The Relationship Between Sleep and Physical Activity in Children

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Statement of Sources

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No parts of this thesis have been submitted towards the award of any other degree or diploma in any other tertiary institution. No other person's work has been used without due acknowledgment in the main text of the thesis. All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required).

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Abstract

The aim of this thesis was to investigate the relationship between physical activity and sleep in children. The thesis has contributed to the empirical body of evidence with three studies. Study 1 (Chapter 2) was a systematic review and meta-analysis of the literature investigating the relationship between physical activity and sleep in children. Overall, the meta-analysis found little association between physical activity and sleep (r = .02, 95% confidence interval = -.03 to .07) and no examined variables significantly moderated the overall effect. Exploratory analyses showed only two significant but weak associations for vigorous physical activity with sleep (r = .09, 95% CI = .01 to .17, I2 = 66.3%), specifically sleep duration (r = .07, 95% CI = .00 to .14, I2 = 41.1%). Study 2 (Chapter 3) investigated both longer-term (i.e., habitual) and day-to-day associations among a large sample of Australian children. Longer-term, the trajectories of change in physical activity over time showed little association with the trajectory of change in sleep. The day-to-day analysis showed that increased physical activity improves sleep the following night and that better sleep predicts an increase in physical activity the following day. Study 3 (Chapter 4) investigated accelerometer wear-time criteria for how valid a night should be and the total number of valid nights that are needed to get reliable estimates of habitual sleep duration, sleep efficiency, time in bed, and sleep timing. The study found that, generally, 5 nights of valid data is enough to get acceptable estimates of habitual sleep behaviour. Implications, strengths, and limitations of the thesis are discussed in Chapter 5.

Chapter 1 | The Relationship Between Sleep and Physical Activity in Children

Introduction

How children spend their time in their daily lives can have lasting and important implications for their long-term health. Health, as defined by the World Health Organization (1), is "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." While pharmaceutical drugs, vaccinations, and other societal interventions have increased the lifespan of humans and reduced child mortality rates by reducing the toll of communicable diseases, the influence of non-communicable diseases still burdens society and is the leading cause of death worldwide (2-4). However, many negative health outcomes associated with non-communicable diseases (e.g., cardiovascular disease) can be prevented and treated by everyday behaviours across the lifespan including physical activity and sleep (5-7). Indeed, physical activity and sleep are important determinants of the overall health and well-being of children (8, 9) and reports of children not adhering to guidelines for physical activity and sleep are concerning (10-12). Adherence to proper guidelines regarding duration of daily physical activity and daily sleep behaviour is one of the most readily available, cost-effective interventions to widely benefit overall public health.

The general guidelines for these behaviours have changed over time and they are likely to continue to evolve (13). For example, the National Sleep Foundation’s (14) most recent recommendations state that 6-13-year-old children should sleep between 9 and 11 hours each night; however, they also now include a provision that between 7 to 8 and 12 hours of sleep at night may be appropriate for some people in this age group. In regard to physical activity, the World Health Organization (15) currently recommends that children of all ages engage in 60 minutes of moderate-to-vigorous physical activity per day. Even more recently, Canada and Australia have incorporated several recommendations into 24-hour movement guidelines for children (16-18). These guidelines, in addition to the above recommendations for sleep and physical activity, also account for sedentary behaviour (e.g. no more than 2 hours of recreational screen time per day) and light physical activity (e.g. several hours of structured and unstructured activities).

These recommendations are in place to ensure the best health and well-being outcomes for children in a critical time of their development. While it is important to look at these behaviours collectively, due to the constrained nature of the 24-hour day it is important for us to understand how these behaviours interact and influence each other as well. That is, does spending more time being physically active help children sleep better or vice versa? To answer this question, I designed three studies to investigate the relationship between physical activity and sleep in children. The first study was a meta-analysis of the current evidence investigating the associations between physical activity and sleep in children. The second study was a longitudinal study investigating day-to-day and longer-term associations between these behaviours. The final study was a reliability study of an objective measure used for movement behaviour in children to determine the number of days needed to obtain reliable estimates of habitual physical activity and sleep.

Sleep

Sleep Definition

Sleep is a reversible, behavioural state of perceptual disengagement from the environment and is typically accompanied by closed eyes, a lying down posture and lack of bodily movement (19). Sleep is a universal and frequent behaviour. Indeed, every human being will spend roughly a third of their lives sleeping. However, much about sleep is still being discovered. In the last 50 years, sleep research, and our understanding of sleep, has grown considerably. Nowadays, the importance of sleep is well recognised and extensively studied among academics and clinicians, alike. Technological advancements and refinements have made it possible to study the underlying behaviour of sleep and specifically, the physiological mechanisms that initiate and maintain sleep, by measuring brain wave activity and other cellular level changes that occur in the body before, during, and after the sleep period. Still, many fundamental aspects about the nature and function of sleep are still unknown (20). We do not fully know why we need to sleep, what happens during sleep, or how sleep occurs (21, 22).

Several theories have been proposed, suggesting that sleep is a time for physical and mental restoration, for the development of the brain, or that sleep serves a preservation type role (23). The restorative theory of sleep states sleep plays a vital role in recovery, muscle growth, and tissue repair. During sleep, various neurotransmitters decrease their activity and growth hormones are released in the body (24). The restorative theory argues that the changes in neurotransmitter and hormone levels indicate that the brain and body are resting and repairing. The developmental or brain plasticity theory of sleep states that sleep is especially important for the development of the brain and memory retention (25). This theory argues that because the sleep need of newborn infants is nearly twice as long as the sleep need of an adult and because infancy is characterised by rapid nervous system development, that sleep serves as an important time for brain and nervous system growth. The theory also suggests that during sleep, information processed that day is consolidated, reorganised, and stored. A third theory is the preservation or inactivity theory. This theory proposes that sleep is an evolutionary process which kept humans from danger. That is, during the night, when humans were at a disadvantage to predators, the need to sleep developed as a safeguard from trouble (21). These theories highlight some of the proposed benefits of sleep; however, none of them completely explain how sleep functions or the complex neural processes involved in the initiation and maintenance of sleep. Regardless of the determinants of sleep, we know that sleep has important implications for health.

