Summer 2022

Relationships Among Sleep, Physical Activity, and Weight Status in Children and Adolescents

Agnes Bucko

RELATIONSHIPS AMONG SLEEP, PHYSICAL ACTIVITY, AND WEIGHT STATUS IN CHILDREN AND ADOLESCENTS

by

Agnes Bucko

Bachelor of Science
Loyola University Chicago, 2014

Master of Science
Arizona State University, 2017

Submitted in Partial Fulfillment of the Requirements

For the Degree of Doctor of Philosophy in

Exercise Science

The Norman J. Arnold School of Public Health

University of South Carolina

2022

Accepted by:

Russell R. Pate, Major Professor

Kerry McIver, Committee Member

Bridget Armstrong, Committee Member

Alexander McLain, Committee Member

Tracey L. Weldon, Vice Provost and Dean of the Graduate School

ACKNOWLEDGEMENTS

I would first like to thank Dr. Pate for his guidance throughout the PhD process at the University of South Carolina. I would also like to thank the professors at the University of South Carolina for all of their help and support, especially the members of my committee, Dr. Armstrong, Dr. McIver, and Dr. McLain. I am grateful for all of the assistance and support I received from the members of the Children's Physical Activity Research Group, especially from Dr. Marsha Dowda, Gaye Christmus and Melissa Bair. Thank you as well to the members of the Behavioral Biomedical Interface Program, especially Dr. Prinz, Aimee Stanczyk-Norrell and Michele Blondin. Finally, a special thank you to my family and friends, who always provided the support I needed to make this achievement possible. Dziękuję Mamo, dziękuję Tato, za wasze wsparcie przez te wszystkie lata.

ABSTRACT

Sleep and physical activity are both associated with multiple behavioral and metabolic health outcomes, and both behaviors have been linked to the development of weight status. Recent estimates suggest that many children are not meeting sleep recommendations or participating in adequate levels of physical activity, which may be related to the high prevalence of childhood overweight and obesity. Much of the research assessing these relationships has focused on adults and older children, and has relied on parent- or child-reported, cross-sectional research in predominantly White samples. Little work has focused on these relationships in very young children. Although more research has been conducted in adolescent samples, these studies rarely consider the effect of weeknights vs. weekend nights or physical activity intensity in their analyses. Therefore, the overall purpose of this dissertation was to examine the longitudinal relationships between sleep, physical activity, and weight status in both very young children and adolescents.

This dissertation was comprised of three studies. The first study used data from the Linking Activity, Nutrition and Child Health (LAUNCH) observational study to evaluate longitudinal associations between sleep and physical activity in 6-24 month-old children. Device-based measures were used to assess daytime, nighttime, and 24 hour sleep durations, nighttime sleep awakenings, and daytime total physical activity. Linear mixed models assessed whether the within- and between-person effects of physical activity were associated with sleep. Children with higher total physical activity levels

slept less during the day compared to children with lower total physical activity levels, and when children were more physically active compared to their own average physical activity levels, their 24-hour sleep duration was lower. Differences in nighttime sleep duration were seen based on race/ethnicity and SES. The findings indicate that mechanisms underlying the sleep and physical activity relationship in young children vary from those that have been suggested in older children and adults.

The second study used data from the LAUNCH observational study to evaluate longitudinal associations between sleep and adiposity in 6-24 month-old children. Device-based measures were used to assess daytime sleep duration, nighttime sleep duration, and daytime total physical activity levels. Diet was assessed via questionnaires completed by the mother. Weight-for-length z-scores were calculated based on measures collected by trained data collectors. Linear mixed models assessed whether the within- and between-person effects of sleep were associated with adiposity. Physical activity and diet were entered into the models as covariates. Children had lower weight-for-length z-scores when they slept less at night compared to their own average nighttime sleep durations, although this relationship was attenuated by daytime physical activity. These associations did not vary based on race/ethnicity, gender, or SES. These results suggest that the relationship between sleep and adiposity is specific to infant's nighttime sleep durations, and that physical activity has a protective effect on the development of adiposity in very young children.

The purpose of the third study was to assess longitudinal associations between sleep and physical activity in adolescent children who participated in the Next Generations Health (NEXT) Study. Both sleep and physical activity were measured via survey. Surveys asked about weeknight and weekend night sleep separately, and separate questions assessed total physical activity (TPA) and vigorous physical activity (VPA). Linear mixed models assessed whether TPA and VPA were associated with sleep, with separate models created for weeknight and weekend night sleep. For every extra day adolescents met TPA guidelines, they slept 31 minutes less per night on weekend nights. This difference increased by nearly 2 minutes per night for every 1 year increase in age. Adolescents who participated in >7 hours of VPA in the past week slept 216 minutes longer per night on weekend nights than adolescents who did not participate in VPA, and this difference decreased by 13 minutes per night for every 1 year increase in age. Differences in sleep duration were seen based on race/ethnicity, gender, and SES. These findings indicate that both physical activity intensity and day type are important factors to consider when assessing the sleep and physical activity relationship in adolescents.

Although both sleep and physical activity are important behaviors that should be included in interventions targeting obesity prevention, it should be noted that the complex relationships between sleep, physical activity and adiposity in children and adolescents may not follow the same patterns as those seen in adults. This is not surprising considering both sleep and physical activity vary greatly as individuals develop from infancy to adulthood. Furthermore, the differences that were seen in sleep duration by different demographic characteristics suggest that more work is needed addressing the large-scale social determinants of health that are directly related to sleep in order to improve sleep in at-risk populations. Collectively, results from the studies included in this dissertation suggest that future research addressing the relationships among sleep, physical activity, and adiposity should consider physical activity intensity as well as the timing of sleep, whether this be daytime vs. nighttime sleep or weeknight vs. weekend night sleep. Obesity prevention research that focuses on increasing sleep and physical activity must take the age of the children into consideration, as well as demographic characteristics that may play a role in both sleep and physical activity levels.

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LIST OF ABBREVIATIONS

AASM .... American Academy of Sleep Medicine

AIC ....Akaike information criterion

BIC .... Bayesian information criterion

BMI .... Body Mass Index

CDC ....Centers for Disease Control and Prevention

HPA.. Hypothalamic–Pituitary–Adrenal

Hz ....Hertz

ICC ....Intraclass correlation coefficient

LAUNCH ....Linking Activity, Nutrition and Child Health

MAR .... Missing at Random

NSF ....National Sleep Foundation

SES..Socioeconomic status

WHO ....World Health Organization

WIC..Women, Infants and Children Nutrition Program

ZCM .... Zero Crossing Mode

-2LL ....Negative 2 Log Likelihood

CHAPTER 1

OVERALL INTRODUCTION

Introduction

According to 2018 Physical Activity Guidelines for Americans, children and adolescents ages 6-17 years old should participate in ≥60 minutes of moderate-to-vigorous physical activity every day. Vigorous-intensity aerobic physical activity, and bone and muscle strengthening physical activities should each be performed on ≥3 days a week.[1,2] The 2018 Physical Activity Guidelines for Americans do not provide a specific dose of PA for children ages 3-5, but they do recommend that they are physically active throughout the day, and that adults caregivers encourage active play and a variety of physical activities. No recommendations are given for children under the age of 2.[1,2] This is due to the lack of research on the associations between physical activity and health in very young children. This line of research is limited primarily by to the fact that measures of physical activity have not been validated in children under the age of 2 years old.[3]

Current estimates report that 25% of children 6 to 17 years of age participate in ≥60 minutes of physical activity every day.[4] Only 26% of adolescents in grades 9-12 participate in moderate-to-vigorous physical activity for ≥60 minutes per day, and 51% participate in muscle strengthening activities ≥3 days a week. Estimates for the number of children 3-5 years old that are physically active for ≥3 hours per day are inconsistent, and range from 41%-92%.[5,6] There is a significant drop in the number of children meeting physical activity guidelines as children transition from grade school to middle school and then to high school.[4] Observational studies have also found differences in physical activity levels by sex, socioeconomic (SES) and race/ethnicity, although these differences are not consistent.[4,6–9]

Physical activity is associated with motor skill development,[10–12] bone health,[3,10,11,13] and the health-related quality of life[10,14] of 3-18 year old youth. Increasing physical activity and decreasing sedentary behavior is associated with improvements in metabolic health in children >5 years old.[10,15] There is some evidence of a positive association between PA and cardiometabolic health among children under the age of 5,[11] but the research on this topic is very limited, and results are not consistent.[3,13]

The National Sleep Foundation (NSF) and the American Academy of Sleep Medicine (AASM) have published sleep duration recommendations. Based on these recommendations, newborns under the age of 3 months should sleep 14-17 hours per day, infants between the ages of 4 and 11 months should sleep 12-16 hours/day, 1-2 year old children should sleep 11-14 hours/day, and 3-5 year old children should sleep 10-13 hours/day. Napping is included in these daily sleep recommendations for children up until the age of 5. Children 6-12 years old should sleep 9-12 hours per day, and children 13-18 years old should sleep 8-10 hours per day.[16,17] Current guidelines focus on sleep duration only.[18] Although some research has started to assess the effects sleep quality has on health outcomes,[19] there are no guidelines that focus on measures of sleep quality specifically.

Among infants and younger children, parent reported data suggest that infants ages 0-23 months old sleep an average of 12.8 hours per day, and wake 0-3.4 times per night. Toddlers 2-5 years old sleep 11.9 hours per day, and wake 0-2.5 times per night.[20] Estimates based on actigraphy data suggest that children 3–5 years old sleep around 9.68 hours per night,[21] just below the 10-13 hours recommended by the AASM and NSF. Adolescents report sleeping an average of 9-10 hours per night, and this average is consistently higher on weekends than weekdays.[22] Similar to the results of observational studies of physical activity, sleep duration appears to vary by race/ethnicity,[23–27] sex,[23,27–29] and SES.[23,30,31]

Poor sleep is associated with negative effects on neurocognitive development.[38] Specifically, greater sleep duration and quality are associated with better emotional regulation,[18] a lower risk of depression and anxiety,[39–44] better cognitive functioning[39,45] and performance in school,[40,46,47] and lower rates of risk taking,[43,44,47–49] hyperactivity, inattention, and symptoms of ADHD.[40] Importantly, adolescents who exhibit poor sleep are more likely to continue experiencing poor sleep into adulthood.[50] There is some inconsistent evidence suggesting that better sleep is also associated with better weight status outcomes and a lower risk of overweight/obesity.[18,44,51–55] Multiple mechanisms have been suggested to explain the relationship between sleep and weight status, including a decrease in diet quality, appetite control, insulin resistance, and physical activity, and an increase in sedentary time.[53,56,57]

Physical activity is considered an inexpensive, nonpharmacological method for improving sleep outcomes.[58] Cohort studies and surveillance data report a moderate, positive, bidirectional association between sleep and physical activity in the general population.[58] A number of psychological and biological mechanisms have been suggested to explain the association between sleep and physical activity.[59] First, an increase in exercise may improve mood by down-regulating activity in the hypothalamic–pituitary–adrenal (HPA) axis.[58] Overactivity in the HPA axis is associated with poor sleep outcomes and impairments in thermoregulation.[58,59] Thermoregulation is an integral component of sleep onset. Sleep onset begins with a drop in body temperature.[60] Elevated body temperatures caused by physical activity are followed by a drop in body temperature after physical activity stops, provide input to regions of the brain that promote sleep onset and maintenance. Chronic exercise improves the body's ability to thermoregulate at night.[58–60] Physical activity may also influence the circadian systems that regulate sleep patterns by readjusting circadian phases to align with healthy circadian rhythms.[58,60] According to the energy conservation/body restoration hypothesis, exercise depletes energy stores, which can only be restored when an individual is asleep. Recovery from any damage, major or minor, can occur at this time as well.[60] Finally, the adenosine hypothesis posits that greater physical activity increases adenosine levels in the brain, which are also associated with an increased sleep need.[58]

Studies assessing the relationship between sleep and physical activity among adolescents show a positive association,[50] with moderate-to-strong effect sizes depending on the type of measurement instruments used to measure sleep and physical activity.[50] Effect sizes are strongest in studies that utilize subjective measures for both behaviors, and weakest when assessing physical activity and sleep using device-based measures.[50] Most of the research is based on cross-sectional studies.[50] The few experimental studies that have assessed the effect of regular exercise on sleep show promising results.[61] There is a very limited amount of research on the association between sleep and physical activity among infants and young children, and the few studies that have been done utilize cross-sectional data and show null or mixed results.[62,63] The association may appear weaker in young children due to biological, behavioral and developmental differences that may impact mechanisms guiding this relationship in adolescents and adults.[64]

Short sleep duration is associated with a number of metabolic and biological changes in children.[53,65] These biological changes are thought to influence dietary patterns, including a greater energy intake associated with obesity.[53,65,66] Shortened sleep may also alter how the brain responds to food. Sleep deprivation is associated with greater activation of brain regions associated with food reward, making food more appealing and desired more strongly by adolescents.[66] A limited amount of evidence suggests that poor sleep results in a negative affect that may lead to emotional eating among some adolescents. Furthermore, adolescents who go to bed late have an increased opportunity to snack, increasing energy consumption.[66] Sleep deprivation can also lead to fatigue, which may contribute to a decrease in physical activity levels and increased sedentary behavior and screen time. These behaviors decrease energy expenditure and would further increase the risk of obesity.[53,65] A limited number of cross-sectional studies show an inverse association between sleep duration and weight status in children under the age of 3 years old. These studies show sleep duration is associated with higher physical activity levels and better diet quality among infants and toddlers.[67–69] A popular framework used to explain the influence of both sleep and physical activity on weight status hypothesizes that poor sleep increases energy intake due to hormonal changes as well as an increased opportunity to eat during the day.[65,66] Poor sleep also leads to greater feelings of tiredness, resulting in a reduction in physical activity and a limited energy expenditure.[65,66] Therefore, a multi-system approach to obesity prevention may be needed, which considers increasing physical activity levels and improving sleep.[68]

Research assessing the relationship between sleep and physical activity in children, along with their individual and combined effects on the development of weight status is limited by a number of factors. More research is also needed on the relationship between sleep and physical activity, especially among very young children.[62] Results of recent studies assessing this relationship are mixed, which may be due to the variation in the methods used to assess both sleep and physical activity in this line of research.[70] Much of the current data is based on parent or self-reported sleep and utilizes cross-sectional study designs,[50,55,62] and more longitudinal studies that utilize objective measures of both sleep and physical activity are needed to reduce the risk of bias. Interventions targeting obesity treatment and prevention in children that address poor diet and inactivity alone have not had very successful results.[71] Successfully incorporating a sleep component into these interventions has not only shown to improve sleep outcomes in participants, but has also led to improvements in weight status outcomes.[72] In order to further improve these interventions, more research should be done assessing the longitudinal relationships between subjectively-measured sleep, physical activity, and weight status in children from a very young age throughout adolescence. While much of the work has focused on sleep duration specifically, very few studies have assessed whether other sleep variables, such as sleep quality, are related to obesity outcomes. More work is also needed assessing whether these relationships vary based on demographic characteristics, such as age, race, ethnicity, SES or sex.[53,71]

To address these gaps in the literature, the overarching purpose of this dissertation was to examine longitudinal relationships between sleep and physical activity in children across the developmental spectrum. Based on previous literature, it was hypothesized that there would be a positive association between sleep and physical activity in both age groups, and that both behaviors would be inversely associated with weight status. Two data sources that included sleep, physical activity, and weight status measures were utilized to address these hypotheses.

Study one examined the longitudinal relationship between objectively-measured sleep and physical activity in children 6-24 months old. Daytime, nighttime, and 24-hour sleep duration along with the number of nighttime awakenings were treated as the dependent variables, and the within-person and between-person effects of physical activity were entered into the models as independent variables. All models adjusted for race/ethnicity, sex, and socioeconomic status.

Study two examined the longitudinal relationship between objectively-measured sleep and weight status in children 6-24 months old, and determined whether these associations differed by race/ethnicity, socioeconomic status, and sex. Length-for-weight z-scores were treated as dependent variables in separate models, and the within-person and between-person effects of daytime, nighttime, and 24-hour sleep duration along with the number of nighttime awakenings were treated as the independent variables in separate models. Associations between sleep and weight status were examined, adjusting for race/ethnicity, sex, and SES. Next, the extent to which these associations varied by race/ethnicity, sex, and SES was examined.

Finally, study three examined the longitudinal relationships between total (TPA) and vigorous physical activity (VPA) and sleep in 15-18 year old adolescents. Weeknight and weekend night sleep duration were treated as the dependent variables in separate analyses, while TPA and VPA were simultaneously entered as the independent variables. All models adjusted for race/ethnicity, sex, and socioeconomic status.

The results of these three studies are able to advance the current literature by describing whether the relationships between sleep, physical activity, and weight status that are seen among adults are also present in younger children and adolescents. The results of the dissertation highlight the need for research utilizing device-based measures of physical activity and sleep in large, diverse samples of children. This will aid in identifying populations who are at risk of poor sleep and low physical activity, and allow for the development of tailored interventions that consider the individual, social, and environmental factors associated with these behaviors. Furthermore, more longitudinal studies are needed that assess the relationship between sleep and physical activity, as well as subsequent effects these behaviors have on the development of weight status in children. This will help elucidate the complex interrelationships between these factors, and help identify the optimal time to intervene on negative health outcomes such as overweight and obesity in a way that is both efficacious and resourceful.

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CHAPTER 2

MANUSCRIPT ONE – LONGITUDINAL ASSOCIATIONS BETWEEN SLEEP AND PHYSICAL ACTIVITY IN INFANTS AND TODDLERS

Abstract

Study Objectives: This study aimed to examine whether average physical activity levels in children from 6-24 months old are associated with sleep duration and sleep quality, and examine whether changes in physical activity levels are associated with sleep duration and sleep quality.

Methods: Data were collected on 109 mother and child dyads when children were 6, 12, 18, and 24 months old (44% female, 50% Non-Hispanic White). Daytime, nighttime, and 24 hour sleep duration and the number of nighttime awakenings were measured with actigraphy. Daytime physical activity was assessed using accelerometry. Demographic characteristics were reported by the child's mother at baseline and included sex, race/ethnicity, and Women, Infants and Children Nutrition Program status. Separate associations of between-person differences and within-person changes in physical activity were estimated with each of the sleep variables as the outcome in separate linear mixed model analyses adjusting for demographic characteristics.

Results: Children with higher total physical activity levels slept less during the day compared to children with lower total physical activity levels. When children were more physically active compared to their own average physical activity levels, their 24-hour sleep duration was lower.

Conclusions: There is an inverse association between sleep and physical activity in infants, which is inconsistent with the results of similar studies in older children and adolescents. Future research should assess whether the relationship varies depending on physical activity intensity once physical activity intensity cut points are established for infants.

Introduction

Sleep plays a critical role in children's health and development, although the strength of the relationship varies depending on the outcome of interest as well as the child's age.[1,2] Current pediatric sleep duration guidelines recommend that infants between the ages of 4 and 12 months sleep 12-16 hours/day, and children ages 1-2 years sleep 11-14 hours/day.[3] Recent surveillance data report that infants and young children >3 years old sleep 12-14 hours/day.[4,5] Some data also suggest that children from minority and low-income populations are at a higher risk of inadequate sleep,[6–9] which may explain, in part, why children from minority and low-income populations are at a higher risk of negative health outcomes associated with sleep.[10,11]

Although surveillance data suggest that most infants and very young children are sleeping an average of over 12 hours per day, it is important to note that most of these data are collected using parent-reported sleep.[4] Parent-reported sleep data are subject to bias, potentially leading to incorrect estimates of sleep.[12,13] In order to account for this issue, actigraphy is a commonly-used, device-based measure of sleep.[14] Actigraphy allows for the objective measurement of sleep in a natural setting over an extended period of time.[14,15] Actigraphy has been validated against the gold-standard measure of sleep, polysomnography, in very young children.[16]

Physical activity is considered a non-invasive and inexpensive method for improving sleep outcomes.[17] Emerging research indicates that a positive relationship between sleep and physical activity may exist in the youngest of populations, with studies showing that higher physical activity levels are associated with better sleep quality and longer sleep duration among infants and toddlers.[18–21] There are a number of mechanisms that have been hypothesized to explain the positive association between sleep and physical activity, although this line of research has been conducted primarily on adolescent and adult populations.[22] In order to better understand whether these mechanisms exist in younger populations, the research must first confirm that similar associations between sleep and physical activity exist across various developmental stages.

The research assessing the relationship between sleep and physical activity in children >3 years old is limited.[23] Very few studies have assessed this relationship using device-based measures of both sleep and physical activity. A majority of these studies are cross-sectional[18,21,24–26] and show mixed results, suggesting positive but weak[18,21,24–26] or null[27] associations. Very few studies have assessed this relationship longitudinally among children under the age of 6, and there have been no longitudinal studies conducted on the sleep and physical activity relationship in infants.[23,28] Longitudinal data analysis, whether it be over a week, month, or year, is a beneficial method for assessing the sleep and physical activity relationship because it allows for the disaggregation of within-person and between-person effects of physical activity over time. This method determines the extent to which changes in an individual's physical activity levels, or the within-person effect of physical activity, are associated with sleep, as well as how differences between subjects' physical activity levels, or the between-subject variation in physical activity, are associated with sleep.[29,30] Only one study, which resulted in null findings, has explored the within- and between-person associations of physical activity and sleep among 3-6 year old children.[31]

Although there appears to be a positive relationship between sleep and physical activity among older populations,[17,22] it is still unclear whether this relationship exists in infants and young children. In fact, the 2018 Physical Activity Guidelines Advisory Committee Scientific Report concluded that, "Insufficient evidence is available to examine relationships between physical activity and sleep in children and adolescents…"[32] Understanding when the association between sleep and physical activity begins to appear would aid in the development of policies and initiatives surrounding children's health behaviors. Therefore, this study will determine whether there is a longitudinal relationship between device-based measures of sleep and physical activity in a diverse sample of children 6-24 months old. Specifically, this study aims to: 1) examine whether average physical activity levels in children from 6 months old to 24 months old are associated with sleep duration and sleep quality; 2) examine whether changes in physical activity levels in children from 6 months old to 24 months old are associated with sleep duration and sleep quality.

Methods

Participants.

Data for these analyses were from the Linking Activity, Nutrition and Child Health (LAUNCH) study.[33] The LAUNCH study was designed to describe physical activity and sedentary behavior in young children as they transition from infancy to preschool, and to describe longitudinal associations between physical activity, sedentary behavior and diet with weight status during this transition. The LAUNCH study collected longitudinal, observational data in children at six time points, at ages 6, 12, 18, 24, 30 and 36 months. The present study focused on the associations between sleep and physical activity using the first 4 time points (when children were around 6, 12, 18, and 24 months old). Participants were children and their biological mothers recruited from communities in South Carolina. The LAUNCH study excluded children with any physical limitation that prevented the use of accelerometry to assess physical activity.

Measures

Sleep. Sleep was measured objectively using an actigraph (MicroMini-Motionlogger, Ambulatory Monitoring, Inc.) Children wore actigraphs on the left ankle for 24 hours/day for seven days, except during water-based activities. Data were downloaded from the monitors and assessed using software available from the manufacturer (Action4, Version 1.16, Ambulatory Monitoring, Inc., Ardsley, New York, USA). Sleep diaries were not used alongside actigraphy in this study. This was done in order to avoid a loss of data resulting from non-compliance with sleep diary completion and to reduce participant burden.[34]

Sleep duration variables were computed using the Sadeh et al. algorithm[35,36] and assessed in 60-second epochs. Wear time was determined using the LIFE channel included in the manufacturer-provided software (MicroMini-Motionlogger, Ambulatory Monitoring, Inc.).[37] Participant were required to have ≥3 days/nights with ≥10 hours of data per day/night to be included in analyses assessing daytime and nighttime sleep duration, respectively, as well as the number of nighttime awakenings. Each participant needed to have ≥3 24-hour days with ≥20 hours of data per night to be included in analyses assessing 24-hour sleep duration.

Nighttime sleep duration was operationalized as the average number of minutes spent sleeping between 7 PM and 7 AM. Daytime sleep duration was operationalized as the average number of minutes spent sleeping between 7 AM and 7 PM. These definitions of nighttime and daytime sleep were based on research suggesting that very young children have an average bedtime between 6:30PM-9:00PM and an average wake time from 6:00AM-8:00AM.[38] Twenty-four-hour sleep duration was operationalized as the average number of minutes spent sleeping between 7 AM and 7 AM the following day. The average number of nighttime awakenings was used as a measure of sleep quality,[39] and was operationalized as the average number of times a child woke up between the hours of 7 PM and 7 AM. The definition of daytime as 7AM-7PM and day time as 7PM to 7AM at night time was used to coincide with the times listed in sleep questionnaires completed by parents at each time point. The daytime and nighttime sleep duration variables and the variable summarizing the average number of nighttime awakenings were normalized by being divided by wear time and extrapolated into 12 hours. The 24-hour sleep duration variable was normalized by being divided by wear time and extrapolated into 24 hours.

Physical activity. ActiGraph accelerometers (GT3X model, Pensacola, FL) were used to collect physical activity data. Children received accelerometers during each data collection visit with parents at his/her home, childcare center or another predetermined location. Accelerometers were worn for seven days and were attached to elastic belts and worn on the right hip and inside a child-sized sweatband and worn on the right ankle. Trained data collectors provided caregivers instructions on how and when the monitor should be worn. Parents were instructed to remove the monitors at night and during water-based activities, and put the monitors back on shortly after waking in the morning.

Accelerometers were initialized prior to data collection and begin collecting data at midnight following accelerometer distribution.

