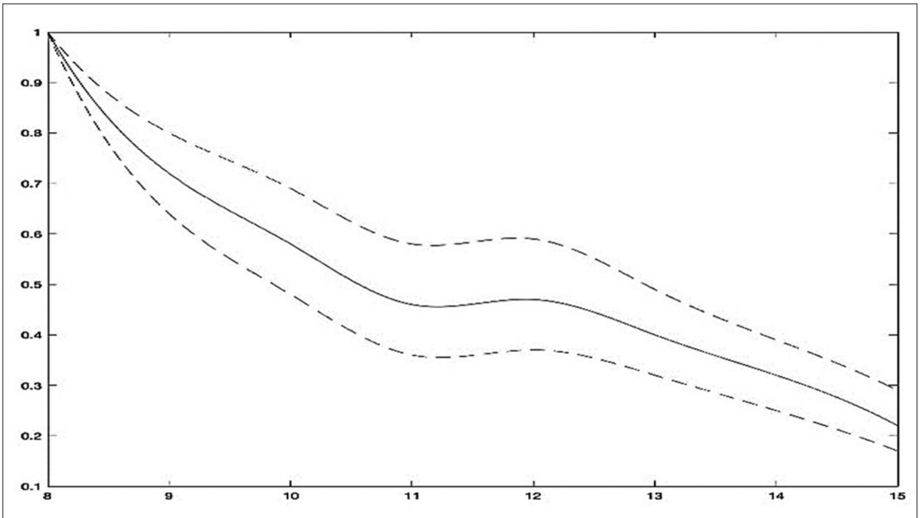


Fig. 2. - Sedentary behavior were modeled by restricted cubic splines using a mixed linear repeated measures model, adjusted for age, gender, BMI, SES, and sedentary behavior.

TABLE III
*Multilevel models analyzing sleep variables predictors of MVPA and sedentary behavior.*

| | MVPA(min) | | Sedentary behavior (min) | |
|---|---|---|---|---|
| | B | SE | B | SE |
| Intercept | 37.34 | 34.64 | 642.39 | 119.95 |
| Gender | -7.87** | 2.59 | 18.00* | 8.98 |
| Age | 3.07 | 2.57 | 4.54 | 8.91 |
| BMI | -2.18 | 1.85 | -8.88 | 6.42 |
| SES | -.89 | I.80 | 7.30 | 6.24 |
| Sleep onset (within-person) | -.067*** | .01 | .41*** | .04 |
| Sleep onset (between-person) | .012 | .02 | .84*** | .10 |
| | MVPA(min) | | Sedentary behavior (min) | |
| | B | SE | B | SE |
| Intercept | 49.24 | 37.15 | 501.40 | 148.00 |
| Gender | -7.80** | 2.60 | 16.50 | 10.38 |
| Age | 3.72 | 2.58 | 10.85 | 10.31 |
| BMI | -2.27 | 1.85 | -2.38 | 7.37 |
| SES | -.67 | 1.79 | 14.07 | 7.15 |
| Sleep offset (within-person) | -.064*** | .01 | -.120*** | .03 |
| Sleep offset (between-person) | -.044 | .03 | .003 | .15 |
| | MVPA (min) | | Sedentary behavior (min) | |
| | B | SE | B | SE |
| Intercept | 57.93 | 37.15 | 1009.57 | 128.10 |
| Gender | -7.61** | 2.60 | 26.42** | 8.83 |
| Age | 3.38 | 2.58 | 12.19 | 8.66 |
| BMI | -2.78 | 1.85 | -15.25* | 6.38 |
| SES | -.95 | 1.79 | 10.56 | 6.05 |
| Sleep duration (within-person) | -.027* | .01 | -.414*** | .03 |
| Sleep duration (between-person) | -.021 | .03 | -.595*** | .11 |
| | MVPA (min) | | Sedentary behavior (min) | |
| | B | SE | B | SE |
| Intercept | 267.62 | 84.31 | -48.62 | 341.11 |
| Gender | -6.49* | 2.59 | 12.81 | 10.49 |
| Age | 3.52 | 2.51 | 10.28 | 10.16 |
| BMI | -3.51 | 1.86 | .60 | 7.53 |
| SES | -.85 | 1.75 | 14.33* | 7.09 |
| Sleep efficiency (within-person) | -.54 | .40 | 1.64 | 1.31 |
| Sleep efficiency (between-person) | 1.91* | .90 | 4.19 | 3.52 |

The results were adjusted for covariates. Analysis included within and between-person level.
BMI = Body Mass Index; SES = Socioeconomic Status; **p<.05*; ***p<.01*; ****p<001.*

were no significant associations between sleep onset and MVPA. Nevertheless, the associations were significant and in the same direction for sedentary behavior, meaning that adolescents who had a later sleep onset than others spent more time in sedentary behavior (B = .84, *p < .01*)

Figure 3 shows how sleep onset minutes at the within-person level (measured every half hour) were inversely associated to the following day MVPA. There is a progressive slope up to minute 270 from the sleep onset (OR = .73, 95% CI = .63, .86) with a greater fall between 270 and 300 minutes.