Adequate sleep is important for the growth, maturation, and development of children (26). Insufficient sleep is associated with several physical, cognitive, and psychological heath deficits. Shortened sleep duration, poor sleep quality and erratic sleep timing have been associated with an impaired ability to concentrate, poorer academic performance, poorer information retention, and decreased working memory (25, 27, 28). Short sleep duration and poor sleep quality are also linked with mood disorders including depression, anxiety, and attention deficit disorder (29, 30). Additionally, short sleep duration and poor sleep quality are associated with an increased risk of injuries and accidents (31), alcohol and drug use (32), suicide (33), and obesity (34, 35).

Paediatric sleep problems are prevalent. Approximately 20-30% of children experience significant sleep problems, and about 35% of adolescents experience insomnia (i.e., difficulties with sleep onset and sleep maintenance) several times a month (36). These sleep problems are typically experienced as difficulty initiating sleep, difficulty staying asleep, or waking too early. Children may also be sleeping less than in the past (11), due to factors such as media use, early school start times, and caffeine consumption (37). Matricciani et al. (38) conducted a large-scale systematic review of trends in sleep in children over the past century. They reported that global trends in sleep have declined at a median rate of .75 min/year, which indicates about a 75-minute decrease in sleep. One study among 11-17 year old adolescents (10), found that 83% of youths reported sleeping less than the recommended nine hours per night, and over 43% slept less than seven hours on weeknights. A more recent study among 6,128 9-11-year-olds from 12 countries reported that on average 41.9% of children adhered to the sleep duration recommendation (39). Given this trend of inadequate sleep in children, more research into methods of improving sleep in children are warranted to help them experience the health benefits of good sleep and increase their physical and mental well-being.

Sleep Stages

While sleep is a state of unconsciousness, it is also an active and complex state. Measurement of brain activity, eye movements, and other physiological indicators such as muscle tension, heart rate, and respiration during sleep reveals distinct stages of activity, which are unique from each other and from wakefulness. Based on physiological parameters, sleep has been divided into two separate states: rapid eye movement (REM) sleep and non-REM sleep. Non-REM sleep is further divided into three stages simply referred to as Stages 1, 2, and 3. Historically, there was a Stage 4; however, the most recent sleep scoring guidelines have omitted Stage 4 and combined it with Stage 3 (40). These states and stages are identified using electroencephalography (EEG). That is, using electrodes attached in various places around the head, we can measure brain waves which vary in height (amplitude) and speed (frequency). Early stages of sleep are characterised by brain wave recordings called sleep spindles and k-complexes. Later stages (i.e., Stage 3 and formerly Stage 4) are characterised by large amplitude and slow frequency brain waves and are often referred to as slow wave sleep. REM sleep is characterised by high frequency EEG activation and bursts of rapid eye movements. It is the REM state of sleep that is most associated with dreaming. Altogether, sleep begins in non-REM Stage 1 and progresses through to the REM state before starting again at Stage 1; this is known as the REM cycle. REM cycles last around 90 minutes, and normal sleepers should go through 4-5 cycles per night (19). This pattern, structure and organisation of sleep depth and sleep cycles, including REM sleep and non-REM sleep, is called sleep architecture. Sleep architecture changes over time. Whereas an adult REM cycle lasts 90 minutes (19), a child’s REM cycle is completed every 60 minutes (41). Compared with adults, children and infants also spend a larger proportion of the night in REM sleep as opposed to non-REM sleep. Daily sleep duration is also different.

Adults are recommended 7-8 hours of sleep, but children need 9-11 hours of sleep and infants as much as 15 hours or more (14).

Sleep Health

The use of EEG in sleep research has provided insight into the active and complex states of sleep architecture. However, obtaining this depth of information during sleep is difficult and cannot be accomplished without specialised equipment and training. From a population health perspective, it is not feasible to collect data from large groups using this method. With that in mind, it may be more useful to examine sleep in terms of sleep health, as defined by Buysse (42). Buysse defined sleep health with population health in mind and it is comprised of the key concepts of sleep that can be more easily assessed. For many years, good sleep was not specifically defined, but was considered the absence of sleep problems, deficiencies, or disorders. However, as the World Health Organization (1) defines health as “not merely the absence of disease or infirmity,” Buysse also argues that sleep health should be defined by the qualities of sleep that promote physical, mental, and social well-being.

Sleep health, therefore, is a multidimensional construct which promotes physical and mental health and well-being. The dimensions of sleep health include: sleep duration (i.e., the total time spent asleep per 24-hour period), sleep efficiency (i.e., the ease of falling asleep quickly, staying asleep and returning to sleep after waking), sleep timing (i.e., the placement of sleep in the day), sleep quality/satisfaction (i.e., the subjective assessment of poor or good sleep), as well as daytime wakefulness (i.e., sustained alertness during waking hours). Taken as a whole, good sleep health is characterised as being highly efficient, highly satisfying, of adequate duration, appropriately timed, and results in alertness throughout the following day. An additional dimension, not included in the definition of sleep health, is sleep architecture. Sleep architecture may be an important dimension of sleep; however, Buysse (42) did not include it in his definition of sleep health, as it lacks a self-report equivalent and some aspects of sleep architecture correlate with sleep quality (e.g., subjective ratings of sleep quality and time spent in Stage 3 or deep sleep). This definition of sleep health provides a framework for future research on sleep and highlights which dimensions of sleep may be the most significant for well-being. Moreover, these five dimensions of sleep health are more easily assessed, especially in large scale studies, than sleep architecture. More research is needed to develop this definition of sleep health and both subjective and objective methods could be needed.