Data were collected in raw data mode at 80 Hz and later downloaded into 15-second intervals.[40] Non-wear time was defined as any ≥60 minute period of consecutive zeros and was excluded from analyses.[41] Missing physical activity data were imputed for children who had >1 days of >8 hours of accelerometry data. Ankle and hip total physical activity counts were operationalized as the average number of vector magnitude counts per hour between 7 AM and 7 PM each day. This physical activity variable was chosen because intensity cut points have not yet been established for non-ambulatory children. Ultimately, only the physical activity data collected at the ankle were used in analyses because hip placement is not able to capture movement well from children who are unable to walk,[43] which was the case when data were collected for children at the first time point.

Demographic characteristics. Demographic characteristics were reported by the child's mother at baseline. These include sex (male/female) and race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic, Other). Socioeconomic status (SES) (highest level of education achieved by mother; Women, Infants and Children Nutrition Program (WIC) status) was collected at each time point. Available responses for maternal education included: Some high school, High school diploma/GED, Some college, 2-year degree, 4-year degree, some graduate school, Graduate degree. These responses were categorized into two categories: college or above (4-year degree, some graduate school, Graduate degree) or less than college (Some high school, High school diploma/GED, Some college, 2-year degree). Available responses for WIC status included: I was enrolled or received WIC food for myself (yes/no) and my baby was enrolled or received WIC food (yes/no). These responses were categorized into two categories: Received WIC (for mother and/or child) or did not receive WIC (for mother or child).

Statistical analyses

All analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC). Skewness assessed the normality of the physical activity data, and the intraclass correlation coefficient (ICC) confirmed the reliability of including participants with ≥3 nights of sleep data in the analyses.[44] Continuous variables (age, total physical activity, nighttime, daytime and 24-hour sleep duration, number of nighttime awakenings) were summarized using means and standard deviations, and percentages were used to summarize categorical variables (sex, race, parent education, WIC status) at baseline. All models were likelihood based and used all observed data, resulting in validity under the missing at random assumption (MAR).

Total daytime physical activity was treated as the independent variable of interest. We estimated the separate associations of between- and within-person changes in physical activity with the sleep outcomes. The between-person variable estimates the association of a child's overall activity level over the course of the study with their sleep outcomes. The within-person variable estimates the association between change in physical activity (for example, from 6 months to 12 months) and sleep. The between-person effects used a child-level average physical activity variable, calculated as the average physical activity data from each of the four time points for each child. The within-person effects used an observation-level mean centered physical activity variable, calculated as the difference between the physical activity level at a specific time point and the child-level average physical activity variable. All physical activity variables were expressed as counts per day/1000 because regression coefficients for the physical activity variables were expressed in the tens of thousands of counts compared to the regression coefficient for the sleep variables, which were expressed in the tens and hundreds of minutes for the 24 hour and daytime/nighttime sleep duration variables, respectively. Sensitivity analysis were conducted assessing for collinearity between age and change in physical activity. Results did not indicate any collinearity between age and change in physical activity.

Unadjusted models were analyzed using the PROC MIXED. Separate models were created where daytime sleep duration, nighttime sleep duration, and 24-hour sleep duration were each used as the dependent variable. The PROC GLIMMIX command specifying a Poisson distribution assessed models where the number of nighttime awakenings was treated as the dependent variable. A negative binomial model was also tested for the analysis treating the number of nighttime awakenings as the dependent variable. Model fit criteria indicated a lower Akaike information criterion (AIC) and Bayesian Information criterion (BIC) for the Poisson model, indicating a better fit for the Poisson model than the negative binomial model.

Time was operationalized as the child's mean-centered age (cluster centered, in months) at each time point. Models included both the average physical activity variable and the mean-centered physical activity variable as independent variables. A mean-centered age by mean-centered physical activity interaction was included in each of the models to estimate whether the association between sleep and physical activity varied over time. An unadjusted model with baseline random effects was compared to a model with random effects for both baseline measures and the slope for each of the four possible models. The best-fitting model was chosen based on the smallest AIC, the -2 Log Likelihood (-2LL), and the BIC. Residual plots were created to check the assumptions of all models, and no violations were found.

Adjusted models followed the same format as unadjusted models, with the addition of covariates. Covariates in included the child's race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic, Other), and sex (male, female). A model with the highest level of education achieved by the mother (college or above, less than college) was compared to a model with WIC status (yes, no) for each of the eight possible combinations of sleep and physical activity variables. The best-fitting model was chosen using the AIC, the -2LL, and the BIC. Model fit for the final models assessing 24-hour, daytime and nighttime sleep duration was quantified by assessing the percent decrease in total model variance from the unadjusted models, which only included a random intercept, to fully adjusted models that included a random slope only.[45]

Results

Preliminary analyses

A total of 150 mothers and their children were enrolled in the study. Observations that did not meet the inclusion criteria for sleep were removed, resulting in a sample size of 109 children with sleep data at >1 time point(s): 88 children had sleep data at time point 1, 72 at time point 2, 56 at time point 3, and 55 at time point 4. One child was excluded due to missing data on WIC enrollment. This resulted in a sample size of N=108 for analyses assessing relationships between physical activity measured at the ankle and sleep duration and sleep quality. Physical activity data were normally distributed. ICCs ranged between 0.71 and 0.88 for the 24-hour sleep duration data, 0.72 and 0.95 for the daytime sleep duration data, 0.88 and 0.93 for the nighttime sleep duration data, and 0.42 and 0.76 for the number of nighttime awakenings data. Models where 24 hour and nighttime sleep duration were treated as dependent variables included both a random intercept and slope, while models that treated the number of daytime awakenings and nighttime sleep duration as the dependent variable only included a random intercept. Model fit was best for adjusted models when WIC status was treated as the SES variable.

There was a 20.73% percent decrease in total model variance from the unadjusted model to the fully adjusted model for nighttime sleep duration, but a 9.49% increase in total model variance for 24-hour sleep, and a 2.24% increase in total model variance for daytime sleep duration. The AIC and BIC of the adjusted Possion model were 932.51 and 959.33, respectively, which was lower than the AIC and BIC of the negative binomial model, which were 934.53 and 964.03, respectively.

Descriptive statistics

Table 2.1 describes the demographic characteristics of children measured at baseline. A majority of the children (50%) were Non-Hispanic White, followed by Non-Hispanic Black (27%), Hispanic (17%), and other (6%). Just over half of the children were male (56%) and 44% were female. Table 2.2 provides means, standard deviations and ranges for children's ages, sleep and physical activity data at each time point.

Unadjusted models

In unadjusted analyses, the between-subject effect of physical activity measured at the ankle was significantly associated with nighttime sleep duration ($p<.01$). In the unadjusted model measuring associations between physical activity measured at the ankle and sleep variables, age was positively associated with the number of nighttime awakenings (p=.05). Based on unadjusted analyses, children who were more physically active slept longer at night compared to children who were less physically active, and children woke up fewer times during the night as they got older. These associations were no longer significant in the adjusted models.

Adjusted models

Table 2.3 provides results of adjusted models assessing the relationship between sleep and physical activity measured using accelerometry at the ankle. The between-subject effect of physical activity was negatively associated with daytime sleep duration (p=.04). The within-subject effect of physical activity was negatively associated with 24-hour sleep duration (p=.0496). The negative association between the number of nighttime awakenings and age approached significance (p=0.07). Non-Hispanic Black children slept less at night compared to Non-Hispanic White children (p=0.01) and children in the Other race/ethnicity category woke up more times at night compared to Non-Hispanic White children (p=0.001). Children whose mothers were enrolled in WIC slept less at night compared to children whose mothers were not enrolled in WIC (p=0.0007).

Discussion

This study examined the longitudinal relationship between physical activity and sleep in very young children under 2 years of age, and found that children with greater average physical activity levels during the day had lower daytime sleep durations in the first two years of life, compared to children with lower average physical activity levels. Comparable associations were not seen between physical activity and children's nighttime and 24-hour sleep durations. Although other studies have found negative associations between sleep and physical activity in very young children,[21,46] these associations were seen in the nighttime[46] and 24 hour sleep period[21] and not in the daytime sleep period. A limited number of studies have found that higher physical activity levels were associated with longer sleep duration in very young children,[20,25] although they were limited by the use of parent-reported sleep data[25] and by not adjusting for the demographic characteristics associated with sleep.[20] The present study expands on previous research by examining these relationships over an 18-month time period and by using device-based measures of physical activity and sleep. The inverse association seen in the present study may be due to time constraints. Because there is a limited amount of time in the day, performing one activity displaces time a child has to perform another.[47] In other words, children who sleep more during the day may have less time to be physically active, and vice-versa. New data analysis techniques are being used to account for this constraint,[48] but they require data that differentiate between the time children spend sedentary and physically active. Physical activity intensity cut points have not yet been established for pre-ambulatory children, which means that a clear and consistent distinction between sedentary behavior and light-intensity physical activity cannot be made. Therefore, these new data analysis techniques cannot be conducted in infants and very young children until physical activity intensity cut points have been established. The novel statistical approach used in the present study also allowed for the assessment of how intra-individual changes in physical activity are associated with sleep. At assessment points when children were more physically active compared to their own average physical activity levels, they had a lower 24-hour sleep duration. The methodology applied to the present study has only been used in one other study assessing sleep and physical activity in very young children, which did not find that changes to average physical activity levels were associated with changes to average sleep durations.[31] The present study expanded on the limited previous research by assessing the sleep and physical activity relationship over a 2 year time period rather than over a week. The results of the current study indicated that 1000 more physical activity counts during the day corresponded with 40 less seconds of sleep over a 24-hour period. Although the sleep and physical activity relationship was significant when assessed over a longer period of time (i.e. 24 months), the magnitude of this relationship may not be clinically relevant. Nonetheless, the negative sleep and physical activity association in this study appears to be counterintuitive based on the findings seen in older children and adults, which suggest a positive relationship between the two behaviors.[17]

Multiple mechanisms have been used to explain the relationship between sleep and physical activity in adults and older children, but these mechanisms might not apply to infants and younger children.[27,31] As children transition from infancy, into toddlerhood, and then into childhood, they also transition from a polyphasic, to a biphasic, and ultimately a monophasic sleep pattern. Considering sleep patterns undergo multiple changes during this transition, it is possible that the relationship sleep has with other health behaviors, such as physical activity, also changes.[27,28] Additionally, very young children have very little control over the timing of activities, including bedtime and time for physical activity. The previously proposed mechanisms that exist in older children and adults may not appear until children begin to gain some autonomy over their schedule.[27] Researchers should avoid applying mechanisms developed in older children and adults to infants and very young children, and should instead consider whether there are other biopsychosocial mechanisms underlying the sleep and physical activity relationship in infancy and young childhood.

The current study did not find any association between physical activity and the number of nighttime awakenings, but found that the number of nighttime awakenings decreased over time. Although relationships between sleep quality and physical activity have been seen in toddlers and children, the results of the current study are consistent with the limited evidence which does not show that this relationship appears in infants.[23,49] The lack of a significant relationship may be potentially due to the measure used to define sleep quality, considering the number of nighttime awakenings was determined by proprietary software (MicroMini-Motionlogger, Ambulatory Monitoring, Inc.) and was not defined by the research team. Using a larger threshold, such as only considering awakenings that lasted >5 minutes, may lead to more accurate estimates of sleep quality,[49,50] possibly influencing results from this line of research. Before more work can be done assessing the relationship between sleep quality and physical activity in infants, more work is needed to define sleep quality in this age group and developing standardized, best-practices for measuring this variable.

Differences in sleep duration were seen across some race/ethnicity and SES groups. Specifically, Non-Hispanic Black children slept 40 minutes less than Non-Hispanic White children, and children whose mothers were enrolled in WIC slept 47 minutes less than children whose mothers were not enrolled in WIC. These results are consistent with data from the 2016–2018 National Survey of Children's Health, which showed that the prevalence of short sleep was highest among Black children and families with lower income.[51] There is a large amount of evidence pointing to various social and environmental factors related to sleep outcomes, including cultural practices surrounding sleep, exposure to discrimination, and the environment in the home and in the neighborhood.[52] Developing tailored interventions that address the individual-level behaviors of parents to improve their child's sleep is not sufficient, and more work is needed addressing the large-scale social determinants of health that are directly related to sleep in order to improve infant and toddler sleep in at-risk populations.

The major strength of this study was the use of device-based measures for both sleep and physical activity in a longitudinal study with a diverse population of infants and toddlers.[27] Furthermore, this study adds to the literature by using an analysis method which allowed for the assessment of differences between children's physical activity levels along with changes in individual children's physical activity levels, and their association with sleep over time, as opposed to only looking at differences between children.[29,30] Nevertheless, there are limitations to these method that must also be addressed. Firstly, the use of accelerometry in this age group can lead to inaccurate estimates due to movements caused by caregiver handling.[53] Furthermore, physical activity cut points have not been established, limiting the ability to assess whether the physical activity and sleep association varies by physical activity intensity. The use of actigraphy is also limited in this age group, as it is not very accurate at discriminating between sleep and wake classifications when the child is either inactive during a wake period or moving during a sleep period.[15] This study did not ask parents to keep sleep diaries in order to reduce participant burden and avoid the risk of additional data loss from non-compliance.[34] Although actigraphs from Ambulatory Monitoring Inc. (AMI) are the most commonly used actigraphs in pediatric sleep research, and the Sadeh et al. algorithm [35,36] utilizing the zero-crossing mode (ZCM) is the most commonly applied algorithm when scoring sleep measured with AMI devices,[54] the proprietary software used in the present study have not been validated for use in infant sleep research.

As more work is conducted on ways to improve sleep, it is important to understand whether physical activity can be used in multi-component interventions targeting improvements in sleep outcomes among infants and young children in the same way it has been used in adults.[55] The few interventions that have been conducted in younger children have resulted in null findings,[28] suggesting that although physical activity may be beneficial for other health outcomes such as the development of healthy weight status and motor development in very young children,[2] it may not be associated with sleep at this developmental stage. Future research should assess whether the sleep and physical activity relationship varies depending on physical activity intensity once established cut points are developed for physical activity in infants and very young children. Similarly, a standardized operational definition of sleep quality should be developed for infants and its longitudinal relationship should be assessed with physical activity. Finally, this study assessed the relationship between sleep and the within-and between-person effects of physical activity, but the relationship between physical activity and the within-and between-person effects of sleep should be considered as well.

Conclusions

The present study found that children with higher total physical activity levels slept less during the day compared to children with lower total physical activity levels. Additionally, when children were more physically active compared to their own average physical activity levels, their 24-hour sleep duration was lower. These results suggest that the mechanisms underlying the sleep and physical activity relationship in young children vary from those that have been suggested in older children and adults. Future research assessing the sleep and physical activity relationship in infants would benefit from the development of physical activity intensity cut points to determine whether the relationship varies depending on physical activity intensity.

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Table 2.1 Demographic characteristics of the study sample at baseline.

Variable	N (%)
WIC status	86
No assistance	54 (62.79)
WIC assistance	32 (37.21)
Race/Ethnicity	88
Non-Hispanic Black	24 (27.27)
Non-Hispanic White	44 (50.00)
Hispanic	15 (17.05)
Other	5 (5.68)
Sex	88
Female	39 (44.32)
Male	49 (55.68)
Maternal Education	87
Less than College	29 (33.33)
College or above	58 (66.67)

Table 2.2 Descriptive statistics of sleep and physical activity data at each time point

	Time point 1			Time point 2		
	N (%)	Mean (SD)	Range	N (%)	Mean (SD)	Range
Age (in months)	88	7.06 (1.52)	5.00-16.92	71	12.78 (1.01)	10.53-16.16
SLEEP						
24 hour sleep duration (mins)	88	742.03 (118.20)	460.05-1315.32	72	748.41 (71.63)	600.06-931.75
daytime sleep duration (mins)	88	190.99 (98.06)	74.50-685.80	72	186.16 (54.42)	59.75-328.43
nighttime sleep duration (mins)	88	549.47 (76.51)	319.00-711.71	72	561.85 (66.95)	393.80-668.87
# nighttime awakenings	88	5.27 (1.93)	1.24-10.00	72	4.77 (2.17)	1.60-11.89
PHYSICAL ACTIVITY						
Ankle VM CPH / 1000 (7AM-7PM)	85	80.46 (33.17)	31.40–166.67	61	91.84 (20.99)	41.49-148.99
Hip VM CPH / 1000 (7AM-7PM)	82	33.17 (12.95)	11.04–67.45	59	52.41 (15.89)	20.25-111.52
	Time point 3			**Time point 4**		
Age (months)	56	19.60 (1.52)	17.45-22.65	55	25.53 (1.53)	23.54-29.00
SLEEP						
24 hour sleep duration (mins)	56	751.16 (108.23)	594.67-1378.15	55	739.64 (68.70)	552.77-892.31
daytime sleep duration (mins)	56	197.01 (125.80)	83.01-879.83	55	168.42 (54.48)	29.82-332.76
nighttime sleep duration (mins)	56	557.05 (87.40)	321.01-681.29	55	571.08 (61.22)	430.65-691.69
# nighttime awakenings	56	4.36 (1.52)	1.20-7.50	55	4.28 (1.61)	0.50-7.89
PHYSICAL ACTIVITY						
Ankle VM CPH / 1000 (7AM-7PM)	56	109.19 (24.82)	59.53-177.40	30	125.74 (39.01)	52.41-227.09
HIP VM CPH / 1000 (7AM-7PM)	55	64.21 (16.96)	10.98-119.67	53	67.19 (12.62)	41.23-94.28

Table 2.3 Associations between physical activity measured at the ankle and sleep duration[a] and sleep quality[a], adjusted for independent factors.

	24HR sleep duration		**Daytime sleep duration[b]**		**Nighttime sleep duration**		**Number of nighttime awakenings[b]**	
	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value
Intercept	785.81 (36.69)	<.01	230.62 (31.55)	<.01	578.96 (26.83)	<.01	1.27 (0.16)	<.01
PA - b/w subject effect	-0.22 (0.31)	.48	-0.57 (0.27)	.04	0.18 (0.23)	.44	0.002 (0.001)	.17
PA - w/in subject effect	-0.67 (0.33)	.04	-0.57 (0.41)	.16	0.09 (0.20)	.65	-0.0005 (0.002)	.83
Age[c]	0.70 (1.05)	.50	1.13 (1.25)	.37	0.18 (0.76)	.81	-0.01 (0.006)	.07
PA[d]*Age[c]	-0.03 (0.05)	.55	0.02 (0.05)	.64	-0.05 (0.03)	.11	-0.00008 (0.0003)	.75
Race/ethnicity								
Non-Hispanic White	Ref		Ref		Ref		Ref	
Non-Hispanic Black	7.22 (21.67)	.74	27.28 (17.74)	.13	-40.56 (15.71)	.01	0.14 (0.09)	.11
Hispanic	30.30 (24.29)	.22	33.98 (20.00)	.09	-26.14 (17.88)	.15	0.07 (0.10)	.51
Other	-24.23 (33.75)	.48	42.57 (28.04)	.13	-39.99 (28.10)	.16	0.40 (0.12)	<.01
Sex								
Male	Ref		Ref		Ref		Ref	
Female	-15.14 (16.32)	.34	-14.78 (12.86)	.25	-9.09 (11.86)	.45	0.07 (0.06)	.27
WIC								

Not enrolled	Ref		Ref		Ref		Ref	
Enrolled	-34.59 (18.60)	.07	16.26 (16.19)	.32	-47.01 (12.72)	<.01	0.04 (0.08)	.63

PA: Physical activity, Ref: Reference category, w/in: within, b/w: between, WIC: Women, Infants and Children Nutrition Program
N=108
[a]Nighttime and daytime sleep duration and number of nighttime awakenings were normalized by dividing values by wear time and multiplying by 12. 24-hour sleep duration was normalized by dividing values by wear time and multiplying by 24.
[b]Model includes random intercept only
[c]Mean centered.
[d]Within subject effect of physical activity

CHAPTER 3

MANUSCRIPT TWO – LONGITUDINAL ASSOCIATIONS BETWEEN SLEEP AND WEIGHT STATUS IN INFANTS AND TODDLERS

Abstract

Study objectives: This study examined whether average sleep duration and changes in sleep duration among children from 6-24 months old were longitudinally associated with weight-for-length z-scores, and whether these associations varied by race/ethnicity, socioeconomic status, and sex.

Methods: Data were collected on 109 mother-child dyads when children were 6, 12, 18, and 24 months old (47% female, 43% Non-Hispanic White). Nighttime and 24-hour sleep duration were measured using actigraphy. Weight-for-length z-scores were calculated based on children's height and weight. Daytime physical activity was assessed using accelerometry. Diet was assessed using a feeding frequency questionnaire completed by the mother. Demographic characteristics were reported by the child's mother at baseline and included sex, race/ethnicity, and Women, Infants and Children Nutrition Program status. Separate associations of between- and within-person changes in nighttime and 24-hour sleep were estimated with weight-for-length z-score treated as the outcome variable in linear mixed model analyses, adjusting for demographic characteristics, physical activity and diet. Additional linear models were assessed that included interactions between sleep and demographic characteristics.

Results: At time points where children slept longer at night compared to their own average, their weight-for-length z-score was lower. This relationship was attenuated by their physical activity levels. The relationship between sleep and weight status did not vary based on demographic characteristics.

Conclusions: There is an inverse, longitudinal association between nighttime sleep duration and weight-for-length z-score in 6-24-month-old children

Key Words: sleep, weight status, physical activity, diet, infant

Introduction

Childhood overweight and obesity are associated with multiple negative health outcomes, including cardiovascular and metabolic disease, asthma, and chronic inflammation.[1] Furthermore, evidence suggests that obesity in childhood tends to persist in to adulthood.[2] Considering nearly 10% of children under the age of 2 years have a weight-for-length z-score that is above the 95th percentile on Centers for Disease Control and Prevention (CDC) growth charts,[3] it is imperative that prevention research develop effective strategies that can reduce the risk of children developing overweight or obesity. Obesity is associated with a number of modifiable health behaviors, including nutrition and physical activity.[4] Most interventions targeting obesity prevention in young children by improving nutrition and increasing physical activity have not been very successful.[5] The few interventions that include an additional sleep component seem to show more promise, suggesting sleep is an important factor to include to improve weight status outcomes even in the youngest of children.[5,6]

Based on sleep duration recommendations made by the American Academy of Sleep Medicine, children <2 years should sleep for at least 11-12 hours over a 24-hour day.[7] Global estimates report that children under the age of 3 years old average just under 13 hours of sleep over a 24-hour day.[8] Although there is also large body of work that suggests longer sleep duration is inversely associated with weight status, the evidence among infants and very young children is still not as conclusive as the findings seen among older children and adolescents.[9] The results from studies conducted on infants and very young children vary depending on the study design as well as the measures used to assess both sleep and weight status. More work is needed to understand whether short sleep duration is associated with higher weight status among the youngest age groups so that prevention efforts can be made at the earliest possible time.[10]

Longitudinal studies that have shown an inverse association between sleep and weight in very young children have relied primarily on parent-reported sleep.[11,12] Furthermore, very few studies have adjusted for other important factors related to weight, including physical activity or diet.[13] Of the few that have adjusted for one or both of these factors, they again rely on parent reports often collected at a single time point.[13] There is also a lack of longitudinal studies that disaggregate the within-person and between-person effects of sleep over time, which would help determine the extent to which differences in an individual's sleep duration (the within-person effect of sleep) are associated with weight status, as well as how differences between subjects' sleep duration (the between-subject variation in sleep) are associated with weight status.[14,15] Finally, there is some evidence to suggest that low-income and minority status children are less likely to meet sleep guidelines,[16–18] and that these children are also at a higher risk of overweight and obesity.[19] Higher rates of poor sleep duration and quality may explain, in part, why minoritized populations are at a higher risk of negative health outcomes associated with sleep, although this topic has been studied primarily among older children and adolescents.[20,21]

This study was designed to address these limitations by determining whether average sleep duration and changes in sleep duration in children from 6 months old to 24 months old are associated with weight-for-length z-scores over time. Additionally, the study assessed whether associations between sleep duration and weight-for-length z-score vary based on the child's race/ethnicity, socioeconomic status, or sex.

Methods

Participants and study design

Analyses were conducted using data from the Linking Activity, Nutrition and Child Health (LAUNCH) study,[22] which was designed to describe the relationships between physical activity, sedentary behavior and weight in young children as they transition from infancy to preschool. The present study used data collected at the first 4 time points, and children were approximately 6, 12, 18, and 24 months old at each time point, respectively. Participants were children and their biological mothers recruited from communities in South Carolina. Children were excluded if they had any physical limitation that prevented the use of accelerometry to assess physical activity.

Measures

Demographic characteristics. The child's mother reported her child's demographic characteristics at baseline. This included the child's sex (male/female) and race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic, Other). A proxy measure of socioeconomic status (SES) was collected at each time point (Women, Infants and Children Nutrition Program (WIC) status). Available responses for WIC status included: I was enrolled or got WIC food for myself (yes/no) and my baby was enrolled or got WIC food (yes/no). These responses were categorized into two categories: Received WIC (for mother and/or child) or did not receive WIC (for mother or child).