Figure 4 shows how the within-person minutes of nighttime sleep onset (measured every half hour) were positively associated to sedentary behavior the next day. There is a growth curve that is significant after 150 minutes from the sleep onset (OR = 1.87, 95% CI = 1.34, 2.62), and it continues to grow until 300 minutes from the sleep onset (OR = 6.86, 95% CI = 4.16, 11.30).

*Sleep offset*. Within-person: a later sleep offset than the individual´s average resulted in less MVPA (B = -.064, *p < .01*) and less sedentary behavior the following day (B = -.120, *p < .01*). Between-person: sleep offset was not significantly associated with MVPA or sedentary behavior.

Figure 5 shows how sleep offset minutes at the within-person level (measured every half hour) were inversely associated to the following day MVPA.

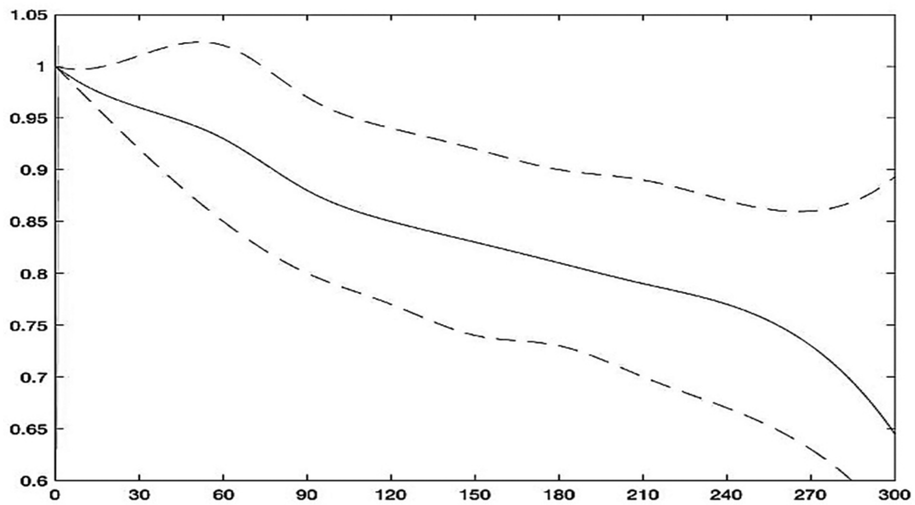


Fig. 3. - Sleep onset were modeled by restricted cubic splines using a mixed linear repeated measures model, adjusted for age, gender, BMI, SES, and sleep onset.

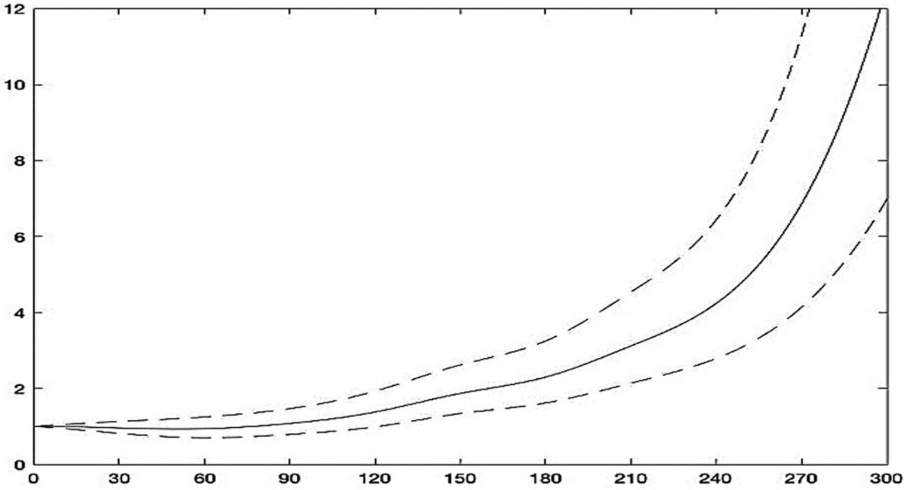


Fig. 4. - Sleep onset were modeled by restricted cubic splines using a mixed linear repeated measures model, adjusted for age, gender, BMI, SES, and sleep onset.