Sleep Measurement

Different types of sleep measurement, such as subjective or objective, may identify different aspects of sleep, and both may be important to understand the whole picture. Objective measures may be preferred for assessing sleep duration, sleep efficiency, and sleep timing and they are required for measuring sleep architecture. Meanwhile, subjective measures may be more suitable for the assessment of sleep quality or satisfaction and daytime wakefulness.

Subjective Measures. Subjective measures of sleep include self-report questionnaires and daily sleep logs (43). The advantages of subjective measures are the cost-effectiveness, easy dissemination, and their ability to capture the subjective sleep experience. However, there are a wide variety of measures used, making comparisons between self-report instruments difficult. Additionally, researchers are unsure if the data retrieved from self-reports accurately reflect respondents' bedtimes and sleep quality. This concern over inaccurate responses can be especially true for adolescents who may report only the most recent, salient or socially desirable sleep patterns (44). Still, well-validated instruments are available, such as the Pittsburgh Sleep Quality Index (Cronbach's alpha ranged from 0.70 to 0.83; 45), the Insomnia Severity Index (Cronbach's alpha = 0.92; 46), the Epworth Sleepiness Scale (Cronbach's alpha = 0.84; 47), and the Paediatric Sleep Survey Instrument (Cronbach's alpha = 0.63-0.80; 48). Alternatively, daily sleep logs kept over a 1-2 week period can provide a wealth of information about sleep times, feelings of being restored and daytime sleepiness (49). Sleep logs are generally viewed as more accurate than questionnaires and have been positively correlated with objective measures of sleep (44, 50).

Polysomnography. The accepted gold-standard in objective sleep assessment is polysomnography (41, 51, 52). Polysomnography is a continuous recording of physiological indicators, such as brain activity, muscle tension, and eye movements during sleep. It usually requires participants to be monitored in a sleep laboratory for one to two nights; however, at-home devices have been developed that decrease some of the participant burden. Typically, polysomnography involves the use of 16 different channels to record a range of physiological activity during sleep including: brain activation (EEG), eye movements (electrooculography), skeletal muscle activation (electromyography), heart rhythm (electrocardiography) and other body functions, such as temperature regulation and oximetry (43). Results from a polysomnography assessment provide the most comprehensive and valid evaluation of sleep including brain activity, sleep stages, number of night awakenings, breathing patterns, oxygen saturation, eye movements, and many others (53). This wealth of information allows sleep experts to identify and diagnose a variety of sleep disorders, which is the primary purpose of polysomnography. Scoring method guidelines have been developed for all age groups to standardise the use of polysomnography (40). However, polysomnography is costly, time-consuming, and still requires an expert to set-up and interpret the recordings and is, therefore, not optimal for all studies. Furthermore, polysomnography with children can be especially challenging as they may have a limited capacity to cooperate with the set-up, which may take about an hour to complete, and to cope with the discomfort of the device during sleep (54). In paediatric populations, other objective measures, such as accelerometry which can estimate sleep duration and sleep efficiency, may be desirable alternatives for sleep research.

Accelerometry. Accelerometry is emerging more frequently in sleep research (55). An accelerometer is an instrument for measuring acceleration of a moving body. Accelerometry provides less detailed information about sleep compared to polysomnography; however, it has many advantages, including being more cost-effective, less-intrusive, and being able to record continuously 24-hours a day for multiple days or weeks (56). Meltzer et al. (57) also argue that accelerometry can be particularly valuable with the paediatric population, where research has previously been reliant on parent-report measures alone which may limit the accuracy of information about children's sleep behaviour. Accelerometers can be worn on many locations on the body, though wrist-worn devices may provide greater wear time compliance compared to other devices (58, 59). Several accelerometers have been developed for research purposes. These devices, however, are each unique in physical characteristics and scoring algorithms. As a result, assumptions regarding validity and reliability are difficult to make from one device and scoring algorithm to another or from one population to another. This means that information regarding validity and reliability should be matched to each individual device, scoring algorithm and population under study (55). For example, the GENEActiv accelerometer (Activinsights, Cambridge, United Kingdom) has been validated for sleep detection using a heuristic algorithm HDCZA (i.e., Heuristic algorithm looking at Distribution of Change in Z-Angle) within an R package known as GGIR (https://cran.r-project.org/web/packages/GGIR/). This study was conducted among adults and found good agreement between accelerometry and polysomnography (60, 61). However, how well the GENEActiv coupled with GGIR estimates sleep in children is still unknown.

Regarding validity, it is common to compare accelerometry-derived sleep data to polysomnography and report the sensitivity (i.e., the proportion of time identified as sleep by polysomnography and correctly scored as sleep by accelerometry), specificity (i.e., the proportion of time identified by polysomnography as awake and correctly scored as awake by accelerometry), and overall agreement (i.e., the total proportion overall correctly scored between polysomnography and accelerometry). While accelerometers and sleep-detection algorithms have their unique validity scores, in a review of accelerometer use in the paediatric population, Meltzer et al. (57) reported that accelerometers tend to be consistently accurate at correctly scoring sleep periods (i.e., sensitivity), but less accurate at identifying wake after sleep onset (i.e., specificity). For example, an adolescent study reported a 95% sensitivity and a 74.5% specificity (62), and a study among pre-schoolers reported a 97% sensitivity but only a 24% specificity (63). Meltzer et al. (57) also reported that nearly half of the specificity scores found in the review were less than 60%. The inability of accelerometers to detect wakefulness after sleep onset is one of their more important limitations. And, despite being significantly cheaper than polysomnography, accelerometers are significantly more expensive and difficult to administer than self-report measures.