Weight status. Age- and sex-specific weight-for-length z-scores were used as a measure of the child's weight status and to account for weight gain due to normal growth and development. Weight-for-length z-score was used instead of BMI z-score because of CDC recommendations.[23] Trained data collectors measured weight and length/height at the 6-month time point. Due to COVID-19, 5% of weight status measures were collected by mothers and 2% of weight status measures were collected by the child's pediatrician during the child's checkup at the 12-month time point; 39% were collected by mothers and 1% was collected by the child's pediatrician during the child's checkup at the 18-month time point; and 87% were collected by mothers and 5% were collected by the child's pediatrician during the child's checkup at the 24-month time point. For time points where data were collected by trained data collectors, Seca Digital Baby Scales and measuring rods (model 334; Chino, CA) were used to measure supine length and weight in children until the age of 2 years old. Seca scales (model 869; Chino, CA) were used to measure weight in children who were able to stand independently at the time of measurement, and height was measured using a Shorr board (Shorr/Weigh and Measure, LLC, Olney, MD). Age- and sex-specific weight-for-length percentiles and z-scores were calculated based on World Health Organization (WHO) growth charts.[24]

Sleep. Sleep was measured using an actigraph (MicroMini-Motionlogger, Ambulatory Monitoring, Inc.), worn on the left ankle for 24 hours/day over one week and removed only during water-based activities. Data were assessed using the manufacturer software (Action4, Version 1.16, Ambulatory Monitoring, Inc., Ardsley, New York, USA). Sleep diaries were not used alongside actigraphy in this study to reduce participant burden and avoid a loss of data resulting from non-compliance with sleep diary completion.[25] Sleep duration variables were assessed in 60-second epochs and computed using the Sadeh et al. algorithm.[26,27] Wear time was determined using the LIFE channel from the manufacturer software (MicroMini-Motionlogger, Ambulatory Monitoring, Inc.)[28]. Only participants with ≥3 days/nights with ≥10 hours of data per night were included in analyses assessing nighttime sleep duration, and only participant with ≥3 24-hour days with ≥20 hours of data per night were included in analyses assessing 24-hour sleep duration. Nighttime sleep duration was operationalized as the average number of minutes spent sleeping between 7 PM and 7 AM. Twenty-four-hour sleep duration was operationalized as the average number of minutes spent sleeping between 7 AM and 7 AM the following day. The nighttime and 24-hour sleep duration variables were normalized by being divided by wear time and extrapolated into 12 and 24 hours, respectively.

Physical activity. Total physical activity was assessed using ActiGraph accelerometers (GT3X model, Pensacola, FL). Accelerometers were worn on the right ankle and were removed at night and during water-based activities. Accelerometers were initialized to begin collecting data at midnight following accelerometer distribution. Data were collected in raw data mode at 80 Hz and downloaded using 15-second intervals.[29] Any ≥60 minute period of consecutive zeros and was considered non-wear time and was excluded from analyses.[30] Missing physical activity data were imputed for children who had >1 days of >8 hours of accelerometry data. This was done using the PROC MI command with 20 imputations to predict missing vector magnitude count values for each individual day. Predictor variables in the regression model used for imputation included the seven days of vector magnitude counts and the number of hours of wear time for each of the seven days. The mean vector magnitude counts over seven days were averaged for each child after imputation. The total physical activity counts variable was defined as the average number of vector magnitude counts per hour between 7 AM and 7 PM each day.

Diet. The child's mother reported how often their child was fed food from a list of 17 different foods at all 4 time points. Questions were derived from the Infant Feed Practices Study.[32] The following scores were applied to responses: more than once per day - 8; every day - 7; 5-6 days - 5.6; 3-4 days - 3.5; 1-2 days - 1.5; Not at all – 0. Scores for the following foods were summed to create a score for the "High quality" category: Breast milk, cow's milk, other dairy, other soy foods, baby cereal, Other cereals/starches, fruit, vegetables, meat/chicken/combo meals, fish or shellfish, peanut butter/other peanut foods/nuts, egg. Scores for the following foods were summed to create a score for the "Low quality" category: Formula, 100% fruit or vegetable juice, sweet drinks, French fries, sweet foods. The decisions for categorizing foods into low or high quality was based on the 2020-2025 US Dietary guidelines.[33] Low quality food scores were reverse scores and summed with the high quality food scores to create an overall food quality score.

Statistical analyses

All analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC). The normality of the physical activity data was determined by assessing their skewness and kurtosis. Skewness values between -2 and 2 and kurtosis values between -7 and 7 were the criteria used to determine whether data were normally distributed.[34] The intraclass correlation coefficient (ICC) was used to provide evidence that aggregating sleep data at the time point level for participants with ≥3 nights of sleep data was appropriate.[35] Continuous variables (age, total physical activity, nighttime, and 24-hour sleep duration, weight-for-length z-score, and total food quality) were summarized using means and standard deviations at each time point, and percentages were used to summarize categorical variables (sex, race/ethnicity, WIC status) at baseline.

Nighttime and 24-hour sleep duration were treated as the independent variables of interest in separate analyses. Nighttime and 24-hour sleep duration data from each of the four time points were averaged for each child to create average nighttime and 24-hour sleep duration variables. These variables represented the between-person effects of sleep. Nighttime and 24-hour sleep duration variables were also mean-centered at each time point based on each child's individual data to create centered nighttime and 24-hour sleep duration variables. These variables represented the within-person effects of sleep, and allowed the variable to be interpreted as the deviation for a person's average sleep duration. All sleep variables were expressed as minutes per day or night/10 because regression coefficients for the sleep duration variables were expressed in hundreds of minutes compared to the regression coefficient for the weight-for-length z-score variable, which was expressed in the single digits.

All models were analyzed using the PROC MIXED command. Separate models were created nighttime and 24-hour sleep duration. included average sleep duration and mean-centered sleep duration as independent variables. Residual plots were created to check the assumptions of all models, and no violations were found. All models used all observed data and were likelihood based, which suggested their validity under the missing at random assumption.

First, unadjusted models were created where the within- and between-subject effect of sleep were included as independent variables. Next, models adjusted for demographic characteristics and included the child's race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic, Other), sex (male, female), and WIC status (yes, no) as covariates. A third model assessed the additional effect of physical activity, and a fourth model assessed the additional effect of diet on the sleep and weight relationship. Models 3 and 4 also included the sleep and demographic characteristics as covariates. Model fit was quantified by assessing the percent change in total model variance from the unadjusted models to the fully adjusted models.[36]

Six separate models were created to assess whether the association between sleep and weight-for-length z-score in children varied by race/ethnicity, socioeconomic status, and sex. Three models were used to assess variations in the 24-hour sleep and weight-for-length z-score relationship, while the other three models assessed variations in the relationship between nighttime sleep and weight-for-length z-score. In all of the interaction models, the sleep duration variables were not averaged or mean centered. Models included the total physical activity counts variable and the overall food quality variable. A separate model was created for each of the demographic characteristics, and this demographic characteristic was included in the model along with a 2-way interaction between the demographic characteristic and the sleep duration variable. Comparisons between groups were made only if there was a significant overall effect of an interaction. All models were analyzed using the PROC MIXED command and included a random intercept.

Results

A total of 150 mothers and their children were enrolled in the study. Observations that did not have a measure of weight-for-length z-score at any time point were removed, resulting in a sample size of 148 children with a weight-for-length z-score measure at >1 time point(s). Two children were missing data on WIC enrollment and three children were missing data on diet. Seven children did not meet inclusion criterial for physical activity measured at the ankle, 36 children did not meet inclusion criterial for 24-hour sleep duration, and 28 children did not meet inclusion criterial for nighttime sleep duration. This resulted in a sample size of N=110 for adjusted analyses assessing relationships between 24-hour sleep duration and weight-for-length z-score, and a sample size of N=116 for adjusted analyses assessing nighttime sleep duration and weight-for-length z-score. Skewness values for physical activity ranged from 0.58-0.74, and kurtosis values for physical activity ranged from 0.32-1.03. These values confirmed that physical activity data were normally distributed. Nighttime sleep duration ICCs ranged from 0.88 and 0.93 and 24 hour sleep duration ICCs ranged from 0.71 and 0.88, confirming the appropriateness of aggregating sleep data at the time point level for participants with >3 days of data. There was a 2.23% percent increase in total model variance explained from the unadjusted model to the fully adjusted model for nighttime sleep duration, and a 2.35% increase in explained total model variance for 24-hour sleep duration.

Descriptive statistics

Table 1 provides information on children's demographic characteristics measured at baseline. Most children (43.75%) were Non-Hispanic White, followed by Non-Hispanic Black (33.33%), Hispanic (18.06%), followed by other (4.86%). Around half of the children were male (52.78%) and 47.22% were female. The average weight-for-length z-score ranged from 0.55 to 0.73 over the study period. Children slept for an average of 12 hours per 24-hour day and 9 hours per night. Children's physical activity levels increased from 6 months to 24 months. Food quality increased from time point 1 to time point 2, and then remained stable throughout the rest of the study period. Table 2 provides means, standard deviations and ranges for children's ages, weight-for-length z-scores, sleep, physical activity, and diet data at each time point.

Weight-for-length z-score and sleep duration

The within-subject effect of nighttime sleep duration was significantly associated with weight for length z-score ($p<.05$) in unadjusted analyses, and approached significance in models adjusting for demographic characteristics ($p=.07$). The between-subject effect of nighttime sleep duration approached significance with weight for length z-score in adjusted models ($p<.10$). In models where 24-hour sleep duration was treated as the primary independent variable of interest, none of the variables were significantly associated with weight-for-length z-score. Details on these analyses can be found in Table 3.

Interactions between sleep and demographic characteristics

In models assessing interactions, none of the 24-hour sleep by demographic characteristic interactions were associated with weight-for-length z-score ($p>.05$). There was a significant interaction between nighttime sleep and race/ethnicity, which showed that children in the "Other" race/ethnicity category slept significantly less than White and Hispanic children. It is important to note, though, that there were only 7 children in this category. Therefore, these results were not interpreted further (Results not shown).

Discussion

This study examined the longitudinal relationship between sleep and weight status in children in the first two years of life. A unique analytic strategy considered both the effect of inter-child differences in average sleep duration on weight status, as well as the effect of intra-individual changes in sleep duration on weight status. No significant relationship was found for the “between-children” association, however there was a “within-child” association shown for nighttime sleep duration and weight status in unadjusted models. Specifically, when children in the present study slept longer at night compared to their own average nighttime sleep duration, they had a lower weight-for-length z-score. These results are consistent with other longitudinal studies showing an inverse association between sleep duration and weight status in very young children.[10,12] Although research on the relationship between sleep and weight status has become more common in the past decade, results among very young children are more mixed than those seen among older children and adults. This may be explained by variability in methods used to measure sleep and weight status as well as the use of cross-sectional study designs.[10] The present study overcomes these limitations by using objective measures for both sleep and weight status, and by assessing the relationship longitudinally.

In the present study, the inverse relationship between sleep and weight-for-length z-score was seen for nighttime sleep duration and not for 24-hour sleep duration. Although daytime naps are considered to be a potential tool for combatting sleep deprivation and are associated with greater cognitive health outcomes, it is still unclear whether daytime and nighttime sleep are both associated with weight status.[37,38] Much of the research has assessed 24-hour sleep rather than looking at nighttime and daytime sleep separately,[37] but the results of this study suggest that the development of weight status may have a specific relationship with nighttime sleep duration in this age group. Considering that short sleep is associated with higher weight status in adolescence[9] and adulthood[39] when sleep is fully consolidated into the nighttime,[40] future research should explore whether biological events that occur only during nighttime sleep are the potential mechanisms driving this relationship.

Some of the biological mechanisms used to explain the association between sleep and the development of weight status consider the way sleep regulates hormones associated with appetite and metabolism, and inflammation. In other words, poor sleep can potentially lead to a higher appetite, a slower metabolism, and greater inflammation, all of which can lead to unhealthy weight gain.[12] Other theories posit that the chronobiological pathways that promote sleep consolidation and aid in the development of sleep patterns are connected to the neuroendocrine and metabolic systems. Chronobiological dysregulation may lead to dysregulation in these other biological pathways, especially among infants.[41] It is important to note that many of these mechanisms have been studied primarily in older children and adults, and the research exploring these potential biological pathways among younger children is highly inconstant and limited.[13]

Another mechanism proposed to explain the inverse relationship between sleep and weight status considers the potential role of physical activity,[42] which was a significant factor in analyses for the present study. It is hypothesized that better sleep leads to less fatigue, which in turn results in higher physical activity levels, lessening unhealthy weight gain.[42] It is important to note, though, that this pathway is not yet supported by research in infants and young children.[13] Even so, the within-subject effect of sleep was only associated with weight status in the present study when physical activity was not included in analyses. Once models adjusted for physical activity, the within-subject effect of sleep was no longer associated with weight status. In other words, the nighttime sleep and weight status relationship seen in Models 1 and 2 in Table 3 was confounded by physical activity. Physical activity is associated with weight status in children of all ages.[43] This study suggests that either the effect of daytime physical activity overrode the effect short nighttime sleep had on weight status, or it potentially eliminated some of the influence of sleep such that it was no longer significantly associated with weight status. Regardless of the exact mechanism, the results of this study show that daytime physical activity has a protective effect on the development of weight status.

Both sleep and physical activity were associated with weight status in the present study, yet research on interventions targeting weight status by improving these two behaviors is still limited among infants and very young children. A review by Yoong and colleagues (2016) examined the effect of interventions that included a sleep component had on weight status, and found that most interventions showed null results. They hypothesized that this was most likely due to the inability to significantly improve sleep in most of the interventions included in the review.[6] Of the few interventions that have shown promise in improving some features of sleep among infants and young children, nearly no follow-up work was has been conducted to understand whether these changes in sleep had an effect on weight status.[42] Based on the results of the present study, obesity prevention interventions should focus in increasing both sleep duration and physical activity levels. These interventions should be incorporated into the home as well as in the childcare setting, if applicable. For example, parents can learn about optimal bedtime routines and what behaviors they and their children should avoid before bedtime.[42]

The association between sleep duration and weight-for-length z-score in children from 6 months old to 24 months old did not vary over time by race/ethnicity, socioeconomic status, or sex. Research has shown that low-income and minority youth are at a higher risk of not meeting sleep guidelines, and that the prevalence of overweight and obesity is higher among low income and minority youth.[13,44] The present study did not see these differences in weight-for-length z-score by demographic characteristics. Although some research has identified differences in sleep duration by race/ethnicity and socio-economic status in this age group,[17] it is still not clear how early the relationship between sleep and weight status may appear. Future research should address this gap so that interventions are implemented at a suitable age.

The major strength of this study was the use of device-based measures for sleep and physical activity and objective measures of weight and length to calculate weight-for-length z-scores in a longitudinal study with a diverse population of infants and toddlers. An additional strength was the analysis method that allowed for the assessment of differences between children's sleep durations along with changes in individual children's sleep durations and their association with weight status over time, as opposed to only looking at differences between children. It is important to note, though, that there are limitations to the use of actigraphs in this age group. Actigraphs are less accurate at differentiating between sleep and wake classifications when very young children are either inactive during a wake period or moving during a sleep period, compared to older children and adults.[45] This accuracy could be improved with the use of sleep diaries, but parents were not asked to complete sleep diaries in order to reduce participant burden and avoid the risk of additional data loss from non-compliance.[25] Because of this limitation, it is difficult to accurately measure sleep quality in infants and very young children,[25] which limits studies that assess relationships between sleep quality (eg., number of nighttime awakenings or sleep efficiency) and the development of weight status. Future research should find ways to better assess sleep quality in this age group.

Conclusions

Children's weight-for-length z-scores were lower at time points where they slept longer compared to their own average nighttime sleep durations. This relationship was attenuated by their daytime physical activity levels. These results suggest that the underlying mechanisms driving this relationship may be specifically related to the biological events that occur during nighttime sleep, and that physical activity may also have a protective effect on the development of weight status in very young children.

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Table 3.1 Demographic characteristics of the study sample at baseline.

	N	%
Race/Ethnicity	144	
Non-Hispanic White	63	43.75
Non-Hispanic Black	48	33.33
Hispanic	26	18.06
Other	7	4.86
Sex	144	
Female	68	47.22
Male	76	52.78
WIC status	139	
No assistance	76	54.68
WIC assistance	63	45.32

Table 3.2 Descriptive statistics at each time point.

	Time point 1			Time point 2		
	N (%)	Mean (SD)	Range	N (%)	Mean (SD)	Range
Age (in months)	144	6.91 (1.41)	4.67-16.92	123	12.68 (0.81)	10.53-16.16
Weight-for-length z-score	141	0.55 (1.14)	-2.13-3.11	123	0.73 (1.03)	-2.64-3.46
24 hour sleep duration[a] (min)	90	74.44 (11.81)	46.01-131.53	70	75.67 (8.03)	60.01-105.59
Nighttime sleep duration[a] (min)	94	55.30 (7.65)	31.90-71.17	78	56.78 (7.23)	39.38-69.12
Physical Activity (ankle)[b]	130	77.86 (24.93)	30.83-166.67	98	91.05 (20.19)	41.49-159.48
Food quality score	137	7.76 (6.26)	-5.00-22.00	120	14.75 (5.85)	0.00-31.00
	Time point 3			**Time point 4**		
Age (in months)	87	19.70 (1.46)	17.45-22.68	86	25.53 (1.51)	23.04-29.26
Weight-for-length z-score	87	0.66 (1.15)	-1.57-4.27	86	0.62 (1.17)	-2.26-3.85
24 hour sleep duration[a] (min)	54	75.17 (11.02)	59.47-137.81	53	73.76 (6.82)	55.28-89.23
Nighttime sleep duration[a] (min)	61	56.40 (8.93)	32.10-68.13	57	56.99 (6.86)	34.93-69.17
Physical Activity (ankle)[b]	81	105.27 (26.44)	41.42-177.40	40	127.55 (37.14)	57.98-227.08
Food quality score	85	15.25 (4.93)	3.00-27.00	86	15.24 (4.85)	-2.00-28.00

[a]Sleep duration is expressed as minutes per 24 hour day or 12 hour night/10.
[b]Physical activity was expressed as average vector magnitude counts per hour/1000

Table 3.3 Associations between weight-for-length z-score and 24-hour and nighttime sleep duration[a]

	Model 1 Unadjusted		Model 2 Demographic char.		Model 3 Physical activity		Model 4[b] Diet	
	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value
24 HR Sleep[a]	N = 112		N = 111		N = 111		N = 110	
Intercept	0.72 (0.76)	.35	0.39 (0.81)	.63	0.41 (0.86)	.63	0.69 (0.88)	.43
Sleep - w/in subject effect	-0.008 (0.008)	.30	-0.009 (0.008)	.25	-0.005 (0.009)	.55	-0.005 (0.009)	.54
Sleep - b/w subject effect	-0.001 (0.01)	.89	-0.0001 (0.01)	.99	-0.003 (0.01)	.81	-0.007 (0.01)	.48
Physical activity (ankle)					0.002 (0.002)	.35	0.001 (0.002)	.63
Food Quality score							0.02 (0.01)	.11
Nighttime Sleep[a]	N = 120		N = 119		N = 117		N = 116	
Intercept	1.56 (0.69)	.03	1.62 (0.85)	.06	1.59 (0.88)	.07	1.57 (0.88)	.08
Sleep - w/in subject effect	-0.02 (0.01)	.05[b]	-0.03 (0.01)	.07	-0.02 (0.01)	.13	-0.02 (0.01)	.12
Sleep - b/w subject effect	-0.02 (0.01)	.18	-0.02 (0.01)	.15	-0.03 (0.01)	.08	-0.03 (0.01)	.06
Physical activity					0.003 (0.002)	.10	0.003 (0.002)	.18
Sum Quality food score							0.01 (0.01)	.20

w/in: within, b/w: between

[a]Nighttime sleep duration was normalized by dividing values by wear time and multiplying by 12. 24-hour sleep duration was normalized by dividing values by wear time and multiplying by 24.

[b]$p = .047$

CHAPTER 4

MANUSCRIPT THREE – LONGITUDINAL ASSOCIATIONS BETWEEN SLEEP AND PHYSICAL ACTIVITY IN OLDER ADOLESCENTS

Abstract

Study Objectives: This study examined whether vigorous physical activity (VPA) and total physical activity (TPA) are longitudinally associated with nighttime sleep duration among older adolescents, and determined if these associations differed between weeknight sleep and weekend night sleep

Methods: Analyses were conducted using data from 1,959 participants (56% female, 47% White) in the Next Generation Health study. Weekend night and weeknight sleep duration were assessed via questionnaire, as were TPA and VPA. TPA was operationalized as the number of days in the past week respondents reported being physically active for >60 minutes per day. VPA was operationalized as the number of hours per week respondents reported participating in VPA.

Results: For every extra day older adolescents participated in >60 minutes of TPA, they slept 31 minutes less per night on weekend nights. Older adolescents who participated in >7 hours of VPA in the past week slept 216 minutes longer per night on weekend nights than those who did not participate in VPA. Neither TPA nor VPA were associated with weeknight sleep.

Conclusions: High levels of vigorous-intensity physical activity were associated with a longer sleep duration on the weekends, while overall physical activity had an inverse association with weekend sleep duration. Both day type and physical activity intensity need to be considered when examining the relationship between physical activity and sleep in older adolescents.

Key Words: sleep; physical activity; intensity; weekend; weekday

Introduction

According to the American Academy of Sleep Medicine, adolescents between the ages of 13 and 18 years should be sleeping 8-10 hours per night.[1] According to the 2nd edition of the Physical Activity Guidelines for Americans, children between the ages of 6-17 years old should be participating in one hour or more of moderate-to-vigorous physical activity (MVPA) every day, and vigorous physical activity (VPA) should occur on >3 days per week.[2] Current surveillance data estimate that 83% of adolescents meet sleep guidelines, but only 18.2% of adolescents are currently meeting physical activity guidelines. Even less are meeting both sleep and physical activity guidelines.[3] Children and adolescents who are from historically marginalized racial or ethnic groups are less likely to meet sleep guidelines compared to White students.[4,5] Differences in physical activity levels by race and ethnicity and socioeconomic status are not as consistent, although there is consistent evidence that males are more likely to meet the physical activity guidelines than females.[6]

Obtaining adequate levels of both sleep and physical activity is important considering these behaviors have been shown to be associated with cognitive,[7,8] psychological,[9,10] cardiovascular,[11,12] and metabolic[13,14] health in adolescents. There is also evidence of a moderate, positive, bidirectional relationship between physical activity and sleep,[15–17] and multiple psychological and biological mechanisms have been suggested to explain this relationship. Unfortunately, a majority of these pathways have been studied exclusively in adults,[18] and it is unclear whether these mechanism also exist in younger populations. Studies assessing the relationship between physical activity and sleep show a weak to moderate association regardless of whether child-reported or device

–based measures are used for both behaviors.[17] Notably, child-reported sleep and physical activity questionnaires are widely used, are low in cost, and are easy to administer in large, epidemiological studies.[17,19,20] Having a clear understanding of the relationship between physical activity and sleep is necessary when considering the relationship both behaviors have with health outcomes like overweight and obesity.[21] Understanding this bidirectional relationship may be the key to improving prevention research targeting overweight and obesity in children and adolescents.

A number of limitations exist in the literature evaluating relationships between physical activity and sleep. First, there is evidence that this relationship is moderated by day type, i.e. weekdays vs. weekends,[22,23] although this line of research is still limited and the strength of relationships that are seen are weak.[24] Assessing the effect differences in weeknight and weekend night sleep (also referred to as social jetlag) have on the physical activity and sleep relationship is especially important among adolescents. Adolescents are naturally more likely to stay up later in the evening due to developmental changes, and wake up earlier in the day during the week due to social obligations, namely school.[8,25] Furthermore, physical activity intensity may be another moderator in the physical activity and sleep relationship, although this line of research also shows mixed results.[16,18] Research is also lacking in analyses that adjust for demographic characteristics, such as gender, race/ethnicity, and socioeconomic status (SES).[17] Therefore, this study will address these limitations by examining the longitudinal relationships between physical activity and sleep in older adolescents participating in the Next Generation Health (NEXT) study. Specifically, this study will assess whether vigorous PA (VPA) and total PA (TPA) are associated with nighttime sleep duration among older adolescents over time, and consider whether these associations vary between weeknight sleep and weekend night sleep.

Methods

Participants

Analyses were conducted using data from the NEXT study. The NEXT study was designed to identify factors that promote positive health behaviors as well as health risk behaviors in older adolescents as they transition into young adulthood. The study collected data yearly beginning when older adolescents were 15 years old and in the 10th grade. Data collection was completed by 2017, when participants were 21 years old. The present study focused on the associations between physical activity and sleep using the first 3 years of data, which is when both sleep and physical activity data were collected. Older adolescents were recruited from 81 schools that chose to participate in the study, which were selected from school districts stratified across nine different U.S. Census divisions. Recruitment took place in tenth-grade classrooms that were randomly selected from each of these schools to create a nationally representative cohort of older adolescents. Black participants were oversampled. Participants provided assent and parents of participants provided consent at each time point. If participants were 18 years old at any time of the study, they provided adult consent and parental consent was not obtained.

Measures

Sleep. In order to assess weeknight sleep duration, participants were asked two questions: "On days that you go to school, work, or similar activities, what time do you usually wake up?" and "On days that you go to school, work, or similar activities, what time do you usually go to sleep the night or day before?". Sleep duration on weeknights was calculated from these times in minutes. In order to assess weekend night sleep duration, participants were asked two questions: "On days that you don't have to get up at a certain time, what time do you usually wake up?" and "On days that you don't have to get up at a certain time, what time do you usually go to sleep the night or day before?". Sleep duration on weekend nights was calculated from these times in minutes. These questions are questions asked in the National Longitudinal Study of Adolescent Health.[26] Participants were excluded if they reported <300 or >900 minutes of sleep per night, based on the cutoff found in Haynie and colleagues (2018), who also used data from the Next Generation Study for their analyses.[27]

Physical Activity. Survey instruments assessed physical activity using two separate questions. Participants were asked to report the number of days in the past week that they were physically active for >60 minutes per day. Responses ranged from 0 to 7 days. This was based on the question used in the National Youth Risk Behavior Surveillance Survey,[28] and was used to operationalize TPA. Participants were also asked to report the number of hours per week they usually engaged in vigorous physical activity so much that they got out of breath or sweat. Responses included: none; about half an hour; about an hour; about 2-3 hours; about 4-6 hours; about 4-7 hours. This was based on the question used in the Health Behavior in School-Aged Children Survey,[29] and was used to operationalize VPA.