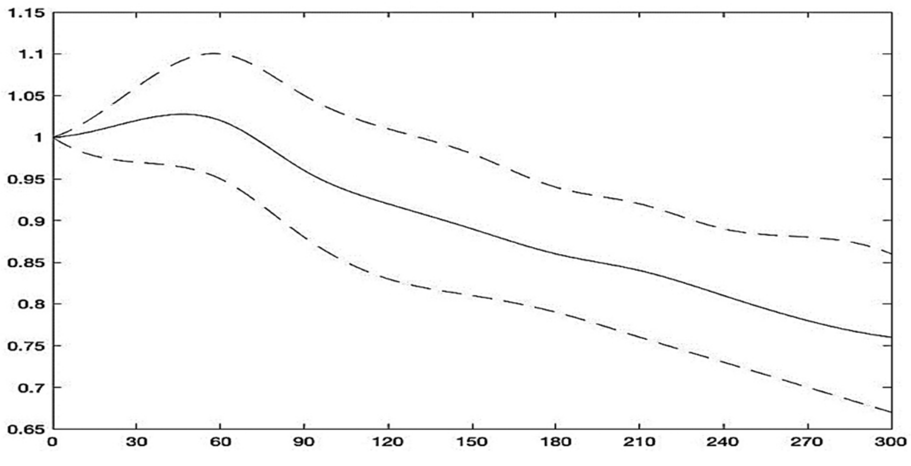


Fig. 5. - Sleep offset were modeled by restricted cubic splines using a mixed linear repeated measures model, adjusted for age, gender, BMI, SES, and sleep offset.

A progressive slope is significant at minute 90 (OR = .89, 95% CI = .81, .98), and it reaches its maximum fall at minute 300 from the sleep offset (OR = .76, 95 % CI = .67, .86).

Figure 6 shows how sleep offset minutes (measured every half hour) at the within-person level were inversely associated to the next day sedentary behavior. The slope reaches its lowest level at minute 90 (OR = .35, 95% CI = .25, .49), after which a slight slope begins and continues until minute 300 (OR = .41, 95% CI = .27, .63).

*Sleep duration*. Within-person: sleep duration was inversely associated with the next day MVPA (B = -.027, $p < .05$). After a longer sleep night than their individual average, adolescents participated in less MVPA the following day. Furthermore, when adolescents slept more than their average, they were less sedentary the following day (B = -.414 $p < .01$). Between-person: the association between sleep duration and MVPA was not significant. Nevertheless, the association between sleep duration and sedentary behavior was significant and in the same direction as at within-person level (B = -.595 $p < .01$).

*Sleep efficiency.* Within-person: sleep efficiency did not predict MVPA or sedentary behavior. Between-person: there was a significant positive association between sleep efficiency and MVPA (B = 1.91 $p < .05$).

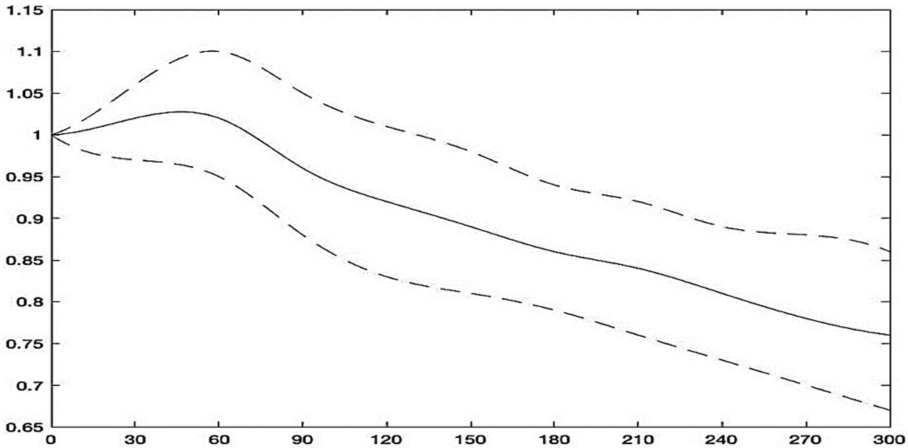


Fig. 6. - Sleep offset were modeled by restricted cubic splines using a mixed linear repeated measures model, adjusted for age, gender, BMI, SES, and sleep offset.