Reliability is another issue related to accelerometer use. For example, to obtain estimates of habitual weekly sleep behaviour, researchers need to know how many nights of measurement are required. Few studies have reported the number of nights needed for reliable estimates of sleep in children and those that have, report inconsistent requirements (64-66). Sleep duration has shown that 3 nights may be appropriate in a sample of 5-year-old children (64), while another study reported that 5 nights were needed from a sample of 7-year-old children (66). Yet, another study reported that 6 nights were needed in their sample of 8-11-year-olds (65). Sleep onset was assessed in two studies and showed a difference of either 4 or 7 nights were needed. In contrast, both these studies also reported that 4 nights were sufficient for sleep efficiency. Additional research is needed to support these findings and to reach a general consensus about the number of nights needed for reliable estimates of sleep behaviours.

In summary, sleep is an active state which, despite an abundance of research, remains a relatively mysterious behaviour in terms of function and purpose. However, we know that sleep has important implications for health and well-being. Due to the multidimensional nature of sleep, different types of measurement may be needed to fully understand the impact of sleep on health outcomes. That is, subjective measures may be useful for assessing sleep quality and daytime tiredness, while objective measures are more useful for assessing sleep duration, efficiency, and timing.

Physical Activity

Physical Activity Definition and Benefits

Physical activity is defined as any bodily movement produced by skeletal muscles that results in energy expenditure (67). Physical activity is widely promoted for its many health benefits for people of all ages and is a major public health concern. Research has repeatedly demonstrated that engaging in daily physical activity can help prevent several chronic conditions and diseases. For example, focusing on young people, a systematic review by Janssen and Leblanc (68) reported that physical activity in children and adolescents 5-17-years-old positively influences bone health, cholesterol, blood pressure, weight management, obesity and metabolic syndrome in youth. Furthermore, physical activity also benefits the mental health of children, showing positive effects on depression and anxiety (69, 70). Although there is consensus among researchers of the benefits of physical activity, and hazards of inactivity, recommendations for how much physical activity and what kind of physical activity is needed have changed over time (13).

Today, it is widely accepted that moderate-to-vigorous intensity physical activity is needed each day in differing amounts depending on age. For children, international guidelines recommend that children engage in at least 60-minutes of moderate-to-vigorous physical activity in order to receive the benefits of physical activity (15). Examples of moderate-to-vigorous intensity activities include running, bicycling, aerobic dancing, playing sport, and other similar activities. The recommendations also state that activity levels higher than 60-minutes per day provides additional health benefits. In addition, while moderate intensity physical activity is considered the minimum intensity required for most health benefits of physical activity to manifest, some health benefits may only arise from higher intensities (71, 72). Much of the 60-minute daily activity should be aerobic in nature; however, it is also recommended that activities which build the strength of muscles and bones should be incorporated three times per week.

Most research in children examines whether children are meeting the guidelines to be active at least 60-minutes per day and the findings are concerning. Many children fall short of the recommended amount of moderate-to-vigorous intensity physical activity. For example, a study in Australia reported that only 63% and 51% of Year 6, 8, and 10 students met the guidelines for physical activity during summer terms and winter terms, respectively (73). This study shows that a substantial proportion of students are less active than recommended. A recent statement produced by the Australian government reported on data available from the Australian Bureau of Statistics 2011–12 National Nutrition and Physical Activity Survey which indicates that 1 in 4 (26%) children 5-12-years-old and 1 in 10 (8%) adolescents 13-17-years-old met the recommendation for physical activity (12). Similar findings have been reported worldwide. A recent study used a grading system to report on the physical activity of children from 49 countries (74). They gave grades from A+ to F based on a variety of different benchmark indicators, including: overall physical activity (i.e., the percentage meeting the recommendation for physical activity), organised sport and physical activity (i.e., the percentage of children participating in organised sport), active transport (the percentage of children who use active transportation), school (i.e., the percentage of schools with active school policies, the percentage of school where the majority of students are taught by a physical education specialist, the percentage of schools where children have access to sport equipment), and many other indicators. The average score for overall physical activity was a "D", indicating that countries were unsuccessful at meeting guidelines with roughly 67-73% of children and youth. Although we know the importance of physical activity, effective methods to increase the physical activity of children are still needed.

As mentioned previously, physical activity is any bodily movement that expends some energy; however, in terms of health benefits, not all bodily movement is equal. For physical activity to be most beneficial, it needs to be regular (e.g., daily), intense, and engaged in for a sufficient amount of time. Researchers often discuss physical activity in terms of volume. A good example is the daily recommendation to be physically active for 60 minutes at a moderate-to-vigorous level. Volume consists of three dimensions of physical activity. The three dimensions are frequency (i.e., the number of episodes in a certain amount of time), duration (i.e., total time spent in the activity), and intensity (i.e., the amount of effort required, usually discussed as light, moderate, or vigorous). Another dimension to consider is the type of physical activity (e.g. walking, strength training, sports, aerobic or anaerobic etc.). When assessing physical activity, each of these dimensions of physical activity should be considered.