Demographic characteristics. Demographic characteristics were reported by the adolescent at baseline. These include sex (male/female), race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic, Other), and SES (highest level of education achieved by either parent). Available responses for parental education included: less than high school diploma, High school diploma/GED, Some college/technical school, associate's degree, bachelor's degree, Graduate degree. This variable was further dichotomized into: high school diploma or less; greater than a high school diploma. Age was provided in months and was converted to years by dividing the original variable by 12.

Statistical analyses

All analyses were conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC). Continuous variables were summarized using means and standard deviations, and percentages were used to summarize categorical variables at each time point. Only participants with sleep, TPA and VPA data at >2 time point(s) were included in the analysis. Comparisons between participants included in analysis and participants excluded in analyses were done using t-tests and chi-square analyses.

Unadjusted and adjusted linear mixed models were assessed using PROC MIXED. In unadjusted analyses, separate models used weeknight and weekend night sleep duration as the dependent variable. TPA and VPA were entered as independent variables, with TPA entered as a continuous variable and VPA entered as a categorical variable. The participant's age in years was used as a measure of time. Interaction terms for TPA by age in years and VPA by age in years were included in analyses as well. Adjusted models included the same variables as unadjusted models, with the addition of the demographic characteristics. Residual plots were created to check the assumptions of the models.

Results

Preliminary analyses

From the original dataset that included 2784 participants, 196 were missing data on VPA, 197 were missing data on TPA, 474 were missing data on weeknight sleep, 748 were missing data on weekend night sleep. This included 717 participants at time 1, 655 participants at time 2, and 548 participants at time 3 that did not meet criteria of 300-900 minutes of sleep on weeknights, and 1,024 participants at time 1, 886 participants at time 2, and 684 participants at time 3 that did not meet criteria of 300-900 minutes of sleep on weekend nights. This resulted in a final sample of 1,959 participants. Excluded participants were significantly different in their distribution of gender and race/ethnicity, and were older by an average of around 2 months at each time point. More detailed information on these differences can be seen in Table 1. Residual plots confirmed that there were no violations to the assumptions of all models.

Descriptive characteristics

A majority of participants in the sample were Non-Hispanic White (47.32%), a majority were female (56.56%) and a majority had parents with a high school education or higher (85.80%). More information regarding demographic characteristics can be found in Table 1. Participants averaged 7.5 hours of sleep per weeknight and just over 9 hours of sleep on weekend nights. One-fourth of participants met physical activity guidelines at baseline. More information on sleep and physical activity at all three time points can be found in Table 2.

Weeknight sleep

Neither TPA nor VPA were associated with weeknight sleep in unadjusted or adjusted models ($p>.05$). Adjusted models showed that Non-Hispanic Black participants slept 30 minutes less per night on weeknights compared to Non-Hispanic White participants ($p<.01$), and Hispanic participants slept 10 minutes less per night on weeknights compared to Non-Hispanic White participants ($p<.01$).

Weekend night sleep

TPA was negatively associated with weekend night sleep duration ($p=.02$), and the TPA by age interaction was positively associated with weekend night sleep ($p=.02$). For every extra day older adolescents met TPA guidelines, they slept 31 minutes less per night on weekend nights. This difference increased by nearly 2 minutes per night for every 1 year increase in age. The negative association between VPA and weekend night sleep approached significance, but only for older adolescents who were acquiring >7 hours of VPA in the past week ($p=.06$). The interaction between VPA and age was also only significant for older adolescents who participated in >7 hours of VPA in the past week ($p=.04$). Older adolescents who participated in >7 hours of VPA in the past week slept 216 minutes longer per night on weekend nights than older adolescents who did not participate in VPA, and this difference decreased by 13 minutes per night for every 1 year increase in age. Age was negatively associated with weekend night sleep in adjusted models ($p<.01$). For every 1 year increase in age, participants slept 10 minutes less per night. Non-Hispanic Black participants slept 16 minutes less per night on weekend nights compared to Non-Hispanic White participants ($p<.01$), females slept 15 minutes less per night on weekend nights compared to males, and participants whose parents had a high school education or higher slept 16 minutes less per night on weekend nights compared to participants whose parents had less than a high school education.

Discussion

The main finding of this study was that TPA was negatively associated with weekend night sleep duration in a large, nationally representative sample of older adolescents over a 2-year period of time. These results were not seen for analyses where weeknight sleep duration was the dependent variable. This negative association is inconsistent with previous literature in this age group.[17] However, it is important to note that very few of the previous studies in this age group have employed a longitudinal study design that is comparable to the present study.[24] In fact, no previous study assessing the relationship between physical activity and sleep has employed a longitudinal study design with a follow-up period of 2 years. Considering much of the previous evidence has relied on studies with small sample sizes and cross-sectional designs,[17] the results seen in the present analysis may be attributed to the unique methodology. Furthermore, this study accounted for day type and physical activity intensity, which are important, but rarely studied, factors in the adolescent physical activity and sleep literature. The results suggest that the relationship between physical activity and sleep in older adolescents is more complex than has been previously understood. As such, the positive association previously thought to exist between these two behaviors may be incorrect.

This study showed that the relationship between physical activity and sleep differed by day type. Associations between physical activity and sleep were only seen when weekend night sleep duration was the dependent variable. The results of the present study were similar to those of Berry and colleagues, who also concluded that being physically active for 6-7 days per week was associated with a longer sleep duration on weekend nights. They concluded that individuals who are more tired may not have the energy to participate in physical activity on the weekends and instead choose to sleep longer. They further suggested that participants who are sleep deficient but participate in sports may not have time to sleep longer but may have higher physical activity levels due to time spent practicing or competing on weekends.[23] This factor has been understudied in the older adolescent physical activity and sleep literature. Older adolescents naturally stay up later in the evening, wake up earlier in the day during the week for school, and sleep in on weekends in an attempt to make up for this sleep loss.[25,30] Therefore, social jetlag, or the difference between weeknight vs. weekend night sleep durations, is very relevant in this age group. The impact of day type on the relationship between physical activity and sleep in the current study suggests more work is needed assessing the effect reductions in social jetlag have on physical activity levels, and whether physical activity is an effective tool for reducing social jetlag among older adolescents.

In addition to day type, this study found that the relationship between physical activity and sleep differed based on physical activity intensity. TPA had a negative association with weekend night sleep duration, while VPA had a positive association with sleep when participants were acquiring >7 hours of VPA per week. In research on adults, physical activity intensity does not appear to influence the relationship between physical activity and sleep in healthy populations, but has been seen to influence this relationship in adults with sleep disorders.[15] This suggests the potential of ceiling or floor effects in the literature, and may explain why a positive association between physical activity and sleep only appeared when older adolescents participated in >7 hours of VPA per week.

The issue of physical activity intensity is very understudied in the older adolescent physical activity and sleep literature.[17] The present results are consistent with the limited evidence in adolescent[31,32] and young adult[33] populations, although it is unclear whether this is due to biological or psychological mechanisms. More research is needed to identify potential mechanisms underlying the relationship between physical activity and sleep in older adolescents, especially through the use of longitudinal study designs in diverse populations.

In an unexpected finding, the association between VPA and weekend night sleep duration was only significant when demographic characteristics were included in the analysis. Race/ethnicity, sex, and SES all contributed to the variance in models assessing relationships between physical activity and weekend night sleep duration. These results are consistent with previous literature that show that females sleep less than males,[23,34] White adolescents have the longest sleep durations, and that SES does not account for the racial disparities seen in sleep duration.[5,35] Whether or not demographic characteristics influence the relationship between physical activity and sleep has not been studied. It is therefore important to consider how other factors, such as stress caused by repeated exposure to systemic discrimination or cultural beliefs surrounding sleep, can influence sleep and potentially moderate the association between physical activity and sleep.[35] Understanding which populations are at the highest risk of poor sleep and subsequent negative health outcomes associated with poor sleep is an integral part of developing targeted interventions that account for these disparities.

The major strengths of the present study included its longitudinal design and the use of a large, nationally representative sample of adolescents. A number of limitations should also be addressed. First, both sleep and physical activity were measured using questionnaires. Although both questionnaires are used in large-scale surveillance studies,[26,28,29] this method of data collection is subject to response bias.[19,20] Additionally, data were collected simultaneously at each time point, as opposed to daily measures of sleep and physical activity over a week. Therefore, causality cannot be determined. Finally, excluded participants were more likely to be Non-Hispanic Black, Hispanic and male. It is therefore important to consider what effect this may have had on the sleep disparities seen in the study and whether their inclusion in the study would have had an impact on our results.

Conclusions

This present study found significant associations between physical activity and sleep in older adolescents, which varied by day type and physical activity intensity. Weeknight sleep was not associated with TPA or VPA, while weekend night sleep was negatively associated with TPA and positively associated with VPA. Importantly, these results argue that the association between physical activity and sleep is more complex than has previously been considered, and that more longitudinal research is needed that takes day type and physical activity intensity into consideration when assessing this relationship in adolescents.

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Table 4.1 T-tests and chi-square analyses assessing the differences between participants in final sample (N=1959) and participants removed from sample due to missing data (N=825)

	Included participants	N	Excluded participants	N	*p*-value
Race/Ethnicity *N (%)*		1959		825	<.01
Non-Hispanic Black	393.00 (20.06)		294.00 (35.64)		
Non-Hispanic White	927.00 (47.32)		219.00 (26.55)		
Hispanic	564.00 (28.79)		271.00 (32.85)		
Other	75.00 (3.83)		41.00 (4.97)		
Gender *N (%)*		1959		820	<.05
Female	1108.00 (56.56)		416.00 (50.73)		
Male	851.00 (43.44)		404.00 (49.27)		
Parental Education *N (%)*		1620		633	.69
Less than high school	230.00 (14.20)		94.00 (14.85)		
High school or above	1390.00 (85.80)		539.00 (85.15)		
Age (months) *Mean (SD)*					
Time 1	195.30 (6.32)	1847	196.80 (7.59)	665	<.01
Time 2	205.90 (6.14)	1858	207.70 (6.99)	566	<.01
Time 3	217.50 (6.29)	1880	218.30 (6.50)	514	<.01
Age (years) *Mean (SD)*					
Time 1	16.27 (0.53)	1847	16.40 (0.63)	665	<.01
Time 2	17.15 (0.51)	1858	17.31 (0.58)	566	<.01
Time 3	18.12 (0.52)	1880	18.19 (0.54)	514	<.01
Excluded participants were significantly different in their distribution of gender and race/ethnicity. Excluded participants were older by an average of around 2 months.					

Table 4.2. Descriptive statistics of sleep and physical activity data at each time point

	Time point 1			Time point 2			Time point 3		
	N (%)	Mean (SD)	Range	N (%)	Mean (SD)	Range	N (%)	Mean (SD)	Range
SLEEP									
Weeknight sleep duration (min)	1654	453.62 (59.75)	300.00-815.00	1770	450.48 (63.44)	300.00-810.00	1818	447.43 (64.86)	300.00-840.00
Weekend night sleep duration (min)	1514	556.38 (93.73)	300.00-900.00	1703	550.63 (92.62)	300.00-900.00	1792	540.43 (90.70)	300.00-899.00
PHYSICAL ACTIVITY									
# days w/ $\geq$60 mins of PA/day									
0	104 (5.62)			161 (8.65)			203 (10.80)		
1	120 (6.49)			164 (8.81)			167 (8.89)		
2	177 (9.57)			227 (12.19)			219 (11.66)		
3	226 (12.22)			268 (14.39)			293 (15.59)		
4	207 (11.20)			220 (11.82)			221 (11.76)		
5	324 (17.52)			297 (15.95)			295 (15.70)		
6	233 (12.60)			175 (9.40)			157 (8.36)		
7	458 (24.77)			350 (18.80)			324 (17.24)		

# hrs/wk engaged in VPA									
None	104 (5.63)			208 (11.16)			237 (12.61)		
About half an hour	237 (12.83)			246 (13.20)			256 (13.62)		
About an hour	351 (19.00)			344 (18.45)			346 (18.41)		
About 2-3 hours	547 (29.62)			508 (27.25)			479 (25.49)		
About 4-6 hours	275 (14.89)			273 (14.65)			287 (15.27)		
7 hours or more	333 (18.03)			285 (15.29)			274 (14.58)		

Table 4.3 Associations between sleep duration and TPA and VPA

	Weeknight sleep duration				**Weekend night sleep duration**			
	Unadjusted N=1955		Adjusted N=1616 [a]		Unadjusted N=1955		Adjusted N=1616[a]	
	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value	Estimate (SE)	p-value
Intercept	485.58 (49.83)	<.01	519.32 (55.04)	<.01	795.47 (78.08)	<.01	754.99 (87.28)	<.01
Age (in years)	-2.18 (2.85)	.44	-2.80 (3.13)	.37	-13.46 (4.47)	<.01	-10.71 (4.97)	.03
VPA								
None	REF		REF		REF		REF	
0.5 HR	-0.50 (60.74)	.99	-11.25 (65.93)	.86	18.78 (96.25)	.85	53.21 (105.12)	.61
1 HR	-24.41 (58.01)	.67	-31.86 (63.15)	.61	-28.74 (90.75)	.75	35.83 (99.31)	.72
2-3 HRS	-10.39 (56.54)	.85	-16.97 (61.87)	.78	38.96 (89.03)	.66	104.94 (98.09)	.28
4-6 HRS	-91.55 (63.46)	.15	-46.81 (69.85)	.50	-35.33 (99.41)	.72	59.76 (110.16)	.59
≥7 HRS	9.03 (65.88)	.89	-13.42 (72.53)	.85	111.37 103.60	.28	216.04 (114.51)	.06
VPA*age								
None	REF		REF		REF		REF	
0.5 HR	-0.004 (3.49)	.99	0.56 (3.79)	.88	-1.29 (5.54)	.82	-3.35 (6.04)	.58
1 HR	1.34 (3.34)	.69	1.68 (3.63)	.64	0.97 (5.22)	.85	-2.78 (5.71)	.63
2-3 HRS	0.61 (3.25)	.85	0.82 (3.56)	.82	-2.74 (5.12)	.59	-6.64 (5.64)	.24
4-6 HRS	5.43 (3.66)	.14	2.63 (4.03)	.51	1.36 (5.73)	.81	-3.94 (6.34)	.53
≥7 HRS	-0.76 (3.80)	.84	0.34 (4.19)	.94	-7.39 (5.98)	.22	-13.32 (6.61)	.04
TPA	5.05 (7.55)	.50	3.81 (8.32)	.65	-27.19 11.81	.02	-31.20 13.03	.02
TPA*age (in years)	-0.25 (0.44)	.56	-0.21 (0.48)	.66	1.50 (0.68)	.03	1.73 (0.75)	.02
Race/eth								
NHW			REF				REF	
NHB			-30.10 (3.52)	<.01			-16.46 (5.20)	<.01
Hispanic			-10.32 (3.25)	<.01			-0.27 (4.78)	.95

Other			-13.64 (6.84)	.05			9.21 (10.07)	.36
Sex								
Male			REF				REF	
Female			-5.07 (2.62)	.05			15.79 (3.85)	<.01
Parent ed								
< HS			REF				REF	
≥ HS			-6.62 (4.04)	.10			-16.20 (5.93)	<.01

[a]Decrease in sample size due to missing data on parent education.

CHAPTER 5

OVERALL DISCUSSION

Significance

Previous research in adult populations has shown that there is a moderate, positive association between sleep and physical activity.[1] This association is understudied in children, especially among very young children. A majority of the research assessing this relationship has utilized a cross-sectional study design, and often results in mixed or null findings.[2,3] The differences seen in adult vs pediatric populations may be due to the fact that sleep and physical activity levels change as children transition from childhood into adolescents, and then into adulthood. There are a number of factors associated with sleep and physical activity in children that may not be relevant in adults. The schedules of very young children are dictated by parents or guardians, who may not be able to provide opportunities to be physically active and who may not be knowledgeable about best practices related to their child's sleep. Furthermore, children who regularly attend childcare may participate in daytime naps and may not have access to environments that promote physical activity. As a result of biological changes that occur during puberty, adolescents naturally shift to later bedtimes. Additionally, adolescents may go to bed later because of new time commitments, such as school clubs, sports, or part-time jobs. Regardless adolescents must wake up at a time that does not allow them to meet their sleep need because of early school start times.[4] Considering many of these factors do not pertain to adult populations, there is a need to explore whether the association between sleep and physical activity seen in adults is similar in children and adolescents.

There is evidence that children who are racial or ethnic minorities and who are from low socioeconomic status (SES) households are less likely to meet sleep guidelines compared to White and middle/upper-class children, respectively, due to a number of social and environmental factors.[5] This may partially explain the health disparities seen among historically marginalized populations that are associated with poor sleep. For example, both sleep and physical activity are associated with a number of health outcomes, including cardiometabolic[6,7] and cognitive health.[6,8] Obesity, which currently affects around 17% of children under the age of 19,[9] is also linked to poor sleep and low physical activity. Interventions that have targeted the energy imbalance caused by inactivity and poor diets to prevent and treat overweight and obesity have had little long-term success. As such, an increasing amount of research has started to include sleep components in interventions with greater success.[10,11] Furthermore, considering both poor sleep and low physical activity levels in childhood have been shown to continue into adulthood,[2] understanding how these two behaviors interact with one another and their relationship with weight status in diverse populations of children is critical.

Purpose

The overarching purpose of this dissertation was to examine longitudinal relationships between sleep and physical activity in children across the developmental spectrum. The purpose of the first study was to examine whether average physical activity levels in children from 6-24 months old are associated with sleep duration and sleep quality, and examine whether changes in physical activity levels are associated with sleep duration and sleep quality. The purpose of the second study was to examine whether average sleep duration and changes in sleep duration among children from 6-24 months old were longitudinally associated with weight-for-length z-scores, and whether these associations varied by race/ethnicity, socioeconomic status, and sex.

Finally, the purpose of the third study was to examine whether vigorous physical activity (VPA) and total physical activity (TPA) are longitudinally associated with nighttime sleep duration among adolescents and young adults, and determine if these associations differed between weeknight sleep and weekend night sleep.

Design and Methods

All three observational studies included in this dissertation used a longitudinal study design. Study one used data from 109 mother-child dyads participating in the Linking Activity, Nutrition and Child Health (LAUNCH) study to address the research aims. Daytime, nighttime, and 24-hour sleep duration along with the number of nighttime awakenings were measured via actigraphy and served as the dependent variable. Daytime physical activity was measured via accelerometry and served as the main independent variable of interest. Mothers reported their child's race/ethnicity, sex, and socioeconomic status at baseline via survey. The between-person differences and within-person changes in physical activity were estimated with each of the sleep variables as the outcome in separate linear mixed model analyses. Study two also used data from 109 mother-child dyads participating in the LAUNCH study. Nighttime and 24-hour sleep duration served as the primary independent variables of interest. Weight-for-length z-scores were calculated based on children's height and weight and were the primary dependent variables of interest. Diet was assessed using a feeding frequency questionnaire completed by the mother. Separate associations of between- and within-person changes in nighttime and 24-hour sleep were estimated with weight-for-length z-score treated as the outcome variable in linear mixed model analyses, adjusting for demographic characteristics, physical activity and diet. The third study utilized data from 1,959 adolescent and young adult participants in the Next Generation Health (NEXT) study. Weekend night and weeknight sleep duration, as well as total physical activity (TPA) and vigorous physical activity (VPA) were assessed via questionnaire. Separate linear mixed models used weeknight and weekend night sleep duration as the dependent variable, and TPA and VPA were entered as the primary independent variables of interest.

Major Findings

The findings of the dissertation showed that there is an inverse association between sleep and physical activity in children. The first study assessed how changes in an individual child's physical activity levels, as well as how differences between children's physical activity levels, are associated with sleep.[12,13] Results indicated that children with greater average physical activity levels during the day had lower daytime sleep durations in the first two years of life compared to children with lower average physical activity levels. Furthermore, when children were more physically active compared to their own average physical activity levels, they had a lower 24-hour sleep duration. The result of the study may be explained by the fact that children have a limited amount of time in the day. Performing one activity, such as physical activity, displaces the time a child has to perform another activity, such as sleep.[14] The present study expands on previous research by assessing the relationship between sleep and physical activity longitudinally, as well as assessing both behaviors via device-based measures.

In the second study, results showed that when children slept longer at night compared to their own average nighttime sleep duration, they had a lower weight-for-length z-score. This relationship was attenuated by their physical activity levels. The relationship between sleep and weight status did not vary based on demographic characteristics. These results are consistent with other longitudinal studies conducted in very young children.[15,16] The results suggest that the development of weight status in infants may have a specific relationship with nighttime sleep duration, rather than 24 hour sleep duration. It further suggests that the effect of daytime physical activity may override the effect poor nighttime sleep had on weight status in very young children, or that it may eliminate some of the influence short sleep has on the development of weight status.

The third study indicated that older adolescents with higher TPA levels had a shorter weekend night sleep duration compared to older adolescents with lower TPA levels, but those with high levels of VPA had a longer weekend night sleep duration compared to older adolescents who did not participate in any VPA. This is inconsistent with the current research in adolescent populations, which shows a weak, yet positive relationship, even when subjective measures of both behaviors are utilized.[2] Importantly, nearly all of the research looking at the sleep and physical activity relationship have used a cross-sectional study design,[2,17] unlike the present study, which used a longitudinal study design. The results of the third study also indicate that relationship between sleep and physical activity differs by day type, which is an important factor to in this age group due to the differences often seen in weeknight and weekend night sleep in this age group.[4] These results suggest that individuals who sleep longer on the weekends are doing so at the cost of time that could otherwise be spent participating in physical activity. Additionally, older adolescents who participate in sports may sleep less on weekends due to scheduled practices or competitions.[18] Furthermore, the relationship between sleep and physical activity appears to differ by physical activity intensity. While

TPA had a negative association with weekend night sleep duration, VPA had a positive association with sleep when participants were acquiring >7 hours of VPA per week. The fact that this association only appeared at the highest level of VPA suggests the potential of a ceiling or floor effect.

Demographic characteristics contributed significantly to the variance explained in sleep duration in studies 1 and 3, but they did not contribute significantly to the variance in weight status in study 2. There is almost no research assessing whether demographic characteristics influence the relationship between sleep and physical activity. Stress caused by repeated exposure to racism or cultural beliefs surrounding sleep and physical activity may influence these two behaviors, and this may ultimately affect their association with each other and with the development of weight status.

Taken together, the findings of this dissertation show that higher physical activity is associated with shorter sleep durations in very young children and in older adolescents. Although the overall findings of this dissertation are inconsistent with evidence in very young children[19] and adolescents,[2] this study addressed multiple gaps in the literature pertaining to study design and sample characteristics. Very few studies have been conducted on this topic utilizing a longitudinal study design, and even fewer have been conducted in samples of very young children.[19] These differing results suggest that the psychological and biological mechanisms used to explain this relationship in adults may not apply to very young children or adolescents, and supports the need for research that explores biopsychosocial mechanisms that link sleep and physical activity in younger ages instead.

Limitations

There are several limitations to this dissertation that need to be addressed. The first two studies utilized device-based measures of sleep and physical activity, which are still being developed in very young age groups. Because physical activity intensity cut points have not yet been developed in pre-ambulatory children, the two studies could not differentiate between sedentary behavior and light intensity physical activity, which limited analyses to assessments of total physical activity only. Furthermore, accelerometry data in pre-ambulatory children may be compromised by the caregiver carrying or handling the child.[20] Actigraphy is not very accurate at discerning between sleep and wake periods, such as when the child is inactive during a wake period or moving during a sleep period.[21] One way of improving this accuracy is by asking parents to keep sleep diaries, although mothers in the LAUNCH study were not asked to keep sleep diaries in order to reduce participant burden and avoid the risk of additional data loss from non-compliance.[22] Importantly, the proprietary software used to score the sleep data in studies 1 and 2 has not been validated for use in infant sleep research.

Data collection for the LAUNCH study was also affected by the COVD-19 pandemic, meaning many of the measures needed to be completed by mothers participating in the study. This meant that the outcome variable for study 2, weight-for-length z-score, was not measured by trained data collectors for most children at the 12-month time point, and was collected by mothers or pediatricians at the 18- and 24-month time points. This variation in administration could have led to measurement bias.

The sample sizes in studies 1 and 2 were small and may have resulted in underpowered analyses. This was not an issue for study 3, although other limitations to this study that need to be considered. Although both the sleep and physical activity data were collected using questions from large-score surveillance studies,[23–25] the data were still subject to response bias.[26,27] Participants who were excluded from the study due to non-response were more likely to be male, Non-Hispanic Black and Hispanic, which may have skewed the results of the study and limited the study's generalizability.

Practical Implications

The results of this dissertation can help guide efforts to prevent childhood obesity by understanding the effects sleep and physical activity have on one another and on health outcomes as children develop from infancy to adolescence. Current interventions that focus on obesity prevention that include both sleep and physical activity components show more success compared to interventions that only include a physical activity component.[10,11] Based on the results of this dissertation, both sleep and physical activity were associated with weight status in infants, although the results also suggested that increasing one behavior was associated with a decrease in the other in both very young children and older adolescents. This may explain why previous interventions, which have focused on increasing both behaviors simultaneously, show mixed results.[10,11]

This results of this dissertation indicate that a number of additional factors must be taken into consideration when developing sleep and physical activity interventions. For example, they must consider daytime and nighttime sleep in younger children and weeknight and weekend night sleep in older adolescents. Although daytime naps in very young children have been shown to improve cognitive outcomes,[28] the results of this dissertation suggest that they are not associated with weight status outcomes and are inversely associated with physical activity levels. In older adolescents, the focus shifts to weeknight vs. weekend night sleep. The results of this dissertation showed that associations between sleep duration and physical activity were only significant on weekend nights and were not significant on weeknights. Furthermore, results showed that the relationship differed based on whether the older adolescent participated in TPA or VPA. Therefore, the relationship between sleep and physical activity in older adolescents appears to be more complex than has been previously established.