## Discussion

The main objective of the present research was to assess the temporal day-to-day associations between wakefulness movement variables (MVPA, sedentary behavior) and sleep (onset, offset, duration, efficiency) in adolescents using accelerometers during a complete week.

Regarding MVPA as sleep variables predictor, within-person results indicated its contribution to a longer sleep duration (due to a later sleep offset). The results obtained are similar with previous comparable studies (Lin et al., 2018; Master et al., 2019). In our study, each MVPA additional hour was associated with an additional 14 minutes of sleep duration, very similar (10 min) to Master et al. (2019). However, MVPA did not predict both sleep onset or increase in efficiency. It should be noted that in Master et al.'s study the sleep efficiency increase was small (6% per additional MVPA hour) and it has some methodological differences with our study, for instance a different algorithm for sleep data. Furthermore, other studies have not seen improvements in sleep efficiency the following day (Kim et al., 2020; Mead et al., 2019). It is possible that other confounding variables are mediating the MVPA predictive role on sleep; environmental or cultural factors such as weather, dinner time and school schedule could be of considerable importance, masking possible real MVPA physiological effects over sleep. A systematic review in children and adolescents concluded that periods of bad weather conditions like rain, wind, low temperatures and snow contributed to reduce physical activity levels (Rich, Griffiths & Dezateux, 2012).

Between-person results, MVPA did not predict sleep onset, as found at the within-person level. In addition, an inverse relationship was found between MVPA and sleep duration and sleep efficiency. These results are in line with previous evidence that have not found a better sleep associated with more physical activity levels at between-person level (Mead et al., 2019; Rognvaldsdottir et al., 2020). This fact goes against previous evidence that found physical activity physiological benefits. For instance, physical activity contributes to a greater slow-wave sleep intensity (Brand et al., 2010a), reduces sleep onset (e.g., better body temperature adjustment) (Youngstedt, 2005) and stabilizes the circadian system (Youngstedt & Freelove-Charton, 2005). Once again, previous literature results are contradictory: Philbrook and El-Sheikh (2016) did not found a positive relation between physical activity levels and sleep quality whereas in another study a better sleep quality was associated with those who were more active (Lang et al., 2013). Similarly, a study observed an inverse relationship between physical activity and sleep duration (Collings et al., 2015) whereas in another the relation was positive (Kim, Umeda, Lochbaum & Stegemeier, 2016). The same arguments used previously at the within-level can be used now to explain these inconsistencies: it is possible that there are factors that influence the MVPA-sleep relationship. In a study with adolescent soccer players, it was suggested that shorter sleep duration in those with higher physical activity levels could be linked to match schedules combined with a busy daily agenda (Brand, Beck, Gerber, Hatzinger & Holsboer-Trachsler, 2010b).

Regarding sedentary behavior as sleep variables predictor, within and between-person, a longer sedentary behavior was associated with shorter sleep duration and sleep time delay (later sleep onset and offset). A previous systematic review in adolescents concluded that sedentary behavior (in this case screen time) was inversely associated with sleep duration (Mei et al., 2018). Other studies that have used accelerometry confirm the inverse association: for instance, Master et al. (2019) found that for each additional hour of sedentary behavior, sleep was reduced by 12-min the following night; results very similar to those found in the present study (11 min). Regarding the sleep period delay, a recent study that used accelerometers support our results (Verloigne et al., 2021). Considering all the above, it can be observed how sedentary behavior delete negatively influences adolescents' sleep, affecting its phase and duration. It is possible that larger sedentary time could mean that the body physiologically is not tired and, therefore, sleep is shorted and delayed. On the other hand, it is necessary to consider that the excessive use of screens by many adolescents could affect their sleep, decreasing melatonin levels and, consequently, delaying their circadian rhythm (Higuchi, Motohashi, Liu & Maeda, 2005). Another explanation could be related to the activities prioritized by the adolescents, who would prefer to perform sedentary activities instead of sleep. In relation to sleep efficiency, our results did not indicate an association with sedentary behavior. However, a previous study found that a sedentary lifestyle was negatively associated with sleep efficiency (Kim, Umeda, Lochbaum & Stegemeier, 2017). The differences with our results could be related to the method of collecting and processing the accelerometer data such as the different algorithms used. Although the mechanisms by which sedentary behavior impacts sleep are unclear, the screen sedentary time effects are more established. According to this hypothesis, screen time increases arousal due to the emotional aspect of the content and reduce melatonin production because of blue spectrum light exposure (Kim et al., 2020). It should be interesting in future studies to analyze the sedentary behavior type to reach more accurate conclusions.