Physical Activity Measurement

Physical activity can be assessed by a wide variety of subjective and objective techniques. Subjective measures include: self-report questionnaires, interviews and activity logs or time-use-diaries (75). The advantages of questionnaires, such as the Physical Activity

Questionnaire for Older Children (PAQ-C) or Adolescents (PAQ-A), is that they are easy to administer, cost-effective and low burden on the participant (76). However, the validity of these questionnaires may still be an issue. For example, Janz et al. (77) assessed the psychometric properties of the PAQ-C and PAQ-A by comparing the questionnaire to an Actigraph activity monitor (model 7164, Fort Walton Beach, FL) and found good internal consistency (Cronbach's alpha = 0.72 and 0.88, respectively) but moderately high concurrent validity for the PAQ-A only (rho = .063 and 0.56 for moderate-to-vigorous physical activity and total physical activity, respectively). Time-use-diaries offer similar advantages to questionnaires, while also being able to collect detailed data over an extended amount of time; however, validity remains as a major disadvantage. Rush et al. (78), for example, report that a 7-day physical activity diary showed limited accuracy compared to doubly labelled water and that the diary may be most useful in describing the pattern and routine of individual's activity. While the validity of these subjective instruments may be limited, the information about duration, type, intensity, and frequency of physical activity can be useful. Objective measures, though, may be preferred for accurate measurement of physical activity.

Objective measures of physical activity can be grouped into four broad categories: physiological (e.g. heart rate), calorimetry (i.e., heat transfer during activity or doubly labelled water), motion sensors (e.g. accelerometers), and direct observation (79). Objective measures can provide more accurate results but are often more difficult to administer than self-report questionnaires. The gold-standard, and criterion measure, in estimating physical activity is doubly labelled water (43, 80). Doubly labelled water is an indirect form of calorimetry which estimates physical activity level based on total energy expenditure and an individual's basal metabolic rate. This method works by replacing some of the oxygen and hydrogen molecules of water with stable isotopes (i.e., oxygen-18 and deuterium, respectively). These isotopes of water are processed by the body differently which allows researchers to track the change in isotope levels. That is, oxygen-18 is lost in water and carbon dioxide (CO2), whereas deuterium is only lost as water. Therefore, the difference between oxygen-18 and deuterium level after physical activity reflects CO2 production over a specific period of time. CO2 production can then be translated to estimate energy expenditure. However, this method is costly and limited to small samples, so it is infrequently used. Accelerometry on the other hand, is relatively cost effective and can be used for larger studies. As a result, accelerometers are currently the most frequently used instrument to objectively assess physical activity (79).

Accelerometry is an attractive instrument for assessing movement behaviour in children (81, 82), given that it can (a) measure 24-hours a day for multiple consecutive days, (b) provide reasonable estimates of both sleep and physical activity, and (c) is relatively low cost and more easily distributed to larger samples, compared to doubly labelled water. Furthermore, a recent validation study found that wrist and thigh worn accelerometers estimate active energy expenditure and total energy expenditure with high precision compared to doubly labelled water (83). While using accelerometers in physical activity research is increasing popular, they come with their own set of challenges and limitations. Some limitations are that accelerometers cannot determine type of physical activity and often need to be removed during contact sports for safety reasons.

One main challenge with accelerometers is ensuring that they are worn for enough time both within one day (e.g., >10 hours) and over the course of an extended research protocol, such as one week or longer. Studies of physical activity have reported different criteria are needed for reliable estimates from as few as two days to as many as seven days (84-86). This variation may be explained by differences in activity intensity, type of accelerometer, or accelerometer wear position (i.e., hip vs. wrist). However, a review of accelerometer use in youth studies reports that, in general, a minimum of four days of monitoring are needed with at least one weekend day included (87).

Innovation with accelerometers, such as waterproofing, ensures that children are required to remove the devices less often; however, wear time adherence remains an issue. Comparing two large scale studies investigating children's movement behaviour with hip worn accelerometers, the International Study of Childhood Obesity, Lifestyle and the Environment and the 2003–2006 National Health and Nutrition Examination Survey, Tudor-Locke et al. (88) reported that 76.7% and 62.6% of participants wearing accelerometers returned valid data (i.e., ≥10 hours/day and ≥4 days), respectively. However, research indicates that wrist worn devices may benefit from better wear time compliance than hip-worn devices (59, 89), possibly due to feeling more comfortable and less embarrassing to wear than hip-worn devices (90). Despite this limitation, accelerometers remain an important tool for capturing daily physical activity and are an ideal measure for 24-hour movement behaviour research. Specifically, accelerometers allow for the objective assessment of both physical activity and sleep using a single device.

Sleep and Physical Activity

Associations between Sleep and Physical Activity

Sleep and physical activity are both individually vital to health; however, a combined focus on sleep and physical activity together may be useful. As guidelines have developed to adopt a 24-hour movement behaviour approach to encourage health and well-being, it is also important to understand how these individual behaviours interact (16-18, 91). Research has indicated that they may be associated in a variety of ways. Both behaviours, for example, seem to influence several common and important health outcomes, and they may have a reciprocal relationship. Short sleep duration and inadequate physical activity have both been linked with similar negative outcomes, including: poorer academic performance; poorer cognitive ability; and an increased risk of obesity, diabetes, cardiovascular disease and depression when compared to sufficient sleep and adequate physical activity (42, 92-96).

Regular physical activity has been recommended as an effective treatment and prevention of sleep disorders, such as insomnia (97), and is considered a non-pharmacological intervention to improve sleep (98). In a randomised controlled trial of adults with at least moderate-severity obstructive sleep apnoea, and who were also overweight, Kline et al. (99) found that those assigned to a 12-week exercise intervention had a greater reduction in symptoms and a greater improvement in sleep quality than those in a stretching control group.

Mechanisms. Many mechanisms have been proposed to explain how physical activity impacts sleep including changes to circadian rhythm, body temperature, heart rate, central nervous system, growth hormone secretion, metabolism, immune system, mood, fitness level, and body composition (97). More research is needed to explore these mechanisms more fully and to understand how they can explain the association between physical activity and sleep; however, a brief description of the mechanisms is provided below.