The studies in this dissertation also showed that demographic characteristics were associated with a significant amount of variability in sleep duration. Interventions that target improvements in sleep duration must be tailored to account for psychological, social, and economic factors associated with sleep that vary by race/ethnicity, SES and sex. For example, cultural practices surrounding sleep such as bed sharing or bedtime routines may vary significantly from one family to another family.

In summary, the implications of these findings offer insight into other factors associated with sleep at different ages, and how they influence the relationship between sleep and physical activity. A better understanding of this association will help guide intervention and prevention efforts targeting childhood obesity that include both sleep and physical activity components.

Considerations for future studies

The results of this dissertation showed that there is an inverse relationship between sleep and physical activity in very young children and in older adolescents. Although this dissertation adjusted for a number of important factors in the analyses, more work is needed investigating additional factors that influence sleep and physical activity, and understand whether these factors influence the relationship between the two behaviors. Both sleep and physical activity have been shown to be influenced by factors found at the individual, social, and environmental level. It is important to note that a behavior that may be positively associated with sleep may be inversely associated with physical activity, and vice versa. For example, children who live in more walkable environments are more likely to use active transportation.[29] These neighborhoods are often described as having more amenities, such as streetlights.[30] These streetlights may make it safer to walk when it is dark outside, but they also create light pollution. Greater light pollution has been linked to poor sleep.[31] Research on short sleep in high-school students has led to the development of policies targeting later school start times, and these policies have been successful at increasing adolescents' sleep duration.[4] Although these delays have not resulted in lower levels of physical activity or sport participation,[32] they may delay students' participation in sports or physical activity. Current sleep hygiene guidelines recommend avoiding vigorous-intensity physical activity later in the day,[33] which may be difficult if adolescents have a limited amount of time to participate in sports or other physical activities.

While the present study found that demographic characteristics were associated with a significant amount of variability in sleep duration, it did not assess whether these demographic characteristics were also associated with a significant amount of variability in physical activity, or the potential factors that may have led to these differences. For example, the high costs associated with sport participation in high school may serve as a barrier to physical activity for adolescents from low SES households.[34] Additionally, children living in low SES households may experience for chaos in the home, which may lead to poorer sleep.[35] This dissertation did not find that demographic characteristics were associated with a significant amount of variability in weight-for-length z-score in very young children, and it did not assess whether this relationship was significant in older adolescents. Considering children from low income and historically marginalized racial or ethnic groups are at a higher risk of negative health outcomes such as overweight and obesity,[36] future research must investigate how specific, modifiable, socio-cultural factors that can address health disparities help explain the association between sleep and physical activity.

Although the use of device-based measures helps reduce the risk of response bias from parent or self-reported sleep and physical activity questionnaires,[26,27] more work is needed to improve the use of accelerometers and actigraphy monitors in very young children. First, establishing physical activity cut points in pre-ambulatory children would allow for assessments of associations between different physical activity intensities and sleep. Furthermore, criteria are needed to determine whether accelerometry data are the result of caregiver handling, rather than child movements. More work is needed to improve the ability of actigraphy to discriminating between sleep and wake classifications,[15] and more validation studies should be conducted for the different proprietary software that are used to measure sleep in very young children.

Conclusions

The three studies in this dissertation addressed multiple gaps in the literature assessing the relationship between sleep and physical activity. The overall findings show that there is an inverse relationship between sleep and physical activity, which is inconsistent with previous evidence on this association. Both physical activity intensity and the time the sleep occurred (daytime vs nighttime; weeknight vs. weekend night) influenced the relationship between sleep and physical activity. Furthermore, results indicated that populations at risk of health outcomes such as overweight and obesity are seeing differences in sleep durations as early as infancy. Efforts to improve sleep and physical activity levels in children in order to reduce the risk of overweight and obesity must consider the complex associations between these two behaviors, rather than approach each behavior individually. Individuals administering these interventions must also ensure that these efforts are culturally sensitive, and consider the barriers children may face when attempting to improve both behaviors.

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CHAPTER 6

PROPOSAL

Introduction

Current physical activity guidelines developed by the U.S Department of Health and Human Services suggest that children and adolescents ages 6 through 17 years participate in ≥1 hours of moderate-to-vigorous physical activity every day, as well as vigorous-intensity aerobic physical activity, and bone and muscle strengthening physical activities on ≥3 days a week. Although the guidelines do not provide a specific dose of PA for children ages 3-5, they do recommend that they are physically active throughout the day, and that adult caregivers encourage active play and a variety of physical activities. No recommendations are given for children under the age of 2.[1,2] Similarly, scientific organizations such as the American Academy of Sleep Medicine (AASM) have published sleep duration recommendations which suggest that infants between the ages of 4 and 12 months sleep 12-16 hours/day, 1-2 year old children sleep 11-14 hours/day, and 3-5 year old children sleep 10-13 hours/day. This includes both nighttime sleep and napping until the child is 5 years old. The AASM recommendations suggest that children 6-12 years old sleep 9-12 hours per night, while children 13-18 years old sleep 8-10 hours per night.[3]

Children and adolescents from low socioeconomic status (SES) households[4–6] and who are racial or ethnic minorities4,[6–9] are less likely to meet sleep guidelines compared to their middle or upper-class and White counterparts, respectively. Although it is still unclear whether male or female adolescents experience better sleep, there is some evidence to suggest that changes in sex hormone levels during puberty can affect sleep architecture.[10] In regards to physical activity, differences in meeting physical activity guidelines by SES or racial/ethnic group are less clear, although differences between the sexes are more evident among older children and adolescents.[11] Higher rates of poor sleep duration and quality may explain, in part, why minorities are at a higher risk of negative health outcomes associated with sleep and physical activity.

One of the health aspects often associated with poor sleep and low physical activity is obesity. Obesity is caused by an energy imbalance that leads to an excess of adipose tissue and is linked with significant negative physical and psychological health outcomes among children.[12] Currently, it is estimated that 17% of children under the age of 19 in the US are obese.[12] Many interventions aimed at preventing or treating obesity often focus on the energy imbalance caused by poor diet and inactivity, but new research has started to explore the role of sleep in this relationship.[13]

Short sleep duration is associated with a number of metabolic, biological and behavioral changes in children that can increase the risk of obesity. This includes changes to leptin and ghrelin levels,[14] higher intake of calorie-dense foods and sugary foods and beverages,[14–16] and greater fatigue during the day, which may lead to decreases in physical activity levels or increases in sedentary behavior.[14,15] Unfortunately, many of these pathways have been studied exclusively in adults, and the few studies that assess these pathways in children utilize subjectively-measured data and a cross-sectional study design.[13,15]

Statement of the Problem

Much of the information that is currently known about the relationship between sleep and physical activity is based on research conducted on adult samples, and the few studies that have assessed this relationship among children and adolescents have primarily utilized a cross-sectional study design and subjective measures of sleep and physical activity.[17] Although we have an understanding of the independent relationship sleep and physical activity each have with weight status in children, more work is needed addressing the relationship between sleep, physical activity and weight status simultaneously among children. A better understanding of whether these relationships vary by different demographic characteristics is also needed. This dissertation aims to advance knowledge and understanding of the relationship between physical activity, sleep, and weight status in children and adolescents. The specific aims and objectives to address this overarching goal are outlined below.

Study 1 Aim: Examine the longitudinal relationship between objectively-measured sleep and physical activity in children 6-24 months old.

Objective 1a. Examine whether average physical activity levels in children from 6 months old to 24 months old are associated with sleep duration and sleep quality over time.

Objective 1b. Examine whether changes in physical activity levels in children from 6 months old to 24 months old are associated with sleep duration and sleep quality over time.

Study 2 Aim: Examine the longitudinal relationship between objectively-measured sleep and weight status in children 6-24 months old, and determine whether these associations differ by race/ethnicity, socioeconomic status, and sex.

Objective 2a. Examine whether average sleep duration and quality in children from 6 months old to 24 months old are associated with weight status over time.

Objective 2b. Examine whether changes in sleep duration and quality in children from 6 months old to 24 months old are associated with weight status over time.

Objective 2c. Examine whether the association between sleep and weight status in children from 6 months old to 24 months old are varies over time by race/ethnicity, socioeconomic status, and sex.

Study 3 Aim. To determine if physical activity and sedentary behavior, measured objectively at 11, 13 and 15 years of age, are associated with subjectively measured weekend and weekday sleep at age 15.

Objective 3a. Determine whether sedentary behavior and moderate-to-vigorous physical activity measured at age 11, 13 and 15 are associated with sleep duration and quality measured at age 15.

Objective 3b. Determine whether changes in sedentary behavior and moderate-to vigorous PA from ages 11, to 15 are associated with sleep duration and quality measured at age 15.

Objective 3c. Determine the extent to which the relationship between sleep and sedentary behavior and moderate to vigorous physical activity vary by race, sex, socioeconomic status, and measures of adiposity.

Significance of Proposed Study

Recent surveillance data suggest that many children are not meeting sleep and physical activity guidelines, which may partially explain the high obesity rates seen among children in the United States. This proposal is significant because it will improve the current understanding of the relationship between sleep, physical activity and weight status through the use of longitudinal study designs and objective measures of sleep, physical activity and anthropometry. Furthermore, it will assess whether demographic characteristics are associated with differences in these relationships. Results of this study can be used to help improve current prevention and intervention strategies targeting childhood obesity.

Literature Review

OVERVIEW OF SLEEP AND PHYSICAL ACTIVITY

What is sleep?

Definition of sleep. Sleep is a behavioral state that characterized by an absence of wakefulness,[18] a lack of movement and a distinctive, recumbent posture.[19] Sleep is regulated simultaneously by two processes. The homeostatic process, also called Process S, represents an oscillation of sleep debt. This sleep debt increases throughout the day when an individual is awake, and then decreases during the night as sleep is obtained. Process S appears to be regulated by adenosine, which is a byproduct of energy expenditure known to inhibit arousal. Process C is primarily controlled by the suprachiasmatic nucleus (SCN), also referred to as the circadian pacemaker, although additional circadian oscillators are thought to exist outside of the SCN. External and hormonal cues, such as bright light or melatonin release, signal wake and sleep, respectively.[7,20]

Electroencephalography (EEG) measures taken during sleep reveal that sleep follows an ultradian rhythm.[7] Multiple sleep phases occur one after the other in a cyclical pattern multiple times throughout the night.[19] The two main sleep phases include a non-rapid eye movement phase (NREM) and a rapid eye movement (REM) phase.[18,19] During REM phase, the eyes, although closed, move rapidly behind the lids. This "rapid eye movement" is what gives the phase its name. REM sleep is thought to be the time when memories created during the day are consolidated and integrated. It is also when the central nervous system undergoes a significant amount of development.7 During REM sleep, EEG waves have a low amplitude and high frequency, similar to the types of EEG waves seen when an individual is awake.[19]

NREM sleep is considered to be the "restorative" sleep phase.[7] During this time, EEG waves decrease in frequency but increase in amplitude, which is also referred to as slow wave activity (SWA). NREM sleep can be broken down into stages 1, 2 and 3, which increase consecutively in their amount of SWA.[19] Sleep stage 3, which has the highest amount of SWA, is also referred to as slow-wave sleep (SWS).[21] A sleep cycle usually lasts 90 minutes, and involves undergoing stages 1-3 of the NREM phase and continuing on to the REM sleep phase. This cycle then concludes and returns to stage 1 of the NREM phase.[19] The time spent in the REM sleep stage increases and the night progresses.[7]

Changes in sleep from infancy to adolescence. Sleep is anecdotally thought to be a state of rest, although it is actually a period of intense neurologic activity and development.[7,22] Newborns sleep upwards of 80% of the time. Nighttime wakings that occur during this period are partially due to an inability to regulate biological rhythms that initiate or maintain sleep. It takes about 6 months for an infant to develop the ability to regulate the hormones that control circadian sleep-wake rhythm, such as cortisol and melatonin. Children also experience shorter ultradian rhythms, which last about 45-60 minutes and gradually increase as they get older. Additionally, a greater proportion of time is spent in REM phase, and this proportion decreases as children get older.[7]

Considering humans undergo a significant amount of physical and neurological development during childhood, it is not surprising that children require and spend more time sleeping than adults,[22] and that characteristics of their sleep differs from adults.[7] As children develop from infancy to adolescence, their sleep undergoes a number of changes. Sleep duration decreases, going from around 14 hours at 6 months of age to 8 hours at 16 years of age. Daytime sleep decreases as children get older, and by the age of 5, sleep is consolidated and occurs primarily at night.[23]

Adolescence experience a decrease in overall sleep time, SWS and REM sleep, as well as a shift to a later sleep onset time.[18] There are a number of biological changes that occur as children mature that may explain these changes. For example, adolescents also undergo a significant amount of brain development and activity, including a decrease in grey matter volume associated with synaptic pruning and an increase in white matter associated with myelination of neural axons.[18,24] Many of the regions undergoing these changes are directly related to sleep duration and quality during adolescence.[24,25] Additional biological factors that lead to changes in sleep habits include alterations to the endogenous forces controlling Process C and Process S. Changes in the sensitivity of the circadian pacemaker to external light cues may lead to a phase delay in the evening, or a stunted response to light cues in the morning. Furthermore, sleep pressure appears to builds up at a slower rate as teens get older.[26,27]

Unfortunately, changes in brain development and activity do not entirely explain decreases in sleep duration and a delayed bed time. There are a number of psychosocial factors that contribute to changes in adolescent sleep habits, including technology use, school start times, and increases in caffeine use.[27] For example, technology use before bed leads to delayed bed times by increasing the exposure to blue light associated with circadian phase delay. Pairing this delay with early morning school start times decreases the window of opportunity teens have to obtain the recommended amount of sleep every night.[26]

Sleep Guidelines

Sleep guidelines for children and adolescents. The National Sleep Foundation (NSF) and the American Academy of Sleep Medicine (AASM) have published sleep duration recommendations. Based on the AASM recommendations, infants between the ages of 4 and 12 months should sleep 12-16 hours/day, 1-2 year old children should sleep 11-14 hours/day, and 3-5 year old children should sleep 10-13 hours/day. Napping is included in these daily sleep recommendations for children up until the age of 5. Children 6-12 years old should sleep 9-12 hours per day, and children 13-18 years old should sleep 8-10 hours per day.[3] The recommendations published by the NSF are similar, although they recommend a slightly narrower window of optimal sleep time. The NSF recommends that 0-3 month old newborns sleep between 14 and 17 hours per day, 4-11 month old infants sleep between 12 and 15 hours per day, 1-2 year old toddlers sleep between 11 and 14 hours per day, 3-5 year old preschoolers sleep between 10 and 13 hours per day, 6-13 year old school-aged children sleep between 9 and 11 hours per day, and 14-17 year old teenagers sleep 8 to 10 hours per day.[28]

The sleep recommendations are based on research assessing the relationship between sleep and health outcomes across the lifespan,[3,28] however this research is limited by a number of factors. Firstly, most of the research utilized to develop sleep recommendations is based on cross-sectional, self or parent-reported sleep data, which have been shown to overestimate sleep duration.[29] Additionally, individual sleep durations and their trajectories vary greatly between individuals, especially in infants.[3,28]

These limitations suggest that the ranges currently provided for optimal sleep may be too narrow.[30]

Furthermore, current guidelines focus on sleep duration only,[29] and some research has started to assess the effects sleep quality has on health outcomes as well. The NSF currently defines “good quality sleep” as sleep that involves: a sleep latency of 15-30 mins, a sleep efficiency of greater than 85%, 1 or fewer nighttime awakenings among children over the age of 1 year old, and 20 minutes or less spent awake after sleep onset in children over the age of 3. Unfortunately, there is a lack of research focusing on indicators of sleep quality, as well as the relationships between poor sleep quality and health outcomes across multiple age groups.[31] The limited evidence suggests that sleep continuity is a good indicator of sleep quality in all age groups, but the results of research on napping and sleep architecture are not consistent within and across different age groups, and clear guidelines have yet to be developed for these indicators.

How many children are meeting sleep guidelines. Meta-analyses and public health surveillance methods have been utilized to obtain accurate estimates of pediatric sleep duration, assess how many children are meeting sleep guidelines, and understand which children are most likely to be at risk of short or long sleep. Among infants and younger children, meta-analyses of studies utilizing subjective measures of sleep show that infants ages 0-23 months old sleep an average of 12.8 hours every 24 hours, and wake 0-3.4 times per night. Toddlers 2-5 years old sleep 11.9 hours every 24 hours, and wake 0-2.5 times per night.[32] This latter estimate is higher than the normative estimates based on actigraphy data, which show that children 3–5 years old sleep around 9.68 hours per night,[33] just below the 10-13 hours recommended by the AASM and NSF.

Current data show that adolescents report sleeping an average of 9-10 hours per night, and this average is consistently higher on weekends than weekdays.[34] Although this average is above the recommended 8 hours per night, the most recent surveillance efforts report that nearly 75% of high school students are not meeting this recommendation. This prevalence of meeting sleep guidelines decreases as students get older, with 34.8% of 9th grade, 26.6% of 10th grade, 21.4% of 11th grade and 17.6% 12th grade students reporting sleep durations of 8 or more hours a night.[35] These data are consistent with other reports showing that adolescent sleep decreases from 8.5 hours per night at age 13 to 7.3 hours per night at age 18.[8] Sime evidence also suggests that sleep duration among children and adolescents between the ages of 5-18 has been decreasing over the last century,[36] and that the number of adolescents sleeping <7 hours per night has increased over 50% between 1991 and 2015.[37]

Differences in meeting sleep guidelines by SES, race/ethnicity, and sex. Children from low socioeconomic status (SES) households have poorer sleep quality[38] and shorter sleep durations,[38–40] and are less likely to meet sleep guidelines[4–6] compared to children from higher SES households. This can be seen from infancy and young childhood[10,39] until adolescence,[4,38,40] and may be a result of an exposure to more stressors among children living in low SES households, such as higher noise levels at night[5,38,41] Furthermore, lower health literacy regarding proper sleep hygiene among parents and children in low SES households may further increase this disparity.[38]

Children and adolescents who are from historically marginalized racial or ethnic groups sleep less at night,[39,42,43] have poorer sleep quality,[43] and are less likely to meet sleep guidelines compared to White students.[4,6–9] Black, Hispanic and Asian children nap more during the day than White children,[39,43–45] which is not associated with the same health benefits as nighttime sleep, and can be considered a reflection of not receiving adequate sleep at night.[43,45] Differences between minorities show that Hispanic youth slept more than Black youth.[42] The evidence for Asian children and other minorities is less clear, but overall it appears that Asian youth sleep shorter than white youth,[42,46] but longer than Black and Hispanic youth.[42]

Higher rates of poor sleep duration and quality may explain, in part, why minoritized populations are at a higher risk of negative health outcomes associated with sleep.[9,42] Furthermore, many interventions targeting sleep only significantly improve sleep among White youth.[42] The impact of culture and cultural practices when it comes to sleep can lead to a difference in beliefs regarding sleep habits.[42] For example, minority youth often have later bedtimes than White youth.[42,45] Some research has also measured the interaction between SES and race when assessing sleep disparities.[47] Although structural and systemic racism has resulted in SES and race/ethnicity being correlated, significant differences in sleep duration and sleep quality are still apparent among children from different ethno-racial backgrounds when controlling for various SES measures, including parent education, income, and poverty.[42]

Although sex differences are not seen in studies assessing parent-reported sleep duration in infants and young children,[10,39,41] significant sex differences in sleep duration have emerged during adolescence.[4,8,44] Changes in sex hormone levels during puberty are known to affect sleep architecture, which may partially explain these differences.[10] Unfortunately, it is still unclear whether male or female adolescents experience better sleep quality. While studies utilizing subjective sleep measures suggest females sleep less than males,[4,8] findings from research utilizing objective measures of sleep report that males sleep less than females.[44]

Why is meeting sleep guidelines important? Adolescents who exhibit poor sleep are more likely to continue experiencing poor sleep into adulthood.[48] Poor sleep is associated with negative effects on behavioral outcomes, neurocognitive development.[49] Specifically, greater sleep duration and quality are associated with better emotional regulation,[29] a lower risk of mood disorders such as depression or anxiety,[25,50–54] better cognitive functioning[25,55] and performance in school,[50,56,57] and lower rates of risk taking,[53,54,57–59] hyperactivity, inattention, and symptoms of ADHD.[50] Most of this research assessing these relationships focuses on older children and adolescents, although the evidence suggests that the associations between sleep and neurocognitive outcomes is weaker among younger populations.[60]

Longer sleep duration and better sleep quality are also associated with better weight status outcomes and a lower risk of overweight/obesity.[15,29,54,61–64] Longitudinal studies show that short sleep duration in early childhood increases the risk of future overweight/obesity in later childhood.[65–67] Multiple mechanisms have been suggested to explain the relationship between sleep and weight status, including a decrease in diet quality, appetite control, insulin resistance, and physical activity, and an increase in sedentary time.[15,68,69]

A relationship between sleep quality and adiposity outcomes can be seen in young children and adolescents,[70] even after controlling for sleep duration.[71,72] Markers of sleep quality that have been assessed include sleep latency, the number of average nighttime awakenings, sleep efficiency, and responses on sleep quality questionnaires such as the

PSQI.[71] Poor sleep habits, such as later bedtimes and a greater difference between weekend and weekday bedtimes, are also associated with greater adiposity.[73]

Although most research supports the negative effects poor sleep quality has on children and adolescent's quality of life,[29] a number of limitations still exist in this line of research. Most of the research is cross-sectional, making it difficult to elucidate the mechanisms underlying these relationships,[61,71] and utilizes self- or parent-reported sleep data, which are subject to recall and social desirability bias.[62,63,65] There is much more research assessing the effect of sleep duration on health outcomes, and more work is needed on other factors, including sleep timing, variability in sleep timing and duration, and sleep quality.[61,62] Most of the research has also focused on relatively healthy participants,[60] and samples lack racial, ethnic and socioeconomic diversity.[49]

Healthy people 2030 sleep goals for children and youth. Considering the effect sleep has on later sleep habits and associated health outcomes in children of all ages, promoting health strategies that target sleep is a critical step in reducing the economic costs associated with poor sleep.[62] Pediatric sleep health topic areas were included in Healthy People 2020, although precise baseline and target data were only provided for adolescents. The target for this objective was to increase the proportion of high-school students who get sufficient sleep from 30.9% to 33.1%.[74] Unfortunately, the latest reports suggest that only 25.4% of high-school students achieve sufficient sleep, and the new Healthy People 2030 target for this objectives is an increase to 27.4%.[75] Healthy People 2030 also includes a sleep health target for children ages 4 months to 14 years, with the goal of increasing the proportion of children getting sufficient sleep from 65.9% to 70.6%.

What is physical activity?