Regarding sleep onset as a wakefulness movement predictor, results showed that it was a significant predictor of both MVPA and sedentary behavior. A later sleep onset was associated, both within and between-person, with more sedentary behavior the following day. Within-person, and consistent with the above, an earlier sleep onset was associated with higher MVPA levels the next day. This shows that the hour when adolescents falls asleep seems to have a great impact on the next day diurnal movement behavior. Physiologically, it is possible that not having slept properly may impact adolescents, making them feeling tired and sleepy the next day. We are aware of only one similar study which showed different results, concluding that within-person a late sleep onset predicted less sedentary behavior, but it did not predict the next day MVPA (Master et al., 2019). Perhaps, contextual and environmental factors such as class schedules or seasons may be behind these discrepancies. Previous research has shown that seasons and weather affects both physical activity levels and sleep patterns (Quante et al., 2019).

Regarding sleep offset as a wakefulness movement predictor, within-person results showed that it predicted the next day MVPA: a later sleep offset meant fewer MVPA minutes the next day. Same results have been found in a similar research (Master et al., 2019). Furthermore, in our case we found that later sleep offset was also significantly associated with lower sedentary behavior. Although having a later sleep offset potentially means to have a longer sleep (sleep onset should be also assessed), the results obtained in the present study could be explained using the displacement time concept, commonly used in sociology (Sharif et al., 2010): thus, when getting up later and lengthening sleep, physical activity and sedentary behavior would be potentially diminished until the next sleep onset, competing with other activities (e.g., academic tasks, screen time).

Regarding sleep duration as a wakefulness movement predictor, within-person results indicated that a longer sleep than usual was associated with less MVPA and less sedentary behavior the next day. Other comparable studies in adolescents with multilevel analysis have found the same results (Kim et al., 2017; Master et al., 2019; Rognvaldsdottir et al., 2020). Furthermore, another study that considered other additional variables to assess diurnal movement also obtained an inverse relationship: thus, a longer night was associated with fewer steps and fewer calories consumed the next day (Mead et al., 2019). Nevertheless, other studies did not find that sleep duration is a MVPA predictor (Kim et al., 2020). Perhaps, among other factors, differences in the algorithms used can explain the discrepancy. Between-person results were similar to within-person, showing that sleep duration was negatively associated with sedentary behavior. In this sense, a randomized experimental study carried out in 18 adolescents during five weeks showed how more sleep duration implied less sedentary time (Van Dyk et al., 2018). There is a similar pattern to the sleep offset predictive role, since more time sleeping potentially limits the time available the next day. Activities such as physical activity probably compete with others (e.g., studying, playing video games) (Youngstedt & Kline, 2006). If this were true, it would be necessary to make adolescents' understand that both behaviors are very important for them, thus, they would consider prioritizing them over other activities.

Regarding sleep efficiency as a wakefulness movement predictor, within-person results showed that sleep efficiency did not predict neither MVPA nor sedentary behavior the next day, which is consistent with previous research (Master et al., 2019). However, another studies found that lower sleep quality the previous night was associated with decreased MVPA on the next day (Kim et al., 2017; Mead et al., 2019). Between-person results showed a significant positive relationship with MVPA: those with higher sleep efficiency had higher MVPA levels the following day. On the contrary, Master et al. (2019) observed a positive relationship between sleep efficiency and sedentary behavior.

Considering we only found a positive relationship at between-person level, these discrepancies require more researches.

This study has some limitations. First, the sample is limited to one city, restricting the results generalizability. Second, the season of the year could affect the results obtained. Third, although accelerometers have been proven to be an objective measurement method comparable with other gold standard measures, it has limitations such as not being able to collect physical activity in water or specific sport modalities (e.g., cycling).

However, the study has several strengths, including within and between-person analyses, objective measurements and data collection in the adolescents' natural contexts.

In conclusion, promoting physical activity among adolescents may benefit their sleep duration. It seems sedentary behavior negatively affects sleep duration, delaying also is phase. The impact of sleep on individuals' wakefulness movement behavior is even less clear. It appears that the physiological benefits of sleep could be mitigated by the conflict of interest in the adolescents' daily tasks. In addition, other variables such as the weather and the high school schedule could be altering the results. More studies including larger samples, different countries, and experimental designs could be of help to the advance in this field of knowledge.

## Conflict of interest statement

The authors have no conflicts to declare.