The circadian rhythm acts like an internal clock that cycles your body through sleep and wakefulness at regular intervals. It is partly influenced by external factors, such as light exposure, but also by exercise (100). Altered circadian rhythms are associated with disrupted sleep/wake cycles. Exercise may help entrain, or align, the circadian rhythm which in turn helps initiate sleep.

Physical activity may also improve sleep by aiding in body temperature regulation (101). Decreasing body temperature is associated with sleep onset and deep sleep. Physical activity during the day increases body temperature and as the body returns to its normal state this can trigger drowsiness (102). This association has led some to suggest that evening exercise may inhibit sleepiness and should be avoided within three hours of bedtime (103).

However, a recent systematic review suggests that evening exercise improves sleep with negative associations resulting only from vigorous physical activity ending one hour before bed (104).

Another mechanism connecting physical activity and sleep could be the immune system. Specifically, certain concentrations of cytokines in the body have shown improvements in deep sleep in animals (105). Physical activity may affect sleep by altering the concentration of these immune system factors (106); however, high concentrations may cause night-time wakefulness (107).

Another potential mechanism is related to mood. Certain moods, such as depression and anxiety, can have negative implications for sleep including an increased risk of insomnia (108, 109). However, physical activity has shown that it can have antidepressant effects and reduce both state and trait anxiety (70). Therefore, physical activity may facilitate good sleep by reducing these sleep impairing moods.

Furthermore, regular physical activity has shown to improve body composition and reduce obesity (110). Insufficient sleep duration is associated with an increased risk of obesity (34) and obesity is associated with sleep disorders such as obstructive sleep apnoea. Therefore, physical activity, through improvements to body composition and respiratory fitness, may help facilitate good sleep and prevent onset of sleep impairing breathing disorders. Similarly, improvements in fitness level are associated with improvements in sleep quality (111) and exercise helps maintain and improve overall fitness level (67). Therefore, physical activity may help regulate sleep quality though improvements in overall physical fitness.

A more in-depth discussion of these mechanisms is reported in two recent reviews (112, 113). Much about these mechanisms is still unclear and further research is needed to explore the physiological associations between physical activity and sleep.

Bidirectional Relationship

Recent research has examined the extent to which sleep and physical activity are bidirectionally related (e.g., that more physical activity promotes better sleep or poor sleep hinders being more physically active; 97, 114). However, few studies have been conducted and have reported mixed results. Dzierzewski et al. (115), for example, investigated self-reported physical activity and self-reported sleep in older adults (mean age = 63.6 years) using daily questionnaires over an 18-week period. They found that general sleep quality and self-reported physical activity had a small but positive reciprocal relationship (i.e., an above average physical activity day predicted an above average sleep quality and sleep quality predicted subsequent physical activity) but found no associations for sleep onset latency or time awake after sleep onset. Another longitudinal study covering 3-11 years of follow-up among older adults (mean age = 60.1 years) used polysomnography and self-reported physical activity to examine bidirectional relationships between sleep and physical activity (116). They reported that moderate physical activity at baseline predicted a lower risk of short sleep duration, higher wake after sleep onset, and lower sleep efficiency at follow-up; however, no bidirectional associations were found.

Mitchell et al. (117) conducted a study among adult women (mean age = 55.5 years) and used objective measures for both sleep and physical activity (i.e., wrist and hip-worn accelerometers). They found no associations at all in either direction between total sleep time or sleep efficiency and moderate-to-vigorous physical activity. However, a similar but much larger study among 10,086 adult women (mean age = 71.6 years), which used a time-use-diary to measure sleep and accelerometry to measure physical activity, found that short and long time in bed was associated with lower physical activity than those who reported optimal time in bed and those with higher physical activity were more likely to report optimal time in bed (118).

Some studies have also investigated bidirectional relationships in adolescents and children. Raudsepp (119) conducted a one-year longitudinal study with 13-year-old adolescent girls. At four time periods, sleep and physical activity were assessed using the Insomnia Severity Index and 3-Day Physical Activity Recall self-reported measures. Higher baseline sleep disturbance was associated with less physical activity over the year and higher reported baseline physical activity was associated with less sleep disturbance indicating a positive bidirectional relationship between increased physical activity and improved sleep quality. Master et al. (120) investigated day-to-day variations in accelerometer-derived physical activity and sleep among 15-year-old adolescents. They reported that days with higher than average physical activity were associated with earlier sleep onset, longer sleep duration, and increased sleep efficiency. Conversely, later wake time and longer sleep duration were associated with less moderate-to-vigorous physical activity. These findings do not support a bidirectional relationship and highlight a limitation with many sleep duration studies, that is sleep duration is often operationalised as longer sleep duration leads to greater benefits; however, sleeping too long can also have negative outcomes (121).

Another study among children ages 8-11-years-old found no significant associations between time in bed, sleep duration, and sleep efficiency and light physical activity or moderate-to-vigorous physical activity using accelerometry during an eight-day period (122). Evidence from another accelerometer-based study even suggests that the bidirectional relationship is negative in children. Pesonen et al. (123) reported increased levels of physical activity during the day were associated with decreased sleep time and reduced efficiency the following night. Furthermore, that an increase in sleep duration and sleep efficiency during the night were associated with decreases in physical activity the following day. As a whole, the existing literature offers mixed results about the bidirectionality of sleep and physical activity. However, longitudinal studies were more likely to report significant bidirectional associations compared to shorter-term day-to-day or cross-sectional designs. Nevertheless, none of the longitudinal studies used accelerometry but primarily relied on self-report measures. Further research in this area should use longitudinal designs and objective measures for both sleep and physical activity to examine this potentially bidirectional relationship.