Definition of physical activity. Physical activity includes all bodily movements that lead to energy expenditure beyond that of resting levels. It can be performed in a number of different ways and in a number of different settings. For example, physical activity can be performed as a result of a person's occupation at or outside of the home, or occur as a means of transportation, recreation, or exercise. Exercise differs from physical activity in that it aims to improve or maintain one's health and fitness through planned, structured and repetitive activities.[76,77] Physical activity intensities are operationalized using metabolic equivalents, or METS. One MET is equal to the amount of energy the body exerts while at rest, also known as sedentary behavior. The light physical activity zone includes activities that require 1.1-2.9 METs, the moderate physical activity zone includes activities that require 3-5.9 METs, and the vigorous physical activity zone includes activities that require ≥6 METs. Children spend most of their time in physical activity at the moderate intensity level.1,[77] In addition to intensity, physical activity can be described based on its frequency, or how often it occurs, and duration, or how long each session lasts.[1]

There are multiple types of physical activity. Aerobic activity results in an increased heart rate and breathing. Muscle strengthening activities involve the use of one's muscles to work against an applied force, such as a heavy object or one's body weight. Bone-strengthening activities promote bone growth and improve bone strength by producing a force on the bone through impact with the ground. Balance activities help improve an individual's balance by strengthening the muscles needed to maintain equilibrium.[1]

Changes in physical activity from infancy to adolescence. Physical activity increases as children transition from infancy to toddlerhood and improve in their motor skills. Physical activity during infancy is considered to be any gross motor movement without any purpose or goal, such as arm waving, rocking, or leg kicking. Older infants engage in behaviors such as crawling, pulling themselves up to a standing position, standing unassisted, and eventually walking.[78]

Younger children are physically active in short and sporadic bouts. Adolescent physical activity is similar to that of adults, and is performed in longer, sustained bouts at moderate to vigorous intensities. Transitioning from play to purposeful activity occurs as children develop and improve in their motor skills, likes and preferences, and behavioral competencies. Active play is the most common form of PA among children. Younger children engage in higher levels of informal play, while older children participate in more structured play activities, such as group sports. Both younger and older children walk or bike as a form of transportation, participate in physical education at school, and perform work at home or outside of the home.[77]

Active transportation and participation in organized physical activity increases throughout childhood. As children transition to adolescence, they tend to experience an increase in physical activity levels related to organized sport and chores, while physical activity levels related to active transportation seem to level off. During adolescence, physical activity levels related to chores appear to stabilize,[79] and physical activity levels related to active transport and organized PA appear to either stabilize or decline.[79,80] Overall physical activity levels decline during adolescents, but results are mixed as to whether the decline is steeper in males or females.[79,80]

Physical activity guidelines

Physical activity guidelines for children and adolescents. The U.S Department of Health and Human Services (HHS) released the 2nd edition of the Physical Activity Guidelines for Americans in 2018, based on recommendations made by the 2018 Physical Activity Guidelines Advisory Committee. According to these guidelines, children and adolescents ages 6 through 17 years should participate in ≥60 minutes of moderate-to-vigorous physical activity every day. Vigorous-intensity aerobic physical activity, and bone and muscle strengthening physical activities should each be performed on ≥3 days a week.[1,2]

The Physical Activity Guidelines Advisory Committee Scientific Report concluded that there was a positive association between health outcomes and physical activity in children under the age of 5. Some research cited in the report suggests that 3 hours of physical activity per day is an appropriate target for children between the ages of 3-5 years old, but this evidence is still limited. Furthermore, measures of physical activity have not been validated in children under the age of 2 years old, limiting the assessment of the physical activity and health relationship in children under the age of 2 as well as the development of a public health target for this age group.[81] Because of these limitations, the physical activity guidelines provided by the HHS do not provide a specific dose of PA for children ages 3-5, but they do recommend that they are physically active throughout the day, and that adults caregivers encourage active play and a variety of physical activities. No recommendations are given for children under the age of 2.[1,2]

In 2002, the Society of Health and Physical Educators (SHAPE America) addressed these limitations by developing physical activity guidelines for children under the age of 5, issuing a updated and revised version in 2020.[82] Although a specific public health target is not provided for children under 12 months old, caregivers are encouraged to interact with infants in settings that allow children to explore their environment, stimulate movement and develop movement skills, and engage in short bouts of structured and unstructured physical activity throughout the day. The guidelines also recommended that toddlers age 12-36 months engage in ≥30 minutes of structured physical activity each day, and preschoolers between the ages of 3 and 5 engage in ≥60 minutes of structured physical activity each day. Both toddlers and preschoolers should engage in ≥60 minutes per day of unstructured physical activity, avoid sedentary behaviors for ≥60 minutes at a time (except when sleeping), and engage in structured and unstructured play in indoor and outdoor settings.[82]

How many children are meeting physical activity guidelines? Current estimates report that one-fourth of children 6 to 17 years of age participate in ≥60 minutes of physical activity every day, and two-third of 6-19 year old children engage in ≥2 hours of screen time per day.[83] Estimates for the number of children 3-5 years old that are physically active for 3 or more hours per day range from 41%-92%.[84,85] Only 26.1% of adolescents in grades 9-12 participate in moderate-to-vigorous physical activity for 60 or more minutes per day, and 51.1% participate in muscle strengthening activities 3 or more days a week. Only 20% of these adolescents meet both the aerobic and muscle strengthening guidelines, and 15.4% do not perform 60 or more minutes of moderate-to-vigorous physical activity on any day of the week. Regarding screen time, 79.3% of adolescents in grades 9-12 watched TV for 2 or more hours a day, and 57% played video or computer games for 2 or more hours per day.[35]

A significant drop in physical activity occurs with increasing age, with 42.5% of 6-11 year olds, 7.5% of 12-15 year olds, and 5.1% of 16-19 year olds meeting physical activity recommendations, based on objective physical activity measurement.[83] Although overall youth physical activity levels have not decreased significantly over the last 40 years, physical activity levels related to active transportation, physical education, and outdoor play have decreased, and time spent sedentary has increased along with an increase in electronic media use.[86]

Differences in meeting physical activity guidelines by SES, race/ethnicity, and sex. The research addressing associations between SES, physical activity and sedentary behavior is particularly understudied among children under 5 years of age.[87,88] Although some research suggests that children who live in households below the poverty level have lower levels of physical activity,[84] most studies do not find a consistent relationship between SES and overall physical activity in this age group due to a number of limitations.[87] Firstly, very few studies assessing physical activity in preschool-aged children overall are longitudinal. For example, a review by Timmons and colleagues found 18 unique, longitudinal studies assessing the relationship between physical activity and health outcomes in children under the age of 4, but none of these studies assessed whether the relationship between physical activity and health outcomes differed by SES in this age group.[89] Secondly, it is unclear which SES measures are the most appropriate to use when assessing this relationship among children. Although some studies show a positive association between children's physical activity levels and parental education, other studies find no association between these two variables.[87]

The relationship between physical activity and SES is inconsistent among older children and adolescents, where associations are only seen among certain measures of SES. For example, the cost of participating in physical activity is associated with physical activity levels of older children, who are more likely to participate in group sports that require membership fees and additional equipment.[87] Living in a high crime area is negatively associated with physical activity levels among children ages 6-11 years old,[90] and the effect of physical activity interventions is lower among children living in areas with higher crime.[83] Active transportation among older children and adolescents is also lower among children from low income households compared to children from high income households.[83]

While a limited amount of research suggests that among preschool-aged children, males are more likely than females to be physically active for 3 or more hours per day,[85] differences in physical activity levels between the sexes are more evident in older children and adolescents. Current surveillance systems report that 6-17 year old males are more likely to meet the physical activity guidelines than females and engage in regular muscle-strengthening activities, and more adolescent males report engaging in active transportation.[83] Although both males and females experience a decline in moderate to vigorous physical activity as they transition from adolescence into adulthood, this decline begins later in males than females.[11] Conversely, males are less likely than females to meet screen time guidelines of 2 hours or less of screen time per day.[83]

Differences in physical activity levels by race and ethnicity are not as consistent. According to the 2005-2006 NHANES survey of 6-19 year old children, African American children are more active than Hispanic youth, and both groups are more active than White youth. The 2017 YRBSS showed the opposite results, with African American children reporting the least amount of physical activity and White youth reporting the highest levels of physical activity.[35,83] According to NHANES data, 35% of White youth reported meeting screen time guidelines of 2 hours or less compared to 25% of African American youth. Conversely, 45% of African American youth engage in active transportation compared to 35% of White youth.[83]

Why is meeting physical activity guidelines important? Among children over the age of 3, physical activity is positively associated with a adiposity outcomes,[81,91,92] motor skill development,[91,93,94] and youths' health-related quality of life[91,95]. Higher physical activity levels are also associated with improved bone health,[81,91–93] including greater bone mineral content, density and structural properties. There is some evidence to suggest that improvements in bone health are maintained for several years following a physical activity intervention.[96] Increasing physical activity and decreasing sedentary behavior is associated with better metabolic health in children over the age of 5.[91,97] This is evident even when physical activity levels are below recommended levels, and regardless of whether weight status changes.[97] There is some evidence of a positive association between PA and cardiometabolic health among children under the age of 5,[93] but the research on this topic is very limited, and results are not consistent.[81,92] Furthermore, physical activity is positively associated with self-reported health status among adolescents. This relationship is stronger among males than females, possibly because physical activity is central to the construct of health in males, while other constructs may be more relevant among females.[98]

Greater physical fitness and higher physical activity levels are associated with greater cognitive functioning, although this association is stronger for physical fitness.[99,100] The relationship between physical activity and academic achievement may be weaker because the benefits of physical activity on academic outcomes may only las a short time, yet most of the research assessing academic outcomes does not account for when physical activities are performed.[100] The heterogeneity of academic performance measures between different studies may also effect the strength of the association, and physical activity may have a stronger association with specific types of academic performance compared to others[99,101] This association is also stronger among older children and adolescents, possibly because other factors, like SES, have more of an impact on academic performance in younger children.[100]

Mental health outcomes are positively associated with physical activity in children and adolescents ages 6-18.[102] There are a number of mechanisms that help explain this relationship. Firstly, participating in physical activity may change the composition of areas of the brain associated with improvements in cognitive and mental health.[103] Secondly, physical activity is associated with feelings of social connectedness and independence, higher self-efficacy, greater self-acceptance, and improvements in body image. Thirdly, physical activity has been shown to be positively associated with other health outcomes such as sleep quality, and the combined effects of these health behaviors may improve mood and cognitive health.[103] The evidence of the physical activity and mental health relationship in children under the age of 5 is limited, and more work is needed in this age group to determine whether any associations exist.[81,92,93,104,105]

A number of limitations exist in the physical activity and health literature. Although physical activity at higher intensities is consistently associated with better health outcomes,[91,93,95,98] the relationship between light physical activity and health outcomes is weak.[91] This may be due to measurement issues, such as the inability to accurately differentiate between sedentary behavior and light physical activity when objectively measuring physical activity in children. Furthermore, very little work has been done assessing the relationship between health indicators and light physical activity specifically.[91] More work is also needed to understand whether physical activity and health associations are moderated by demographic characteristics.[92] Most of the research mentioned above has been limited to older children and adolescents, and results may not be generalizable to infants and toddlers. Therefore, more research is needed on the association between physical activity and health outcomes in children under 3 years of age.[93]

Healthy people 2030 physical activity goals for children and youth. The therapeutic and preventative effects of physical activity reduce the morbidity and mortality associated with a number of chronic diseases, and can ultimately reduce their economic burden.[106] Furthermore, individuals with better physical activity habits during childhood and adolescence tend to be more physically active in adulthood.[107] Therefore, it is necessary to promote public health strategies that target increasing physical activity levels and decreasing sedentary behavior among children and adolescence.

Similarly to sleep goals, physical activity goals for adolescents were included in the Healthy People 2020 objectives. These goals included increasing the proportion of adolescents who met current Federal physical activity guidelines for aerobic, muscle strengthening, and both aerobic and muscle strengthening physical activity from 28.7% to 31.6%, 55.6% to 61.2%, and 21.9% to 24.1% respectively.[108] Unfortunately, these objectives were not met, and targets were revised for the Healthy People 2030 goals. The new goals include increasing the proportion of adolescents who met current Federal physical activity guidelines for aerobic, muscle strengthening, and both aerobic and muscle strengthening physical activity from 26.1% to 30.6%, 51.1% to 56.1% and 20.0% to 24.1%, respectively.[109]

THE SOCIAL-ECOLOGICAL MODEL

Model Definition

Many health-related behaviors, including sleep and physical activity, are influenced by factors at the individual, or micro-system, level. This may include an individual's genetic or biological makeup, as well as an individual's beliefs or knowledge on a health behavior or health outcome. These individual level factors are nested within social-level factors, like one's home environment, formal or informal social networks, and organizations or institutions that a person is involved with. The community formed by these organizations and institutions can also be used to influence the health behaviors of their members. Social factors are nested within societal level factors, such as local, state and national laws and policies.[110,111] There are multiple levels of influence that individually affect health behaviors and health outcomes, and factors that appear at one level can interact and reinforce factors found at another. Therefore, public health interventions and prevention strategies should target multiple factors at various levels of influence.[110–114]

Factors associated with sleep

Many factors are associated with sleep duration and quality among children, and these factors vary depending on child's age and developmental status. Individual-level characteristics may be more strongly associated with adolescent sleep compared to sleep among infants and younger children, as adolescence is a time when individuals begin making decisions for themselves regarding their health behaviors.[26] Social and environmental factors play a larger role in infant sleep, with caregiver qualities and behaviors having the most impact on infant sleep development.[115,116]

The rate at which sleep regulation and consolidation occurs in infancy varies from child to child.[115] Individual-level characteristics related to poorer infant sleep outcomes include low birth weight, prematurity, negative infant temperament, atypical hormonal rhythms, and greater physiological reactivity.[115] Differences in the rate of brain maturation in infancy, which is associated with an increased rate of sleep consolidation and a reduction in REM sleep duration, along with medical issues such as allergies, ear infections or digestive problems can lead to poor sleep in children as well.[117]

The home environment, namely parental influence, can also shape sleep outcomes in infants and young children.[7,115,116] This includes parental practices related to bedtime, such as putting the child to bed when they are tired but not fully asleep, maintaining a consistent bedtime, and avoiding feedings immediately before bed.[7,115] Parents should also provide greater emotional availability at bedtime, which involves correctly responding to their child's cues, and comforting them in a way that leads them towards sleep.[115,116] Parents who are overly sensitive to their child's cues at night can lead to more nighttime wakings, and prevent children from learning to self soothe if awoken at night.[7,115,116] Greater maternal depression is associated with poorer infant sleep, as is exposure to media devices such as televisions, smartphones and tablets.[7,116] This may be caused by greater exposure to blue light, leading to alterations in melatonin levels, cognitive arousal due to inappropriate content, or a displacement of sleep time.[7,116] Cultural differences also play a role in shaping sleep in infancy. For example, ethno-racial differences in sleeping arrangements, such as bed sharing, can lead to shorter sleep durations.[116,117]

Although sleep duration appears to decrease as children transition into adolescence, there does not appear to be a concurrent decrease in sleep need.[26] Multiple factors may be related to sleep quality and duration during this developmental period. Individual-level factors include unmodifiable factors, such as sex or race and ethnicity, as well as modifiable factors, such as health related behaviors, and cognitive or emotional arousal. Overall, variations in biological processes are thought to explain differences in sleep patterns among males and females,[10] while social processes such as beliefs and attitudes about sleep may partially explain sleep disparities between different races and ethnicities.[118] Health behaviors such as higher levels of physical activity and lower caffeine and tobacco consumption have also been shown to be associated with longer sleep duration and better adolescent sleep quality.[119] Delays in bedtimes, which can lead to a smaller window of opportunity for sleep at night, may result from many adolescents' lack of time management skills, which are needed to balance school work, part-time employment, and sports or other extra-curricular activities.[18] Stressors such as these can increase pre-sleep cognitive and emotional arousal, which is associated with poor sleep outcomes and difficulty obtaining the optimal amount of sleep.[120]

Research on social-level factors associated with adolescent sleep focuses primarily on behaviors and characteristics in the adolescent's home. Individual's living in more chaotic households have poorer quality sleep,[121] while adolescents whose parents set stricter rules around bedtime report longer sleep durations.[122] This is especially important to consider in low SES households, considering adolescents who live in higher SES households sleep better than children in lower SES households.[72] Current research on the mechanisms that explain associations between social level factors and adolescent sleep point to their effect on individual-level factors. For example, living in a more chaotic household may lead to greater pre-sleep cognitive arousal, while parent-set bedtimes may be a reflection of greater social support within a family, leading to healthier sleep outcomes.[123]

While evidence exists suggesting that adolescents living in low SES areas experience poorer sleep outcomes than children in higher SES areas,[124] more research is needed regarding other societal level factors that influence adolescent sleep. For example, a limited number of studies have looked at the effect of Daylight Savings Time on sleep patterns in adolescents. Most of the research has focused on adult populations, and has found that this policy is associated with disrupted sleep and greater daytime sleepiness.[125]

Some policies have been developed with the direct goal of improving sleep health among adolescents. Adolescents go to bed and fall asleep later than younger children due to a shift in their biological clock.[27] Waking up early for school the following morning may be difficult to do, as their window of sleep opportunity may be too short for them to obtain the adequate amount of sleep. Therefore, policies delaying school start times by as little as 15 minutes have been developed in some areas, and have been shown to significantly increase adolescents' sleep duration.[126]

Factors that influence physical activity

There are a number of factors that serve as facilitators and barriers to physical activity among children, and they vary depending on the age and developmental status of the child. The non-modifiable factor that has the strongest relationship with physical activity levels is sex, with females consistently participating in less physical activity than males.[127] Modifiable factors at the individual level that are associated with higher physical activity levels include greater self-efficacy and enjoyment.[127,128] Children are more likely to participate in physical activities if they enjoy being physically active, are confident in their abilities related to the physical activity and feel motivated to be physically active in order to improve their appearance or achieve fitness goals.[128] Preferences for sedentary behaviors such as screen media use are a barrier to physical activity, and children who are overweight or obese are also less likely to participate in physical activities.[127] Interventions targeting these individual level factors can occur in clinic based settings, although this is not yet a common practice.[128]

Social-level factors that influence physical activity among infants and young children can be found at the home and in formal or informal childcare centers. Children and adolescents with family members who encourage and support physical activity in the home, as well as children with caregivers who model these behaviors are more likely to be physically active.[127] Parents who have busy schedules are less likely to participate in physical activities with their children, and less likely to choose active forms of transportation.[127] Furthermore, small living spaces that are not structured for physical activities, a lack resources that provide opportunities for physical activity, and the overuse of televisions in a home are all associated with lower physical activity levels.[128]

Childcare providers provide opportunities for structured and unstructured activity by allotting specific time during the day for these activities and can also model and support physical activity. Similarly to the home environment, the structure of the childcare environment, can hinder or encourage physical activity. Messaging surrounding physical activity in the home and childcare setting should be consistent and supportive. For example, parents should provide children with proper clothing which allows them to participate in indoor and outdoor physical activities.[127]

Many interventions targeting physical activity are based in school settings because they can target large populations of older children and adolescents. These interventions can be in the form of enhancing physical education programs, incorporating physical activity before and after school, or adding it to regular lesson plans as exercise breaks or physically active learning activities. Overall, the results of these types of interventions suggest that promoting physical activity in the school setting has the potential to increase children's overall physical activity levels.[128]

A child's built environment and cultural norms also play a role in encouraging physical activity in children at the societal level. Afterschool and summer programs can provide opportunities for participation in organized sports or active transportation. The built environment should be structured in a way that promotes active transportation and access to various physical activity facilities for all people. This includes lowering crime rates, and taking weather and climate into consideration when structuring recreational areas. Mass media campaigns can also be used at the local or national scale to increase physical activity among children of all ages.[127,128] Policies and laws created to promote physical activity and increase access to resources for at-risk populations include mandating physical education, Title IX legislation, and the Americans with Disabilities Act. Furthermore, the development of PA guidelines by the federal government also provides support for PA promotion in the US.[128]

Although less research has been done on the determinants of change in physical activity among children and adolescents, there is evidence that higher levels of physical activity, greater self-efficacy, and more social support early on in childhood is associated with smaller declines in physical activity throughout childhood.[129] Among very young children, parental monitoring is positively associated with changes in total physical activity levels, while physical activity training from childcare providers has been shown to lead to a greater increase in MVPA over time.[130]

MEASUREMENT

Sleep

Pediatric sleep duration and quality can be assessed using objective and subjective measures. Studies measuring sleep in children and adolescents must consider the advantages and disadvantages of each instrument when selecting a measurement strategy, which include the cost, ease of use, and psychometric properties of each instrument. Objective measures include polysomnography (PSG), videosomnography and actigraphy, and subjective measures include parent- or child-reported sleep logs, diaries, and questionnaires.[48,131]

Objective measures. PSG data are collected in a sleep laboratory, and include measures of electrical brain activity, muscle activation, eye movements, and oxygen saturation. Two nights of sleep are required to account for first-night effects, which gives an individual the opportunity to become accustomed to the equipment.[131] Although the scoring methods are complex and must be completed by a trained professional, PSG data provide detailed information on sleep architecture and brain activity which can be used to determine sleep duration and quality. PSG is considered to be the "gold standard" measurement tool and is often used for validation studies and for determining whether an individual suffers from a clinical sleep disorder.[48,131]

Videosomnography involves video recording an individual while they sleep in their natural setting. This measurement can be used to assess bedtimes, wake times, the number and duration of nighttime awakenings, and parent involvement or a child's behavior during waking episodes such as self-soothing methods. This measure is a good option if a researcher is interested in parent-child interactions at bedtime or throughout the night. Scoring videosomnography data is very time-consuming. Furthermore, there are a number of privacy concerns associated with recording a child at night, which may extend to other family members if the parents practice co-sleeping or if the child shares a room with other siblings.[131]

Actigraphy is used to assess sleep duration, sleep and wake patterns, and sleep quality in the natural setting over an extended period of time using a small device worn on the wrist by children and adolescents, or on the ankle or calf by infants.[131,132] A motion sensor in the device collects signals, and this data is applied to an algorithm that helps determine whether the individual wearing the monitor was awake or asleep at any given epoch based on the intensity of activity that occurred in that interval of time.[132] The most commonly used devices are Ambulatory Monitoring, Inc. (AMI) devices, and the

Sadeh et al[133,134] algorithm is one of the most commonly applied algorithms to process data collected on AMI devices.[135] Actigraphy has been validated against PSG in multiple populations, including very young children136 and adolescents,[48] and at least 5 nights are required for pediatric sleep data to be reliable.[135] Validation studies are still needed to assess daytime naps via actigraphy. Algorithms based on nighttime sleep are currently applied to data collected during the day, which may be inappropriate.[132]

Actigraphy data can be affected by movement artifacts, which particularly effects sleep measurement of young children. Picking up a child or moving a child in a stroller while they are sleeping may incorrectly register as awake on a monitor.[131] Although some research instructs parents to keep detailed sleep logs or diaries to help with identifying these artifacts,[135] this strategy may place an unnecessary burden on caregivers participating in these studies.[132] There are a number of different monitors, scoring programs and algorithms to choose from, but the availability of multiple devices and the use of multiple algorithms makes it difficult to compare the results of different studies assessing sleep outcomes.[131,132]

Subjective measures. Questionnaires are widely used to assess sleep duration along with sleep quality and daytime sleepiness, and involve very little participant burden and cost. There are multiple sleep questionnaires that have been developed and validated for special populations including infants, children and adolescents, but this makes it difficult to compare results across studies. Questionnaires are also subject to recall and desirability bias.[137] Sleep logs, or daily sleep diaries, are also fairly easy and inexpensive ways to measure sleep duration and quality, and tend to be more accurate than questionnaires.[48,131] Unfortunately, adolescents and parents who complete sleep logs and diaries tend to overestimate their sleep duration,[137,138] and a more accurate estimate of sleep duration is produced when adolescents keep a sleep diary over multiple nights.[137]

Physical activity

Similar to sleep, there are a number of subjective and objective instruments available for measuring physical activity. When selecting an instrument, it is important to consider: the characteristics of the study being conducted, including the study objective, sample size, and the budget; the characteristics of the population being studied, including their age, disability status and primary language; the aspects of physical activity being assessed, such as sedentary behavior, sports participation, or intensity; the setting behaviors are being assessed in, such as in the home, outdoors, or in a classroom; and characteristics of the available instruments, such as their psychometric properties, cost, and what they can and cannot measure.[139–141] Measuring physical activity in children is very different from measuring physical activity in adults because the nature of their physical activity is different. Bouts are shorter, which affects the measurement, processing and interpretation of physical activity data.[140]

Objective measures. Doubly Labelled Water is used to estimate total caloric expenditure, and it is the gold standard for measuring energy expenditure. This measurement requires a participant to ingest water labeled with two isotopes, which are eliminated from the body over 5-14 days. The rate at which the two isotopes leave the body is used to determine carbon dioxide production, which in turn is used to calculate energy expenditure based on pre-determined equations.[142] This method of measurement is a relatively non-invasive way to measure physical activity, but it is limited by the fact that it must be done over multiple days or even weeks, therefore it cannot be used to measure energy expenditure for acute bouts of physical activity. The isotopes are also expensive, which limits this measurement to studies with small sample sizes.[48,141,143]

Indirect calorimetry measures energy expenditure by comparing oxygen consumption with carbon dioxide production during rest and exercise.[143] It is commonly used as a criterion measure validating other instruments like accelerometers. Unfortunately, the equipment needed for measurement is large and expensive, making it difficult to us in studies measuring physical activity in a large population or individuals during free-living conditions.[143]

Data collected by heart rate monitors can be used to calculated energy consumption because of the linear relationship between heart rate and oxygen consumption.[143] Different techniques have been developed to distinguish between sedentary behavior and different physical activity intensities using heart rate measurements, although some techniques are more expensive and burdensome than others.[143]

Pedometers are devices worn on the hip, and are used to measure vertical acceleration when walking. This information is used to calculate the number of steps an individual takes throughout a pre-selected period of time, usually over a day. Pedometers should be worn for at least 7 days, and this should include at least 1 weekend day for measures to be valid.[140,144] Although the moderate to high validity and reliability of pedometers has been established among children over the age of 5, more work is needed on the psychometric properties of pedometers in children under the age of 5.[140,143,144] These monitors are less expensive than other tools like accelerometers, but they are limited by the fact that they are unable to assess physical activity intensities and physical activity patterns over time.[140,143]

Accelerometry is one of the most common tools used to assess children's physical activity.[141] Accelerometers measure physical activity by calculating the change in velocity of a body over multiple different planes during a predetermined set of time. Raw data, in the form of counts, are used to calculate the frequency, duration and intensity of physical activities.[78,140,143] Count data can also be combined with biodata, such as weight, age and gender, to determine energy expenditure.[143] Because devices are small and don't hinder regular activity, they can be used to measure physical activity over multiple days, even in very young children and infants.[78,143] They are also relatively inexpensive, making them good tools for longitudinal studies with larger sample sizes.[145] Each device contains different internal hardware, and uses different software and algorithms to calculate physical activity levels and intensities. This makes it difficult to compare results across different studies if different devices are used.[140,141,145] Cut points can be used to estimate the amount of time an individual spends in the different physical activity intensities, and these cut points vary based on a person's age. A wide range of cut points are available, and physical activity outcomes in a study can be affected by the cut points that are selected.[140,145] Unfortunately, cut points for physical activity intensity categories have not been developed for infants and very young children.[78] Physical activity outcomes can also be affected by variations in epoch length, accelerometer placement, and the duration of monitoring.[145] The monitor cannot account for the additional energy expenditure involved in walking up a hill or a set of stairs.[141] Physical activities that involve limited torso movement are also difficult to measure, and monitors are unable to distinguish between sedentary behaviors and standing.[141,143] Furthermore, the movement caused by infants being handled by a caregiver can be incorrectly registered by the monitor, leading to inaccurate readings.[78]

Subjective measures. A number of direct observation tools have been developed to assess physical activity in children from many different populations, and vary based on the setting of the study and the sample characteristics. Specific behavioral coding systems are used to measure the frequency, duration and intensity of physical activity over a set period of time in a controlled setting. These tools are often used as a criterion measure of physical activity when assessing the validity of new instruments such as questionnaires,[78,140,143] but they are limited by a high experimenter burden, and potential reactivity from participants.[140,143]