## Acknowledgements

This work was supported by the Ministry of Science, Innovation and Universities of Spain (RTI2018-099256-B-I00) and the Severo Ochoa's programme of the Principado de Asturias.

## REFERENCES

Antczak, D., Lonsdale, C., Lee, Hilland, T., Duncan, M. J., del Pozo Cruz, B., ... & Sanders, T. (2020). Physical activity and sleep are inconsistently related in healthy children: A systematic review and meta-analysis. *Sleep medicine reviews*, *51*, 1-43.

Bartel, K. A., Gradisar, M., & Williamson, P. (2015). Protective and risk factors for adolescent sleep: a meta-analytic review. *Sleep medicine reviews*, *21*, 72-85.

Beltran-Valls, M. R., Janssen, X., Farooq, A., Adamson, A. J., Pearce, M. S., Reilly, J. K., ... & Reilly, J. J. (2019). Longitudinal changes in vigorous intensity physical activity from childhood to adolescence: Gateshead Millennium Study. *Journal of science and medicine in sport, 22*(4), 450-455.

Biddle, S. J., Ciaccioni, S., Thomas, G., & Vergeer, I. (2019). Physical activity and mental health in children and adolescents: An updated review of reviews and an analysis of causality. *Psychology of sort and exercise*, *42*, 146-155.

Brand, S., Gerber, M., Beck, J., Hatzinger, M., Pühse, U., & Holsboer-Trachsler, E. (2010a). High exercise levels are related to favorable sleep patterns and psychological functioning in adolescents: a comparison of athletes and controls. *Journal of adolescent health*, *46*(2), 133-141.

Brand, S., Beck, J., Gerber, M., Hatzinger, M., & Holsboer-Trachsler, E. (2010b). Evidence of favorable sleep-EEG patterns in adolescent male vigorous football players compared to controls. *The world journal of biological psychiatry, 11*(2), 465-475.

Cappuccio, F. P., D'Elia, L., Strazzullo, P., & Miller, M. A. (2010). Sleep duration and all-cause mortality: a systematic review and meta-analysis of prospective studies. *Sleep*, *33*(5), 585-592.

Choi, L., Liu, Z., Matthews, C. E., & Buchowski, M. S. (2011). Validation of accelerometer wear and nonwear time classification algorithm. *Medicine and science in sports and exercise*, *43*(2), 357-364.

Cole, T. J., & Lobstein, T. (2012). Extended international (IOTF) body mass index cut-offs for thinness, overweight and obesity. *Pediatric obesity*, *7*(4), 284-294.

Colley, R., Gorber, S. C., & Tremblay, M. S. (2010). Quality control and data reduction procedures for accelerometry-derived measures of physical activity. *Health reports*, *21*(1), 63-69.

Collings, P. J., Wijndaele, K., Corder, K., Westgate, K., Ridgway, C. L., Sharp, S. J., ... & Ekelund, U. (2015). Prospective associations between sedentary time, sleep duration and adiposity in adolescents. *Sleep medicine, 16*(6), 717-722.

Currie, C., Inchley, J., Molcho, M., Lenzi, M., Veselska, Z., & Wild, F. (2014). *Health Behaviour in School-aged Children (HBSC) study protocol: Background, methodology and mandatory items for the 2013/14 Survey*. St. Andrews University.

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.

Fatima, Y., Doi, S. A. R., & Mamun, A. A. (2015). Longitudinal impact of sleep on overweight and obesity in children and adolescents: a systematic review and bias-adjusted meta-analysis. *Obesity reviews*, *16*(2), 137-149.

Full, K. M., Kerr, J., Grandner, M. A., Malhotra, A., Moran, K., Godoble, S., ... & Soler, X. (2018). Validation of a physical activity accelerometer device worn on the hip and wrist against polysomnography. *Sleep health*, *4*(2), 209-216.

Garrow, J. S., & Webster, J. (1985). Quetelet's index (W/H2) as a measure of fatness. *International journal of obesity*, *9*(2), 147-153.

Gradisar, M., Gardner, G., & Dohnt, H. (2011). Recent worldwide sleep patterns and problems during adolescence: a review and meta-analysis of age, region, and sleep. *Sleep medicine*, *12*(2), 110-118.

Guthold, R., Stevens, G. A., Riley, L. M., & Bull, F. C. (2020). Global trends in insufficient physical activity among adolescents: a pooled analysis of 298 population-based surveys with 1·6 million participants. *The lancet child & adolescent health*, *4*(1), 23-35.