Reviews of Sleep and Physical Activity

Recent reviews have examined the associations between sleep and physical activity. In a meta-analysis among adults, Kredlow et al. (124) focused on experimental studies to test the efficacy of acute (i.e., less than one week) and regular (i.e., greater than one week) exercise as interventions to improve sleep. Their findings supported both acute and regular exercise as an intervention for improving sleep. Acute exercise was found to have a small but beneficial effect on total sleep time, slow wave sleep, sleep onset latency, sleep efficiency, wake time after sleep onset and Stage 1 sleep. Furthermore, regular exercise was found to have a moderate and robust positive effect on sleep quality, and a small but positive effect on total sleep time, sleep efficiency and sleep onset latency.

Additionally, this meta-analysis found significant moderator variables including: sex, age, baseline physical activity level, type of exercise, exercise time of day, duration and adherence (124). Acute exercise was more beneficial for men than women in reducing the proportion of the night spent in Stage 1 sleep and wake after sleep onset. Regular exercise was found to be more beneficial for younger adults to reduce sleep onset latency than older people. A higher baseline activity level was associated with greater benefit on slow wave sleep from acute exercise than those with a lower baseline activity level. Regarding type of exercise as a moderator, acute cycling improved slow wave sleep more than acute bouts of running. Concerning time of day, acute exercise less than 3 hours and more than 8 hours before bedtime showed greater reductions in wake time after sleep onset and Stage 1 sleep than exercising 3-8 hours before bedtime. Another moderator was exercise duration. Increased duration (minutes) of acute exercise bouts was associated with more beneficial effects on total sleep time, slow wave sleep, sleep onset latency and stage 4 sleep. Longer regular exercise duration of individual bouts (minutes) was also shown to be more beneficial for sleep onset latency than shorter bouts. Finally, greater adherence rates to regular exercise programs were associated with greater sleep quality (124). Importantly, this meta-analysis suggests that improvements in sleep can be made by increasing physical activity behaviour in adults. These findings coincide with earlier reviews that also examined the relationship between physical activity and sleep (125, 126).

Another meta-analysis by Lang et al. (43) investigated evidence for the relationship between physical activity and sleep from a younger age group of 14-24-year-old adolescents and young adults. An important contribution of this review was the examination of different methods for assessing sleep and physical activity and the extent to which methodological approach influenced the strength of the relationship between physical activity and sleep. Specifically, they examined four subgroups of studies which included (1) an objective assessment of physical activity and an objective assessment of sleep, (2) an objective assessment of physical activity and a subjective assessment of sleep, (3) a subjective assessment of physical activity and an objective assessment of sleep, and (4) a subjective assessment of physical activity and a subjective assessment of sleep. Their review highlighted the need for greater use of objective measures in this field of research as a whole, and among this population, specifically. Only two studies in their analysis objectively measured sleep and physical activity, despite objective measures being believed to offer more robust and precise estimates and avoid response bias (79). Surprisingly, accelerometers were not used in any studies as both the measure of physical activity and sleep. Furthermore, while overall their findings indicated that those with higher levels of objective and subjective physical activity were more likely to experience good sleep, objectively and subjectively, the strongest effect sizes were found when the same assessment approach (i.e., objective for both physical activity and sleep or subjective for both) was used rather than mixing assessment methods (e.g., objective physical activity and subjective sleep). This review demonstrates that more research could take advantage of accelerometers for assessing both sleep and physical activity behaviours.

The discussed reviews have covered adults and adolescents (from ages 14-88 years-old), but reviews on children's sleep and physical activity behaviour are limited. A narrative review by Jensen et al. (127) investigated relationships among children's and adolescents' (age range 7-18 years) sleep, physical activity and dietary behaviour. This review differs from the previously discussed reviews because it attempted to investigate the relationship between sleep and physical activity in both directions, whereas the other discussed reviews examined the impact of physical activity on sleep alone. Jensen and colleagues reported a positive association between longer sleep duration and physical activity and a negative association between sleep disturbance time (i.e. wakefulness during sleeping hours) and physical activity, but this review was limited. Only five cross-sectional studies investigating the relationship between physical activity and sleep were included, meaning that the generalisability of these findings is small, and the direction of the relationship cannot be explored. In addition, the review primarily investigated adolescent youth (age >13) with only one study included of children younger than 13-years-old. Research about physical activity and sleep among children has increased in recent years; however, to date, no systematic review of the relationship between physical activity and sleep in children alone has been conducted. Thus, a review of the evidence pertaining specifically to children's physical activity and sleep behaviour is warranted.

Research Problem

Individually, sleep and physical activity have important health consequences. They are also associated in a variety of ways; however, the evidence concerning the relationship between sleep and physical activity in children has yet to be systematically reviewed. The use of accelerometers to investigate this relationship is increasing as well, but these devices need to be tested for use within the child population. For example, the GENEActiv accelerometer with the van Hees sleep detection algorithm has been validated for use among adults but not children and the number of days needed to get reliable estimates of movement behaviours, especially sleep, is unknown (60, 61). Furthermore, high quality studies, with longitudinal designs that implement objective measurement methodologies, are needed to provide the best quality data possible to determine how physical activity and sleep are related in children.

The aims of this thesis were to determine the relationship between physical activity and sleep in children by contributing to the empirical evidence with three planned studies: (1) a systematic review and meta-analysis of the literature investigating the relationship between physical activity and sleep in children, (2) a longitudinal investigation of the day-to-day and longer-term changes in physical activity and sleep outcomes over two years, and (3) an investigation into the number of nights needed to obtain reliable estimates of habitual sleep behaviours in children using accelerometers.