Self- or proxy-reports of physical activity data often involve the use of questionaries' or diaries that collect information on a child's temperament, his or her movement patterns throughout the day, or a child's behaviors over a set period of time. Children, parents or other caregivers may be asked to recall physical activity from the last 24 hours or average physical activity levels from the past year.[78,141] Studies assessing the psychometric characteristics of self-report tools in older children and adolescents show that they are moderately valid, compared to objective measures, and have moderate to high reliability when used to assess physical activity and energy expenditure.[146] This format is best for large epidemiological studies or for physical activity surveillance, because it is low in cost and easy to administer, but recall bias can lead to inaccurate estimates of physical activity.[141,143] Although using an interviewer to administer these questionnaires can help with accuracy, this can also introduce response bias.[143] Another method to increase the accuracy of self-reported physical activity is through the use of dairies, where participants or their caregivers can log physical activity daily over a set period of time. This method has a high participant burden, and it is recommended that this method only be used with participants over the age of 10.[143]

ASSOCIATIONS BETWEEN PHYSICAL ACTIVITY AND SLEEP

Physical activity is considered a simple and inexpensive, nonpharmacological method for improving sleep outcomes without causing any serious side effects.[147] Cohort studies and surveillance data report a moderate, positive association between sleep and physical activity in the general population.[147] Although some research shows a stronger association between sleep and physical activity levels the following day compared to the opposite direction, the cross-sectional nature of most observational research on this association suggests a bidirectional relationship.[147] Furthermore, most of these data are collected using self-report methods, and are unable to provide information on the mechanisms that explain these association.[147]

Experimental studies have been performed to address these limitations, and results show that the effect of acute and chronic exercise leads to small-to-moderate effects on sleep quality and duration.[147] Specifically, acute exercise during the day leads to improvements in sleep duration, REM sleep duration, wake time after sleep onset, sleep efficiency, and slow wave sleep the following night.[148,149] Participating in regular exercise training is associated with a longer sleep duration, a greater sleep efficiency, a shorter sleep onset latency, and a greater overall sleep quality compared to individuals in control conditions.[147–149] The time of day physical activity is performed moderates this relationship, with stronger effects seen when physical activity is performed closer to bedtime. Exercise intensity does not appear to moderate these associations.[147,148] Limitations exist in this line of research as well. Most experimental research is conducted on healthy individuals, and a ceiling effect may be the underlying reasons why only small to moderate improvements in sleep are seen. In other words, good sleepers can only improve their sleep a small amount, and the effects of exercise on sleep outcomes may be greater among poor sleepers.[147] Furthermore, there is a lot of variation in the methods used to assess both sleep and physical activity in this line of research, which may help explain why results are mixed, especially among understudied populations.[149]

Young children

Limited analyses assessing cross-sectional relationships between sleep and physical activity in very young children show mixed results, suggesting weak but positive, or null associations between the two variables.[45,64,150–152] A recent meta-analysis found limited evidence to suggest that outdoor play time and moderate-to-vigorous physical activity levels were associated with better sleep outcomes in toddlers and preschoolers, but found that the evidence for these relationships in infants is less conclusive.[17]

Very little longitudinal research has been done assessing the sleep and physical activity relationship in very young children. One intervention by Yoong and colleagues showed that improving nighttime sleep in 3-6 year old children led to an increase in objectively-measured MVPA that was still apparent 3 months after the intervention was completed.[153]

A meta-analysis by Antczak et al. concluded that the variation in methodologies used in experimental studies assessing the sleep and physical activity relationship in 3-13 year-old children may partially explain the inconsistent results seen in this line of research.[154] They concluded that there was not enough evidence to support a positive association between sleep and physical activity in younger children, but that this association does appear in older children. They argued that this association may be weaker in children due to biological and developmental differences that may impact mechanisms guiding this relationship in adolescents and adults.[154] Another limitation of this line of research suggested by Matricciani et al. is that it does not consider the fact that there are only 24-hours in a day, and that time spent doing one activity cannot be used to perform another. In other words, increasing time spent being physically active will displace time spent sedentary or sleep time, making these outcomes inter-related. Traditional methods of data analysis, such as regression or correlation, may not be appropriate for analyzing these type of data, and may partially explain mixed or null results.[155]

Adolescents

Studies assessing the relationship between sleep and physical activity among adolescents show a positive association, with moderate-to-strong effect sizes depending on the type of measurement instruments used to measure sleep and physical activity.[48] Effect sizes are strongest in studies that utilize subjective measures for both behaviors, and weakest when measuring physical activity objectively and sleep subjectively.[48] Specifically, self-reported sleep quality was positively associated with physical activity levels,[73] and higher levels of MVPA are associated with earlier bedtimes, a longer sleep duration, and better sleep efficiency.[119,156] Higher levels of sedentary behavior are associated with delays in sleep onset and offset and a shorter sleep duration.[156] Like research in very young children, most studies are cross-sectional and rely on self-report data.[48]

Although few experimental studies have been conducted assessing the effect of regular exercise on sleep, they show promising results. For example, an intervention by Kalak et al. assessing the effect of morning running on sleep outcomes in adolescents.[157] Compared to the control group, adolescents who ran for 30 minutes every morning over the course of 3 weeks showed significant improvements in objective sleep outcomes, including an increase in slow-wave sleep and a decrease in sleep onset latency, as well as improvements in subjective sleep quality and a decrease in daytime sleepiness. These results are promising considering there are very few limitations to running, and improvements in sleep outcomes were seen very quickly.[157]

The issue of compositional analysis needs to be addressed in adolescents as well. Although there is research assessing changes in sleep and physical activity levels individually as children transition from childhood to adolescence, more research is needed to understand how combinations of PA, SB and sleep behaviors during a 24-hour period change over time.[158] More work is also needed to understand how the composition of multiple health behaviors that occur in a finite amount of time influence each other and subsequent health outcomes.[159]

Mechanisms

A number of psychological and biological mechanisms have been suggested to explain the association between sleep and physical activity, but a majority of these pathways have been studied exclusively in adults.[160] In regards to psychological mechanisms, both physical activity and sleep are associated with mood. An increase in exercise has been shown to improve mood, potentially by down-regulating activity in the hypothalamic–pituitary–adrenal (HPA) axis.[147] This overactivity is associated with depression and anxiety, as well as poor sleep outcomes. Furthermore, HPA axis overactivity is associated with impairments in thermoregulation.[147,160]

According to the thermogenic hypothesis, sleep onset begins with a drop in body temperature, primarily as a result of an increase in peripheral skin blood flow.[161] Elevated body temperatures caused by physical activity are followed by a drop in body temperature after physical activity stops, provide input to regions of the brain that promote sleep onset and maintenance. Chronic exercise may also improve the body's ability to thermoregulate at night, which may be impaired among individuals suffering from impaired sleep.[147,160,161]

Physical activity may also influence the circadian systems that regulate sleep patterns, adjusting circadian phases to align with healthy circadian rhythms. This is especially the case when physical activity is performed outdoors because it increases an individual's exposure to bright light, which is also known to shift circadian rhythms and improve sleep. Unfortunately, little is known about the time of day physical activities should be performed and the length of time these physical activities must be performed for in order to see a significant shift the circadian system that leads to improvements in sleep outcomes.[147,161]

Even less research has been conducted assessing the energy conservation/body restoration hypothesis and the adenosine hypothesis. According to the energy conservation/body restoration hypothesis, exercise depletes energy stores, which can only be restored when an individual is asleep. Recovery from any damage, major or minor, can occur at this time as well.[161] The adenosine hypothesis posits that greater physical activity increases adenosine levels in the brain, which are also associated with an increased sleep need.[147]

INFLUENCE OF SLEEP AND PHYSICAL ACTIVITY ON THE DEVELOPMENT OF WEIGHT STATUS

Childhood obesity

Overweight and obesity are defined using body mass index (BMI), calculated by dividing weight in kilograms by height in meters squared. Based on Centers for Disease Control and Prevention (CDC) growth chats, children and adolescents between the ages of 2 and 19 with a BMI between the 85th and 95th percentiles for their age and sex are overweight, while those in the 95th percentile or greater for their age and sex are obese.[12] Among children under the age of 2, excessive weight can be defined one of two ways. This includes a weight-for-recumbent length z-score that is 2 z-scores above the World Health Organization's (WHO) sex-specific weight-for-recumbent length growth standards,[162] or a z-score that is above the 95th percentile on the CDC sex-specific weight-for-recumbent length growth charts.[163] Current estimates indicate that 17% of children in the US are obese.[12] Specifically, 20.6% of adolescents ages 12-19, 18.4% of children ages 6-11, and 13.9% of children 2-5 years of age are obese, and 8-9% of infants and children under 2 years of age have a high weight-for-recumbent length.[163,164]

Obesity is caused by a number of lifestyle and biological factors that lead to excessive food intake and low energy expenditure, in other words, a poor quality diet, and low levels of physical activity or high levels of sedentary behavior. The consequence of this is an energy imbalance the creates an excess of adipose tissue, leading to significant, negative physical and psychological health outcomes among children, including an increased risk of heart disease, type 2 diabetes, cancer and mood disorders.[12] In addition to these immediate health outcomes, childhood obesity is associated with a five-fold increase in the likelihood of an individual being obese as an adult.[165] Current interventions aimed at preventing or treating obesity by addressing the energy imbalance caused by poor diet and inactivity are only moderately successful.[13] This has lead researchers to explore other potential factors, including sleep. Because sleep is a modifiable health behavior that is associated with both weight status, diet quality and physical activity levels in children, it has become a strong candidate for this line of research.[13]

Sleep, physical activity and weight

A Conceptual Framework for Examining Relationship among Sleep, Physical Activity and Weight. Short sleep duration is associated with a number of metabolic and biological changes in children, such as an increase in insulin resistance.[14,15] Although some research in adults suggests that sleep restriction leads to changes to leptin and ghrelin levels,[14] this research is still inconclusive among children.[15,16] These biological changes are thought to influence dietary patterns, including a higher intake of calorie-dense foods and sugary foods and beverages resulting in the greater energy intake associated with obesity.[14–16] Shortened sleep is also though to alter how the brain responds to food. Sleep deprivation is associated with greater activation of brain regions associated with food reward, making food more appealing and desired more strongly by adolescents.[16] A limited amount of evidence suggests that poor sleep results in a negative affect that may lead to emotional eating among some adolescents. Furthermore, adolescents who go to bed late have an increased opportunity to snack, increasing energy consumption.[16] Furthermore, sleep deprivation can lead to fatigue, which may contribute to a decrease in physical activity levels and increased sedentary behavior and screen time. These behaviors decrease energy expenditure and would further increase the risk of obesity.[14,15]

Research assessing the pathways linking sleep and obesity has primarily focused on adults.[15] Much of the literature is limited by a lack of longitudinal or experimental studies, and the inconsistent use of subjective and objective measurement strategies to assess sleep, physical activity, or diet. More work is needed to address whether other sleep measures in addition to sleep duration, such as bedtime and sleep quality, are related to obesity outcomes. Covariates, including age, race, ethnicity, SES and sex should be explored in more detail as well.[13,15]

Young Children. Results of cross-sectional research shows an inverse association between sleep duration and weight status in children under the age of 3 years old. Furthermore, studies show sleep duration is associated with higher physical activity levels and better diet quality among infants and toddlers.[151,152,166] These results, although limited, support a multi-system approach to obesity prevention.[152]

A recent randomized control trial showed that an intervention targeting sleep duration was successful in reducing the odds of obesity among 2-year-old toddlers, and performed better than an intervention targeting improvements in diet and physical activity without addressing sleep.[167] Unfortunately, interventions targeting improvements in sleep in order to prevent the development of overweight or obesity in children across multiple developmental stages have not been successful.[153] This may be due to the fact that most interventions have not been able to significantly improve sleep outcomes in these populations. In the few that have successfully improved sleep outcomes, improvements were also seen in BMI, physical activity and diet outcomes.[153]

Older Children and Adolescents. Much of the research assessing the sleep, physical activity and weight status association among adolescents is also cross-sectional, and it too supports an approach that addresses multiple health behaviors when targeting obesity prevention. Overall, acquiring the optimum amount of multiple movement behaviors has the highest benefit on health outcomes. For example, adiposity outcomes are the best when children exhibit high levels of physical activity and sleep, along with low levels of sedentary behavior.[168,169] Not meeting sleep recommendations of 8 or more hours of sleep per night is also associated with higher levels of sedentary behavior and poorer diet quality,[170] and adolescents who do not meet screen time or sleep guidelines are less likely to meet physical activity guidelines.[171] Similarly to sleep duration, later bedtimes are associated with poorer diet and greater overweight severity, while poorer sleep quality is associated with poor diet and lower levels of physical activity.[73]

Studies addressing the influence of different movement behaviors on weight status outcomes must therefore assess each behaviors' individual effects, as well as their interactions with each other. New methods which account for day-to-day or within-subject variability in these measures are becoming more common, and include compositional analysis and isotemporal substitution analysis. Compositional analysis allows researchers to look at the effects of multiple behaviors on health outcomes, while also considering the fact that performing one behavior displaces time that could be spent performing another behavior.[172] Preliminary research utilizing this method of analysis suggests that while reducing MVPA and replacing it with higher levels of sedentary behavior, light physical activity or sleep increases BMI, replacing the other behaviors with MVPA had a weaker effect on BMI outcomes.[172] Isotemporal substitution analysis is another strategy used to analyze how changes in one movement behavior effect weight status while also accounting for time spent in other movement behaviors.[172] Some research utilizing isotemporal substitution has shown that replacing sedentary behavior with light physical activity, moderate-to-vigorous physical activity, or sleep has the potential to improve BMI in 5-19 year-old children.[173]

MAJOR FINDINGS

Summary

Sleep and physical activity are behaviors that change as children develop over time and are associated with a number of health outcomes, including overweight and obesity.[7,27,61,63,64,77,79,91,92] Both objective and subjective methods have been used to measure sleep duration, sleep quality and physical activity levels,[131,139] and these methods have been used to develop professional guidelines for both sleep and physical activity.[1–3,28] Unfortunately, many children do not meet sleep and physical activity guidelines,[34,35,83,84] with children from lower SES households and racial or ethnic minorities less likely to meet these guidelines.[42,43,83] It is important to address these behaviors early on, as evidence shows that sleep and physical activity patterns, along with the health outcomes associated with them, persist into adulthood.[48,107,165]

There is a positive, bidirectional association between sleep and physical activity in children and adolescents,[147] and a number of psychological and biological mechanisms have been suggested to explain this relationship.[147,160,161] Furthermore, sleep and physical activity are both associated with weight status outcomes in children, making them popular targets for interventions aiming to prevent and treat overweight and obesity.[13] Similar conceptual frameworks proposed by Duraccio and colleagues[16] and Taheri[14] were developed to explain the multiple pathways linking sleep and physical activity with weight status outcomes. According to these frameworks, poor sleep increases energy intake due to hormonal changes as well as an increased opportunity to eat during the day.[14,16] Poor sleep also leads to greater feelings of tiredness, resulting in a reduction in physical activity and a limited energy expenditure.[14,16]

Limitations

Research assessing the relationship between sleep and physical activity in children, along with their individual and combined effects on the development of weight status is limited by a number of factors. More work is needed to address associations between physical activity levels and health outcomes in very young children. Objective physical activity measures for children under 3 years of age are still being developed and validated, limiting the assessment of the physical activity and health relationship in infants and very young children. This has prevented the development of a specific, public health target for this age group.[78,81] More research is also needed on the relationship between sleep and physical activity, especially among very young children.[17] Results of recent studies assessing this relationship are mixed, which may be due to the variation in the methods used to assess both sleep and physical activity in this line of research.[149] Much of the current data is based on parent or self-reported sleep and utilizes cross-sectional study designs,[17,48,64] and more longitudinal studies that utilize objective measures of both sleep and physical activity are needed to reduce the risk of bias.

Interventions targeting obesity treatment and prevention in children that address poor diet and inactivity alone have not had very successful results.[13] Successfully incorporating a sleep component into these interventions has not only shown to improve sleep outcomes in participants, but has also led to improvements in weight status outcomes.[153] In order to further improve these interventions, more research should be done assessing the longitudinal relationships between subjectively-measured sleep, physical activity, and weight status in children from a very young age throughout adolescence. While much of the work has focused on sleep duration specifically, future studies should assess whether other sleep variables, including bedtime or sleep quality, are related to obesity outcomes. More work is also needed assessing whether these relationships vary based on demographic characteristics, such as age, race, ethnicity, SES or sex.[13,15]

STUDY METHODOLOGY

GLOBAL INTRODUCTION

Combinations of lifestyle and biological factors, such as a poor-quality diet, low levels of physical activity and high levels of sedentary behavior, lead to an energy imbalance that can ultimately result in excess adiposity among children of all ages. This excess adiposity is associated with health outcomes like heart disease, type 2 diabetes and mood disorders,[12] as well as an increased risk of obesity later on in adulthood.[165] Although multiple interventions have been developed aiming to prevent or treat obesity by improving diet and physical activity levels in children, the prevalence of childhood obesity continues to be alarmingly high among children of all ages.[163,164]

Because interventions targeting obesity prevention have only been moderately successful, research has moved towards exploring other potential modifiable behaviors.[13] For example, both sleep duration and sleep quality have been shown to be inversely associated with weight status and the risk of overweight/obesity, and positively associated with diet quality and physical activity levels in children in cross sectional[15,29,54,61–64] and longitudinal studies.[65–67] Meeting physical activity, sleep and sedentary behavior guidelines is associated with a reduced risk of obesity among children and youth, but current surveillance data show that only around 5% of adolescents currently meet guidelines for all three of these behaviors.[174]

Low income and minority youth are at a higher risk of not meeting sleep, physical activity and sedentary behavior guidelines. What's more, the prevalence of overweight and obesity is higher among low income and minority youth.[13,15] What is still unclear, though, is whether sleep is more strongly associated with weight status among low-income or minority youth compared to higher-income or White youth, respectively.

Emerging technologies have made it easier to collect objective data on health behaviors in large population of children and adolescents. Instruments like actigraphy monitors and accelerometers, which are used to collect objective sleep and physical activity data, respectively, reduce the risk of bias often associated with the use of subjective measures like parent or child reports.[131,141] More work is needed utilizing these instruments to measure health behaviors and subsequent health outcomes in diverse samples of children and adolescents as they develop over time.[145,175]

Much of our current understanding of the relationship of sleep with physical activity is based on research conducted in older children and adult populations.[17] More work is needed to understand this relationship among children, especially infants and very young children. In fact, the Physical Activity Guidelines Advisory Committee concluded in their 2018 report that, "Insufficient evidence is available to examine relationships between physical activity and sleep in children and adolescents and whether the relationships vary according to race/ethnicity, socioeconomic status, or weight status."[81] Therefore, the overarching purpose of this dissertation is to enhance our understanding of the relationship between sleep and physical activity in children, as well the association of both behaviors with weight. This dissertation will be comprised of three studies, beginning with the first study assessing the longitudinal relationship between sleep and physical activity in infants from the age of 6 months old until they are 24 months old. The second study will utilize the same sample of children but will instead assess the relationship between sleep and weight status controlling for physical activity, and will determine whether the relationship varies based on demographic characteristics. Finally, the third study will assess the relationship between physical activity from age 11 to age 15 and sleep outcomes at the age of 15 in a separate sample of adolescents, and will determine whether demographic characteristics and weight status influence the sleep and physical activity relationship.

STUDY 1

Introduction

In infants and young children, sleep plays a critical role in early and future health outcomes, especially in the development of overweight/obesity.[64,176,177] Current pediatric sleep guidelines recommend that infants between the ages of 4 and 12 months sleep 12-16 hours/day, and children ages 1-2 years sleep 11-14 hours/day.[3] Recent surveillance data report that infants and young children 0-3 years old sleep 12-14 hours/day,[32,34] although the data also suggest that minority and low-income children are at a higher risk of inadequate sleep.[5,39,178,179] It is important to consider that while average sleep durations reported by surveillance data are consistent with sleep recommendations, they are based on parent reports. Parent reported sleep data are subject to bias, potentially leading to incorrect estimates of sleep.[137,180] Emerging research also indicates that higher physical activity levels are associated with better sleep quality and longer sleep duration.[150,151,166,181] Results of research examining the association between sleep and physical activity have also been shown to vary, depending on whether subjective or objective measures were used.[150]

Study 1 Aim: Examine the longitudinal relationship between objectively-measured sleep and physical activity in children 6-24 months old.

Objective 1a. Examine whether average physical activity levels in children from 6 months old to 24 months old are associated with sleep duration and sleep quality over time.

Objective 1b. Examine whether changes in physical activity levels in children from 6 months old to 24 months old are associated with sleep duration and sleep quality over time.

Methods

Data sources. Data addressing study 1 is be from the Linking Activity, Nutrition and Child Health (LAUNCH) study.[182] The LAUNCH study was designed to describe physical activity and sedentary behavior in young children as they transition from infancy to preschool, and to describe longitudinal associations between physical activity, sedentary behavior and diet with weight status during this transition. The LAUNCH study collected longitudinal, observational data in children at six time points, at ages 6, 12, 18, 24, 30 and 36 months. The present study will build upon this research by focusing on the associations between sleep and physical activity, and will focus on the first 24 months of data. Data collection for the LAUNCH study is currently underway, and 24-month data collection has been completed.

Participants. Participants are children and their biological mothers recruited from communities in South Carolina. Data were collected on 144 participants at the 6 months timepoint, 131 participants at the 12 month time point, 91 participants at the 18 month time point, and 98 participants at the 24 month time point. Race/ethnicity distributions at the 6-month time point were as follows: 38% non-Hispanic White, 37% non-Hispanic African American, 20% Hispanic, and 5% other. Additionally, 54% of children at the 6-month time point were male. The LAUNCH study excluded children born before 37 weeks gestation, as well as children with any physical limitation that prevented the use of accelerometry to assess physical activity.

Measures. The primary exposure of interest in Aim 1 will be physical activity, and sleep will be treated as the outcome variable. Covariates included in analyses include race/ethnicity, socioeconomic status, and sex.

Sleep. Sleep was measured objectively using an actigraph (MicroMini-Motionlogger, Ambulatory Monitoring, Inc.) Children wore actigraphs on the left ankle for 24 hours/day for seven days, except during water-based activities. Data were downloaded from the monitors and assessed using software available from the manufacturer (Version 1.16, Ardsley, NY), using the Sadeh et al.[134] algorithm for assessing sleep in children. Nighttime, daytime, and 24-hour sleep duration, and the average number of nighttime awakenings were calculated for each participant. The average number of nighttime awakenings will be used as a measure of sleep quality.[177] The primary approach for determining daytime, nighttime and 24 hour sleep duration as well as the number of nighttime awakenings will be based on data provided by the manufacturer. Other options for defining daytime sleep and number of nighttime awakenings, such as only considering napping as >30 minute sleep periods that occurred between the hours of 7AM to 7PM[183] and only including nighttime awakenings if they lasted more than 5 minutes[177], will also be explored. The definition of daytime as 7AM-7PM and day time as 7PM to 7AM at night time was used to coincide with the times listed in sleep questionnaires completed by parents at each time point. Operational definitions of sleep variables can be found in table 6.1.

Table 6.1 Operational definitions of sleep variables

Variable	Source	Operational Definition
24-hour sleep duration	Actigraphy	The number of minutes spent sleeping / 24 hours (7AM-7AM)
Daytime sleep duration	Actigraphy	The number of minutes spent sleeping / day (7AM to 7PM)
Nighttime sleep duration	Actigraphy	The number of minutes spent sleeping / night (7PM-7AM)
Number of nighttime awakenings	Actigraphy	The number of awakenings lasting 5 minutes or longer at night (7PM to 7AM)

Physical activity. ActiGraph accelerometers (GT3X-BT model, Pensacola, FL) were used to measure objective total physical activity. Children received accelerometers during each data collection visit with parents at his/her home, childcare center or another predetermined location. Accelerometers were worn for seven days and were attached to elastic belts and worn on the right hip for all age groups, as well as on the right ankle. Trained data collectors provided teachers and mothers instructions on how and when the monitor should be worn. Mothers were instructed to remove the monitor at night and during water-based activities and put the monitor back on shortly after waking in the morning. Accelerometers were initialized prior to data collection and begin collecting data at midnight following accelerometer distribution. Data were collected in raw data mode and later downloaded into 15-second intervals.[184] Non-wear time was defined as any ≥60 minute period of consecutive zeros and was excluded from analyses. Furthermore, only days where the accelerometer was worn for ≥16 hours and observations with ≥3 days of valid data were included in analyses. Total daily physical activity and total daytime physical activity were calculated for each participant. This method was chosen because intensity cut points have not yet been established for non-ambulatory children. Operational definitions of physical activity variables can be found in table 6.2.

Table 6.2 Operational definitions of physical activity variables

Variable	Source	Operational Definition
Total Daily Physical Activity	Accelerometry	Average counts per minute (24-hour)
Total Daytime Physical Activity	Accelerometry	Average counts per minute (7AM-7PM)

Demographic characteristics. Demographic characteristics were reported by the child's mother at baseline. These include sex (male/female), race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic, Other), and socioeconomic status (highest level of education achieved by mother; WIC status). Available responses for maternal education included: Some high school, High school diploma/GED, Some college, 2-year degree, 4-year degree, some graduate school, Graduate degree. Operational definitions of demographic characteristic variables can be found in table 6.3.