Higuchi, S., Motohashi, Y., Liu, Y., & Maeda, A. (2005). Effects of playing a computer game using a bright display on presleep physiological variables, sleep latency, slow wave sleep and REM sleep. *Journal of sleep research, 14*(3), 267-273.

Huang, W. Y., Ho, R. S. T., Tremblay, M. S., & Wong, S. H. S. (2021). Relationships of physical activity and sedentary behaviour with the previous and subsequent nights' sleep in children and youth: A systematic review and meta-analysis. *Journal of sleep research*, *30*(6), 1-24.

Kalak, N., Gerber, M., Kirov, R., Mikoteit, T., Yordanova, J., Pühse, U., ... & Brand, S. (2012). Daily morning running for 3 weeks improved sleep and psychological functioning in healthy adolescents compared with controls. *Journal of adolescent health*, *51*(6), 615-622.

Kim, Y., Umeda, M., Lochbaum, M., & Stegemeier, S. (2016). Peer reviewed: Physical activity, screen-based sedentary behavior, and sleep duration in adolescents: Youth Risk Behavior Survey, 2011–2013. *Preventing chronic disease*, *13*, 1-6.

Kim, Y., Umeda, M., Lochbaum, M., & Stegemeier, S. (2017). Day-to-day reciprocal associations between sleep health, physical activity, and sedentary behavior in adolescents. *Medicine & science in sports & exercise*, *49*(5s), 974.

Kim, Y., Umeda, M., Lochbaum, M., & Sloan, R. (2020). Examining the day-to-day bidirectional associations between physical activity, sedentary behavior, screen time, and sleep health during school days in adolescents. *PloS one*, *15*(9), 1-18.

Kline, C. E. (2014). The bidirectional relationship between exercise and sleep: implications for exercise adherence and sleep improvement. *American journal of lifestyle medicine*, *8*(6), 375-379.

Knebel, M. T. G., Borgatto, A. F., Lopes, M. V. V., Dos Santos, P. C., Matias, T. S., Narciso, F. V., & Silva, K. S. (2020). Mediating role of screen media use on adolescents' total sleep time: A cluster-randomized controlled trial for physical activity and sedentary behaviour. *Child: care, health and development*, *46*(3), 381-389.

Kracht, C. L., Champagne, C. M., Hsia, D. S., Martin, C. K., Newton Jr, R. L., Katzmarzyk, P. T., & Staiano, A. E. (2020). Association between meeting physical activity, sleep, and dietary guidelines and cardiometabolic risk factors and adiposity in adolescents. *Journal of adolescent health*, *66*(6), 733-739.

Lang, C., Brand, S., Feldmeth, A. K., Holsboer-Trachsler, E., Pühse, U., & Gerber, M. (2013). Increased self-reported and objectively assessed physical activity predict sleep quality among adolescents. *Physiology & behavior, 120*, 46-53.

Lang, C., Kalak, N., Brand, S., Holsboer-Trachsler, E., Pühse, U., & Gerber, M. (2016). The relationship between physical activity and sleep from mid adolescence to early adulthood. A systematic review of methodological approaches and meta-analysis. *Sleep medicine reviews*, *28*, 32-45.

Lin, Y., Tremblay, M. S., Katzmarzyk, P. T., Fogelholm, M., Hu, G., Lambert, E. V., ... & ISCOLE Research Group. (2018). Temporal and bi-directional associations between sleep duration and physical activity/sedentary time in children: An international comparison. *Preventive medicine*, *111*, 436-441.

Marfell-Jones, M. J., Stewart, A. D., & De Ridder, J. H. (2012). *International standards for anthropometric assessment*. Wellington, New Zealand: International Society for the Advancement of Kinanthropometry.

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), 1-14.

McMahon, E. M., Corcoran, P., O'Regan, G., Keeley, H., Cannon, M., Carli, V., ... & Balazs, J.

(2017). Physical activity in European adolescents and associations with anxiety, depression and well-being. *European child & adolescent psychiatry*, *26*(1), 111-122.

Mead, M. P., Baron, K., Sorby, M., & Irish, L. A. (2019). Daily associations between sleep and physical activity. *International journal of behavioral medicine*, *26*(5), 562-568.

Mei, X., Zhou, Q., Li, X., Jing, P., Wang, X., & Hu, Z. (2018). Sleep problems in excessive technology use among adolescent: a systemic review and meta-analysis. *Sleep science and practice*, *2*(9), 1-10.