Table 6.3 Operational definitions of demographic characteristics

Variable	Operational Definition
Child's race/ethnicity	Non-Hispanic Black, Non-Hispanic White, Hispanic, Other
Child's sex	Male, Female
Mother's socioeconomic status	Highest level of education achieved (Some high school, High school diploma/GED, Some college, 2 year degree, 4 year degree, Some graduate school, Graduate degree); WIC status

Study 1 Analyses

Linear mixed model analyses will be used to assess the cross-sectional and longitudinal associations between physical activity and sleep. Models will assess the extent to which within-subject variation, or the longitudinal effect of physical activity, and between subject variation, or the cross-sectional effect of physical activity, explain sleep outcomes and changes in sleep outcomes, respectively. In other words, the longitudinal effect of physical activity is the expected within-person difference in sleep for a 1-unit change in an individual's physical activity levels. The cross-sectional effect of physical activity is the difference in average sleep outcomes between individuals based on their average physical activity levels. Testing whether the longitudinal and cross-sectional effects of physical activity are equal will determine whether differences in children's average physical activity levels over time have the same association with sleep as changes in a child's physical activity levels over time.[185]

Unadjusted and adjusted linear mixed models will be assessed using the PROC MIXED code from SAS version 9.4 (SAS Institute, Inc, Cary, NC). Separate models will be analyzed with either total daily physical activity or total daytime physical activity treated as the exposure variable. In order to account for the developmental changes in physical activity related to age, I will create a physical activity z-score for each child at each measurement time point using the study population mean and standard deviation. This z-score will have a mean of 0 with a standard deviation of 1. Z-scores will only be created for the physical activity independent variables, and not for any other variables or for the dependent variable. Parameters for both cross sectional and longitudinal effects of physical activity will be included in the model. Separate models will be run using 24-hour sleep, daytime sleep, and nighttime sleep as an outcome variable. A model using the number of nighttime awakenings as an outcome variable will also be created, and an appropriate analysis will be selected to account for the fact that nighttime awakenings is a count variable. Covariates included in the model will include the child's age (in weeks), race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic, Other) socioeconomic status (Highest level of education achieved -college or above, less than college; WIC status – yes, no), and sex (male, female). A model with baseline random effects will be compared to a model with random effects for both baseline measures and the slope. The best-fitting model will be chosen using the Akaike information criterion (AIC), the -2LL, and the Bayesian Information criterion (BIC). A contrast statement will be used to determine whether the cross-sectional and longitudinal effects of physical activity are equal.

The underlying hypothesis for objective 1a is that there is a positive association between infants' average physical activity levels and their sleep duration/sleep quality over time. This will be determined using the beta coefficient for the cross-sectional effect of physical activity entered in the model. The underlying hypothesis for objective 1b is that there will be a positive association between changes in infants' physical activity levels and changes in their sleep duration/sleep quality over time. This will be determined using the beta coefficient for the longitudinal effect of physical activity entered in the model. The Intraclass Correlation Coefficient (ICC) will be used to examine the effect size of the model.

STUDY 2

Introduction

Sleep, physical activity and sedentary behavior occur on a continuum, and optimal amounts of each behavior are associated with positive health outcomes, including healthy weight status.[168] Sleep, in particular, has been shown to have a strong, inverse association with overweight/obesity.[65] Interventions aimed at improving diet and physical activity alone have not been shown to consistently improve weight-status outcomes in infants, while interventions that include a sleep component have shown greater promise in reducing the risk of obesity.[167] Results from the 2015-2016 National Health and Nutrition Examination Survey (NHANES) showed that 9.9% of infants under the age of 2 years old had high weight-for-recumbent length based on CDC growth charts.[163] Infant weight gain has been shown to predict childhood obesity,[186] making these early years a critical developmental period for studying sleep, activity and weight status.[187] Unfortunately, evidence regarding the developmental trajectories of these factors in early life is limited.[187]

Study 2 Aim: Examine the longitudinal relationship between objectively-measured sleep and weight status in children 6-24 months old, and determine whether these associations differ by race/ethnicity, socioeconomic status, and sex.

Objective 2a. Examine whether average sleep duration and quality in children from 6 months old to 24 months old are associated with weight status over time.

Objective 2b. Examine whether changes in sleep duration and quality in children from 6 months old to 24 months old are associated with weight status over time.

Objective 2c. Examine whether the association between sleep and weight status in children from 6 months old to 24 months old are varies over time by race/ethnicity, socioeconomic status, and sex

Methods

Data source. The data for Study 2 will also utilize the LAUNCH data, and will focus on the associations between sleep and weight status in children from 6 to 24 months of age.

Participants. Participants for study 2 will include the same sample as study 1, and will include children and their biological mothers recruited from communities in South Carolina. Data were collected on 144 participants at the 6 months timepoint, 131 participants at the 12 month time point, 91 participants at the 18 month time point, and 98 participants at the 24 month time point. Race/ethnicity distributions at the 6-month time point were as follows: 38% non-Hispanic White, 37% non-Hispanic African American, 20% Hispanic, and 5% other. Additionally, 54% of children at the 6-month time point were male. Exclusion criteria included children born before 37 weeks gestation, as well as children with any physical limitation that would prevent the use of accelerometry to assess physical activity.

Measures. The primary exposure of interest in Aim 2 is sleep, and weight status will be treated as the outcome variable. Physical activity and diet variables will be included in the model as covariates, and race/ethnicity, socioeconomic status, and sex will be included in the model as moderators.

Sleep. Sleep was measured objectively using an actigraph (MicroMini-Motionlogger, Ambulatory Monitoring, Inc.) Children wore actigraphs on the left ankle for 24 hours/day for seven days, except during water-based activities. Data were downloaded from the monitors and assessed using software available from the manufacturer (Version 1.16, Ardsley, NY), using the Sadeh et al.[134] algorithm for assessing sleep in children. Nighttime, daytime, and 24-hour sleep duration, and the average number of nighttime awakenings were calculated for each participant. The average number of nighttime awakenings will be used as a measure of sleep quality.[177] The primary approach for determining daytime, nighttime and 24 hour sleep duration as well as the number of nighttime awakenings will be based on data provided by the manufacturer. Other options for defining daytime sleep and number of nighttime awakenings, such as only considering napping as >30 minute sleep periods that occurred between the hours of 7AM to 7PM[183] and only including nighttime awakenings if they lasted more than 5 minutes,[177] will also be explored. The definition of daytime as 7AM-7PM and day time as 7PM to 7AM at night time was used to coincide with the times listed in sleep questionnaires completed by parents at each time point. Operational definitions of sleep variables can be found in table 6.4.

Table 6.4 Operational definitions of sleep variables

Variable	Source	Operational Definition
24-hour sleep duration	Actigraphy	The number of minutes spent sleeping / 24 hours (7AM-7AM)
Daytime sleep duration	Actigraphy	The number of minutes spent sleeping / day (7AM to 7PM)
Nighttime sleep duration	Actigraphy	The number of minutes spent sleeping / night (7PM-7AM)
Number of nighttime awakenings	Actigraphy	The number of awakenings at night (7PM to 7AM)

Anthropometry. Age- and sex-specific weight-for-length percentiles and z-scores were used to measure weight status and to account for weight gain due to normal growth and development. Trained data collectors measured weight and length/height at each measurement time point. Seca Digital Baby Scales and measuring rods (model 334; Chino, CA) were used to measure length and weight in children who were unable to stand independently at the time of measurement. Seca scales (model 869; Chino, CA) were used to measure weight in children who were able to stand independently at the time of measurement, and height was measured using a Shorr board (Shorr/Weigh and Measure, LLC, Olney, MD). Age- and sex-specific weight-for-length percentiles and z-scores were calculated based on World Health Organization (WHO) growth charts.[162] Infants and toddlers with a weight-for-length >98th percentile were classified as having a high weight-for-length. Operational definitions for anthropometry variables can be found in table 6.5.

Table 6.5 Operational definitions of anthropometry variables

Variable	Operational Definition
Weight	Mass in kg
Length/Height	Length/height of child in cm
Age- and sex-specific weight-for-length percentile and Z-scores	Defined by WHO growth charts[162]; High weight-for-length: $\geq 98^{th}$ percentile

Infant/Child feeding practices. At each time point, mothers completed a modified version of the Infant/Child Feeding Practices Survey developed by the CDC.[188] This questionnaire assessed how frequently children were fed from a list of 18 food items and beverages. Additionally, this questionnaire was used to report whether children were breastfed, the age mothers completely stopped breastfeeding and pumping milk. Practices related to formula feedings were also reported by mothers at each time point. Operational definitions of dietary behavior variables are presented in Table 6.6.

Table 6.6 Operational definitions of dietary behavior variables

Variable	Source	Operational Definition
Frequency children fed different foods/beverages	Child/Infant Feeding Practices	Frequency children were fed 18 food items and beverages measured on 6-point Likert scale: More than once a day; Every day; 5-6 days; 3-4 days; 1-2 days; Not at all
Breastfeeding	Child/Infant Feeding Practices	Whether child was breastfed and age when mothers stopped breastfeeding child and pumping milk.
Baby-led feeding	Child/Infant Feeding Practices	Practices related to formula feedings.

Physical activity. ActiGraph accelerometers (GT3X-BT model, Pensacola, FL) are used to measure objective total physical activity. Children receive accelerometers during each data collection visit with parents at his/her home, childcare center or another predetermined location. Accelerometers are worn for seven days and are attached to elastic belts and worn on the right hip for all age groups, as well as on the right ankle until the child is 18 months old. Trained data collectors provide teachers and mothers instructions on how and when the monitor should be worn. Mothers were instructed to remove the monitor at night and during water-based activities and put the monitor back on shortly after waking in the morning. Accelerometers are initialized prior to data collection and begin collecting data at midnight following accelerometer distribution. Data are collected in raw data mode and later downloaded into 15-second intervals.[184] Total daily physical activity and total daytime physical activity will be calculated for each participant. This method was chosen because intensity cut points have not yet been established for non-ambulatory children. Operational definitions of physical activity variables can be found in table 6.7.

Table 6.7 Operational definitions of physical activity variables

Variable	Source	Operational Definition
Total Daily Physical Activity	Accelerometry	Average counts per minute (24-hour)
Total Daytime Physical Activity	Accelerometry	Average counts per minute (7AM-7PM)

Demographic characteristics. Demographic characteristics were reported by the child's biological mother at baseline. These include sex (male/female), race/ethnicity (Non-Hispanic Black, Non-Hispanic White, Hispanic Black, Hispanic White, Other), and socioeconomic status (highest level of education achieved by mother). Operational definitions of demographic characteristic variables can be found in table 6.8.

Table 6.8 Operational definitions of demographic characteristics

Variable	Operational Definition
Child's race/ethnicity	Non-Hispanic Black, Non-Hispanic White, Hispanic Black, Hispanic White, Other
Child's sex	Male, Female
Mother's socioeconomic status	Highest level of education achieved, WIC status

<u>Study 2 Analyses</u>

Linear mixed model analyses will be used to assess the cross-sectional and longitudinal associations between sleep and weight status. Models will assess the extent to which within-subject variation, or the longitudinal effect of sleep, and between subject variation, or the cross-sectional effect of sleep, explain weight status outcomes and changes in weight status outcomes, respectively. In other words, the longitudinal effect of sleep is the expected within-person difference in weight-for-length z-score for a 1-unit change in an individual's sleep. The cross-sectional effect of sleep is the difference in average weight-for length z-score between individuals based on their average sleep. Testing whether the longitudinal and cross-sectional effects of sleep are equal will determine whether differences in children's average sleep over time have the same association with weight status as changes in a child's sleep duration over time.[185]

Unadjusted and adjusted linear mixed models will be assessed using the PROC MIXED code from SAS version 9.4 (SAS Institute, Inc, Cary, NC). Age- and sex-specific weight-for-length percentiles or Z-scores will be entered as the dependent variable. Separate models will be analyzed with each of the sleep variables treated as the exposure variable. In order to account for the developmental changes in sleep related to age, I will create a sleep duration and quality z-score for each child at each measurement time point using the study population mean and standard deviation. This z-score will have a mean of 0 with a standard deviation of 1. Z-scores will only be created using the study population mean and standard deviation for the sleep independent variables, and not for any other variables or for the dependent variable. It is important to note that the dependent variable in study 2 is weight status, and will be based on the weight for length z-score. This z-score will be based on WHO growth charts, and not created using the study population mean and standard deviation. Parameters for both cross sectional and longitudinal effects of sleep will be included in the model. Covariates included in the model assessing objectives 2a and 2b will include the child's age (in weeks) physical activity, feeding practices, race/ethnicity, socioeconomic status, and sex. A model with baseline random effects will be compared to a model with random effects for both baseline measures and the slope. The best-fitting model will be chosen using the Akaike information criterion (AIC), the -2LL, and the Bayesian Information criterion (BIC). A contrast statement will be used to determine whether the cross-sectional and longitudinal effects of sleep are equal. In order to assess objective 2c, the longitudinal and cross-sectional effects of sleep will be removed and only one sleep parameter will be included in the model. Additionally, sleep by demographic characteristic interactions will be included in the model.

The underlying hypothesis for objective 2a is that there will be a negative association between infants' average sleep duration/sleep quality and their weight status over time. This will be determined using the beta coefficient for the cross-sectional effect of sleep entered in the model. The underlying hypothesis for objective 2b is that there will be a negative association between changes in sleep duration/sleep quality and changes in weight status over time. This will be determined using the beta coefficient for the longitudinal effect of sleep entered in the model. The underlying hypothesis for objective 2c is that the association between sleep and weight status outcomes in children from 6 months old to 24 months old will vary by race/ethnicity, sex and SES. This will be determined using the beta coefficient for the sleep by race/ethnicity, sex and SES interaction terms, respectively. The simple slopes technique will be used to probe significant interaction terms.[189]

STUDY 3

Introduction

Meeting physical activity, sleep and sedentary behavior guidelines is associated with better cardiometabolic health and adiposity outcomes among children and youth.[169] Unfortunately, recent estimates suggest that only 25.4% of adolescents in the US meet sleep guidelines, 26.1% meet physical activity guidelines,[35] and only 5% meet guidelines for sleep, physical activity and sedentary behavior.[174] Although some evidence indicates that there is a positive association between physical activity levels and sleep duration, findings among children and adolescents are not consistent and are limited by a predominantly cross-sectional study design.[48,149,190] Although low income and minority youth are at a higher risk of not meeting both sleep and physical activity recommendations,[44,174] it is unclear whether the sleep and physical activity relationship varies by racial, ethnic or socioeconomic group.[13]

Study 3 Aim. To determine if physical activity and sedentary behavior, measured objectively at 11, 13 and 15 years of age, are associated with subjectively measured weekend and weekday sleep at age 15.

Objective 3a. Determine whether sedentary behavior and moderate-to-vigorous physical activity measured at age 11, 13 and 15 are associated with sleep duration and quality measured at age 15.

Objective 3b. Determine whether changes in sedentary behavior and moderate-to vigorous PA from ages 11, to 15 are associated with sleep duration and quality measured at age 15.

Objective 3c. Determine the extent to which the relationship between sleep and sedentary behavior and moderate to vigorous physical activity vary by race, sex, socioeconomic status, and measures of adiposity.

Methods

Data source. This study will conduct secondary analyses using data from the Avon Longitudinal Study of Parents and Children (ALSPAC). This prospective cohort study assesses the influence of genetics and environmental factors on health outcomes and development, following children from pregnancy into adulthood.[191] The present study will focus on the associations between sleep, physical activity, and sedentary behavior using data collected at clinic visits when children were 11, 13 and 15 years of age. Anthropometric data were collected by trained research staff at the these clinic visits as well, and demographic variables were collected via questionnaire throughout the duration of the study. The ALSPAC team provided data from this study at the request of the researcher.

Participants. Mothers living in Avon County, England were recruited for the ALSPAC study between 1990-1992, and were eligible to be part of the study if their child was born between April 1st, 1991 and December 31st, 1992. Data from mother and child completed questionnaires were collected at 68 time points for 14,009 children between birth and 18 years of age. Clinical assessments were conducted by trained research staff at 9 different time points between ages 7 and 18, and data were collected for 7,153, 6,141, and 5,509 11-, 13-, and 15-year-old children, respectively.[192]

Measures. The primary exposure of interest in Aim 3 are physical activity levels, and sleep at age 15 will be treated as the outcome variable. Demographic and weight status variables will be included in the model as covariates to address Objectives 1 and 2 of the study, and will be treated as moderators in models addressing Objective 3.

Physical activity. Accelerometry was used to objectively measure physical activity and sedentary behavior when participants were 11-, 13-, and 15-years of age. Children wore MTI ActiGraph accelerometers (AM7164 2.2 model, Fort Walton Beach, FL) at age 11 and CSA ActiGraph accelerometers (7164 or 71256 models, Pensacola, FL) at ages 13 and 15. Monitors were initialized to record activity in 60 second epochs, beginning at 5AM the day following the participant's clinic visit. The monitor was worn on the right hip during all waking hours for 7 days, and only removed during water-based activities. Monitors were returned by mail after 7 days, and data were uploaded and analyzed using manufacturer-provided software. Non-wear time was operationalized as any ≥10 minute interval of consecutive zeros. A valid observation required ≥10 hours of wear time per day, ≥3 days per week.[193] Operational definitions of sedentary behavior and physical activity variables are provided in Table 6.9. These variables were derived at 11-, 13-, and 15-years of age, and were calculated for the entire week, for weekdays, and for weekend days. Cut points for sedentary behavior and physical activity thresholds were determined by a calibration study conducted by the ALSPAC team.[194]

Table 6.9 Operational definitions of sedentary behavior and physical activity variables

Variable	Source	Operational Definition
Sedentary behavior (entire week, weekday, weekend day)	Accelerometry	Average minutes/day spent <200 counts/minute
Moderate-to-vigorous physical activity (entire week, weekday, weekend day)	Accelerometry	Average minutes/day spent ≥3600 counts/minute

Sleep. Sleep duration and quality were measured via a questionnaire, which was administered to participants attending clinic visits when they were 15 years old. Sleep duration was measured using a modified version of the School Sleep Habits Survey.[195] Total sleep time was calculated by measuring the time between when children usually fell asleep and the time they usually woke up. Children were asked about the time they usually started trying to go to sleep as well as the time they usually fell asleep to calculate sleep onset latency, which will be used as a measure of sleep quality.[31] Other sleep quality variables included reports of how easily adolescents found waking up on weekends and weekdays, the number of times adolescents woke up at night, and how sleepy they felt during the day, all assessed using a likert scale. Although the psychometric properties of these questions have not been assessed previously, they have been used recently in a study analyzing ALSPAC data.[196] Furthermore, weekend catch-up sleep was calculated as the difference in average sleep duration between weekend nights and weeknights, with higher values indicating a greater sleep need and therefore poorer sleep during the week.[197] Operational definitions of sleep duration and quality variables are provided in Table 6.10. Variables assessing sleep duration, sleep onset latency, and ease of waking up were calculated for the entire week, for weeknights, and for weekend nights. All other variables were reported as weekly averages.

Table 6.10 Operational definitions of sleep variables

Variable	Source	Operational Definition
Sleep duration (weeknight and weekend night)	Sleep Questionnaire	Average length of time (hours and minutes) spent sleeping at night
Sleep onset latency (weeknight and weekend night)	Sleep Questionnaire	Time (minutes) it usually takes to fall asleep at night
Ease of waking up (weekday and weekend day)	Sleep Questionnaire	How easy participant finds it to get up in the morning (Very easy; Easy; Not easy; Hard)
Nighttime awakenings	Sleep Questionnaire	How often participant wakes up at night (Never; Once; 2 or 3; More than 3; Unsure)
Daytime sleepiness	Sleep Questionnaire	How much of a problem participant had with sleepiness during the day (None; Little; More than a little; Big; Very big)
Weekend catch-up sleep	Sleep Questionnaire	Difference in average sleep duration between weekend night and weeknight

Demographic characteristics. Demographic characteristics included the child's age at each of the measurement time points; the child's sex, reported by the mother at baseline; the child's ethnicity, reported by the child via questionnaire at age 11 (What do you consider yourself to be? White; Mixed color; Asian; Black; Other); and the child's socioeconomic status, based on the highest maternal/paternal social class (categorized according to the UK Registrar General's occupational coding (Standard Occupation Classification 1990): I, professional; II, managerial and technical; III, skilled manual or nonmanual; IV, semiskilled manual; V, unskilled; VI, armed forces).[198] Operational definitions of demographic characteristics are provided in Table 6.11.

Table 6.11 Operational definitions of demographic characteristics

Variable	Operational Definition
Child's age	Age (years) during each clinic visit
Child's race/ethnicity	White; Mixed color; Asian; Black; Other
Child's sex	Male; Female
Socioeconomic status	highest maternal/paternal social class (UK Registrar General's Standard Occupation Classification, 1990): I, professional; II, managerial and technical; III, skilled manual or non-manual; IV, semiskilled manual; V, unskilled; VI, armed forces

Anthropometry. All anthropometric variables were measured during clinic visits when the participants were 11-, 13-, and 15-years old. Height (in centimeters) was measured using a Harpenden Stadiometer (Holtain Ltd, Crymych, Pembs, United Kingdom). Weight (in kgs, measured to the nearest 50g) and body fat percentage were measured using a Tanita TBF 305 body-fat analyzer and weighing scales (Tanita UK Ltd, Yewsley, Middlesex, United Kingdom). The machine was set to "Female Standard" for all children at age 11. At ages 13 and 15, the machine was set to either "Male Standard" or "Female Standard" depending on the child's sex. Children undergoing bioelectrical impedance were asked to pass urine before the measurement took place, and undress to their undergarments or lightweight sports clothing. The child was then asked to stand on the machine with both feet parallel to one another, with the heels and toes in contact with their respective electrodes and without bending their knees. The participant's Body Mass Index (BMI) was calculated at each time point using a standard formula (kg/m2). BMI z-scores were calculated using the LMS methods and reference data available from the 1990 British Growth Reference.[199] BMI z-scores below 1.04, corresponding with a BMI percentile below 85%, were classified as normal weight. BMI z-scores between 1.04 – 1.63, corresponding with a BMI percentile between 85% - 95%, were classified as overweight, and BMI z-scores above 1.63, corresponding with a BMI percentile above 95%, were classified as obese.[200] A measuring tape placed between the iliac crests and the lowest ribs was used to measure waist circumference. Operational definitions of anthropometry variables are provided in Table 6.12.

Table 6.12 Operational definitions of anthropometry variables

Variable	Operational Definition
BMI z-score[199]	BMI: Weight(kg)/height(m)^2; Z-score: Calculated using LMS methods and reference data available from the 1990 British Growth Reference
BMI percentile[200]	$<85^{th}$: z-score < 1.04 (Normal weight) $\geq 85^{th}$ - $<95^{th}$: ≥ 1.04 - <1.63 (Overweight) $\geq 95^{th}$: ≥ 1.63 (Obese)
Body fat percentage	Proportion of total mass that constitutes fat mass
Waist circumference (cm)	The minimum circumference of the abdomen between the iliac crests and the lowest ribs

Analysis for Objective 3a. The underlying hypothesis for objective 3a is that higher physical activity levels at each age will be significantly associated with better sleep quality and longer sleep duration at age 15. This hypothesis will be tested using regression analyses, assessed using the PROC REG code from SAS version 9.4 (SAS Institute, Inc, Cary, NC). Physical activity measures at ages 11, 13 and 15 will be entered simultaneously as independent variables, and sleep at age 15 will be entered into the model as the dependent variable. Separate models will be developed treating each of the sleep quality and quantity variables listed in Table 3B as dependent variables (weeknight and weekend night sleep duration, sleep onset latency, and ease of waking up; nighttime awakenings, daytime sleepiness, weekend catch-up sleep). Separate models will also be developed treating each of the physical activity variables listed in Table 3A treated as the independent variable (weekday, weekend day and total week sedentary behavior and moderate-to-vigorous physical activity). Covariates listed in Table 3C (race, SES, sex) will be included in the model as well, along with an anthropometry measure chosen from Table 3D (BMI z-score, percentile, body fat percentage, waist circumference). Furthermore, additional models will include interaction terms for physical activity and race/ethnicity (White vs historically minoritized populations (Mixed color; Asian; Black; Other)), SES (highest maternal/paternal social class (I, professional, II, managerial and technical and VI, armed forces vs. III, skilled manual or non-manual; IV, semiskilled manual; V, unskilled), sex (male vs. female) and weight status (Normal weight vs. overweight/obese). Any significant interaction terms will be followed up by stratified analyses.

Analysis for Objective 3b. The underlying hypothesis of objective 3b is that changes in physical activity levels from ages 11-15 will be significantly associated with sleep quality and sleep duration at age 15. Specifically, adolescents who maintain high levels of physical activity over time and those who exhibit increases in their physical activity levels will have better sleep quality and longer sleep duration at age 15 than adolescents with consistently low physical activity levels or those decreases in their physical activity levels. Participants will first be categorized into groups based on their physical activity trajectories using longitudinal cluster analysis. Trajectory groups will be created for each of the physical activity variables listed in Table 3A (weekday, weekend day and total week sedentary behavior and moderate-to-vigorous physical activity), with time measured using the measurement time point (1-3). Regression analyses using the PROC REG code from SAS version 9.4 (SAS Institute, Inc, Cary, NC) will be used to test the association between these trajectory groups and sleep at age 15. Separate models will be run for each of the physical activity variables, as well as each of the sleep variables listed in Table 3B (weeknight and weekend night sleep duration, sleep onset latency, and ease of waking up; nighttime awakenings, daytime sleepiness, weekend catch-up sleep). Race, SES, sex, age at baseline, and anthropometric variables will be included in final, adjusted model as covariates.

Analysis for Objective 3c. The underlying hypothesis for objective 3c is that the associations between physical activity trajectory and sleep at age 15 will vary by demographic and anthropometric characteristics. This will be assessed by creating physical activity trajectory groups stratified by race (White vs. non-White), SES (high vs low), sex (male vs. female), and weight status (Normal/underweight vs. overweight/obese at age 15), using the PROC REG code from SAS version 9.4 (SAS Institute, Inc, Cary, NC) to test the association between these trajectory groups and sleep at age 15 via linear regression analyses. Separate models will be run for the sleep quality and quantity variables listed in Table 3B (weeknight and weekend night sleep duration, sleep onset latency, and ease of waking up; nighttime awakenings, daytime sleepiness, weekend catch-up sleep), which will be treated as the dependent variable in each model. Separate models will be run for the physical activity variables listed in Table 3A (weekday, weekend day and total week sedentary behavior and moderate-to-vigorous physical activity), which will be treated as the independent variables.

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