Memon, A. R., Gupta, C. C., Crowther, M. E., Ferguson, S. A., Tuckwell, G. A., & Vincent, G. E. (2021). Sleep and physical activity in university students: a systematic review and meta-analysis. *Sleep medicine reviews*, *58*, 1-19.

Moore, M., & Meltzer, L. J. (2008). The sleepy adolescent: causes and consequences of sleepiness in teens. *Paediatric respiratory reviews*, *9*(2), 114-121.

National Sleep Foundation (2021, March 10). *How much sleep do we really need?.* https://www.sleepfoundation.org/how-sleep-works/how-much-sleep-do-we-really-need

Peat, J. K., Mellis, C., Williams, K., & Xuan, W. (2020). *Health science research: A handbook of quantitative methods*. London: Routledge.

Philbrook, L. E., & El-Sheikh, M. (2016). Associations between neighborhood context, physical activity, and sleep in adolescents. *Sleep health*, *2*(3), 205-210.

Poitras, V. J., Gray, C. E., Borghese, M. M., Carson, V., Chaput, J. P., Janssen, I., ... & Sampson, M. (2016). Systematic review of the relationships between objectively measured physical activity and health indicators in school-aged children and youth. *Applied physiology, nutrition, and metabolism*, *41*(6), S197-S239.

Quante, M., Wang, R., Weng, J., Kaplan, E. R., Rueschman, M., Taveras, E. M., ... & Redline, S. (2019). Seasonal and weather variation of sleep and physical activity in 12–14-year-old children. *Behavioral sleep medicine*, *17*(4), 398-410.

Rich, C., Griffiths, L. J., & Dezateux, C. (2012). Seasonal variation in accelerometer-determined sedentary behaviour and physical activity in children: a review. *International journal of behavioral nutrition and physical activity, 9*(49), 1-8.

Rognvaldsdottir, V., Johannsson, E., Soffia, H. M., Stefansdottir, R. S., Arngrimsson, S. A., Cheng, K. Y., ... & Gudmundsdottir, S. L. (2020). 0260 Association between free-living physical activity and sleep in Icelandic adolescents. *Sleep*, *43*, A99.

Sadeh, A., Sharkey K. M., & Carskadon M. A. (1994). Activity-based sleep-wake identification: an empirical test of methodological issues. *Sleep, 17*(3), 201-207.

Sharif, I., Wills, T. A., & Sargent, J. D. (2010). Effect of visual media use on school performance: a prospective study. *Journal of adolescent health, 46*(1), 52-61.

Shochat, T., Cohen-Zion, M., & Tzischinsky, O. (2014). Functional consequences of inadequate sleep in adolescents: a systematic review. *Sleep medicine reviews*, *18*(1), 75-87.

Torsheim, T., Cavallo, F., Levin, K. A., Schnohr, C., Mazur, J., Niclasen, B., & Currie, C. (2016). Psychometric validation of the revised family affluence scale: a latent variable approach. *Child indicators research*, *9*(3), 771-784.

Trost, S. G., Loprinzi, P. D., Moore, R., & Pfeiffer, K. A. (2011). Comparison of accelerometer cut points for predicting activity intensity in youth. *Medicine and science in sports and exercise, 43*(7), 1360-1368.

Van Dyk, T. R., Krietsch, K. N., Saelens, B. E., Whitacre, C., McAlister, S., & Beebe, D. W. (2018). Inducing more sleep on school nights reduces sedentary behavior without affecting physical activity in short-sleeping adolescents. *Sleep medicine*, *47*, 7-10.

Verloigne, M., Van Oeckel, V., Brondeel, R., & Poppe, L. (2021). Bidirectional associations between sedentary time and sleep duration among 12-to 14-year-old adolescents. *BMC public health*, *21*(1), 1-9.

World Health Organization (2020). WHO guidelines on physical activity and sedentary behavior. https://www.who.int/publications/i/item/9789240015128

World Medical Association (2013). World Medical Association Declaration of Helsinki Ethical Principles for Medical Research Involving Human Subjects. *Jama*, E1 – E4.
Youngstedt, S. D. (2005). Effects of exercise on sleep. *Clinics in sports medicine*, *24*(2), 355-365.
Youngstedt, S. D., & Freelove-Charton, J. D. (2005). Exercise and sleep. In G. E. Faulkner, A. H. Taylor (Eds), *Exercise, health and mental health* (pp. 177-207). London: Routledge.
Youngstedt, S. D., & Kline, C. E. (2006). Epidemiology of exercise and sleep. *Sleep and biological rhythms*, *4*(3), 215-221.

*Manuscript submitted January 2022. Accepted for publication July 2022.*