Research Questions

1. What is the relationship between sleep and physical activity in children?
2. Is there evidence to suggest a direction to the association between physical activity and sleep? Is it bidirectional?
3. How many valid nights are required to obtain reliable estimates of children’s habitual sleep behaviour?

Chapter 2 | Physical Activity and Sleep are Inconsistently Related in Healthy Children: A Systematic Review and Meta-Analysis

Preface

This chapter has been published (128) in Sleep Medicine Reviews (IF = 10.52, SJR = 3.55). I was the first author on the publication and contributed the majority (i.e., greater than 75%) of the work (see Research Portfolio Appendix). I have retained most of the language and text as published. I made some minors text changes for the context of this thesis for tables, figures, and references to appendices rather than online only supplementary material.

Summary

Physical activity is considered an effective method to improve sleep quality in adolescents and adults. However, there is mixed evidence among children. Our objectives were to investigate this association in children and to examine potential moderating variables. Eight databases were systematically searched, and we included all study designs with a sample of healthy children ages 3-13-years-old. We identified 47 studies for meta-analysis. Overall, we found little association between physical activity and sleep (r = .02, 95% confidence interval = -.03 to .07). There was a high amount of heterogeneity in the overall model (I^2 = 93%). However, none of the examined variables significantly moderated the overall effect, including age, gender, risk of bias, study quality, measurement methodology, study direction, and publication year. Exploratory analyses showed some weak, but statistically significant associations for vigorous physical activity with sleep (r = .09, 95% CI = .01 to .17, I^2 = 66.3%), specifically sleep duration (r = .07, 95% CI = .00 to .14, I^2 = 41.1%). High heterogeneity and the lack of experimental research suggest our findings should be interpreted with caution. The current evidence, however, shows little support for an association between physical activity and sleep in children.

Keywords: Physical activity, Children, Meta-analysis, Systematic review, Sleep health

Introduction

Physical activity is widely promoted as an effective method to improve sleep quality (103, 113, 114, 129-131). Recent meta-analyses offer support for this premise, with positive associations between physical activity and sleep found in adolescents and young adults (e.g., effect size between objectively measured physical activity and objectively measured sleep; $d = 1.02$, 95% CI = 0.16 to 2.20) (43) and in adults (e.g., effect size between regular exercise and total sleep time; $d = 0.25$, 95% CI = 0.07 to 0.43) (124). However, the evidence among children is unclear with inconsistent findings among empirical studies and no meta-analytical review conducted to date (132).

International guidelines recommend that children 3-5 years of age obtain between 10 and 13 hours of sleep per night and that children 6-13 years of age sleep between 9 and 11 hours per night (14). However, there is evidence that young people worldwide tend to sleep less than these recommended levels (11, 38, 133). For example, in their examination across 12 different countries, Roman-Vinas et al. (39), reported only 42% of children met this recommendation. Moreover, 20-30% of children experience paediatric sleep problems (e.g., bedtime problems, night awakenings, etc.) (36). These sleep deficits are concerning because adequate sleep is important for children’s growth, maturation and development (26).

Buysse proposed five components of sleep that are important when considering sleep health: duration, efficiency, timing, subjective quality, and daytime tiredness (42). Shortened sleep duration, poor sleep efficiency, and erratic sleep timing are associated with impaired concentration and poorer academic performance (27), information retention, and working memory (25, 28). Short sleep duration and poor sleep quality are also linked to affective disorders, such as depression, anxiety and attention deficit disorder (29, 30). Furthermore, short sleep duration, daytime tiredness, and poor sleep quality in children are linked with an increased risk of injuries and accidents (31), alcohol and drug use later in adolescence (32), and obesity (34, 35).

Physical activity is widely promoted for its many health benefits for people of all ages (71, 72). International physical activity guidelines for children aged 5-17 years recommend at least 60 minutes of at least moderate-intensity physical activity per day (15). In a systematic review of children and adolescents aged 5-17 years, Janssen and Leblanc reported that physical activity positively influences bone health, cholesterol, blood pressure, weight management, obesity, and metabolic syndrome (68). Physical activity also benefits children's mental health, showing positive associations on depression and anxiety (70).

Physical activity and sleep are individually important for health; however, it is also important to understand how these behaviours interact (16-18, 91). Lang et al. (43) demonstrated that both subjective ratings and objective recording of time spent being physically active had a positive impact on subjective ratings and objective recording of time spent sleeping in adolescents and young adults, with objective measurements showing the strongest effects. In adults, Kredlow et al. (124) have also shown positive effects from acute and regular exercise on a variety of sleep outcomes including sleep duration, sleep efficiency, and sleep quality. In their meta-analysis, Kredlow et al. (124) also show that effects were moderated by gender, age, baseline fitness level, and a variety of exercise characteristics. However, both these meta-analyses have focused on the effect of physical activity or exercise on sleep and not the other direction. Additionally, no meta-analysis examining the relationship between physical activity and sleep has included children under 13-years-old (103, 113, 114, 129-131). Thus, the efficacy of physical activity as a method to improve sleep in children is unknown. It is also unknown if the association between physical activity and sleep is bidirectional (97). Indeed, some evidence suggests that poor sleep may decrease the amount of physical activity that children accumulate (134). As this association between physical activity and sleep in children is unclear, a meta-analysis of the existing literature is needed for this age group (123, 132, 135).

Our objectives in this systematic review were to (i) investigate the associations between physical activity and sleep behaviour among healthy children, (ii) if these associations exist, examine evidence regarding direction of the associations, and (iii) identify potential moderators in the associations between physical activity and sleep. Based on findings from meta-analyses involving adolescents and adults (43, 124), we hypothesized that there would be (a) a positive association between physical activity and sleep in healthy children, (b) that the associations would be stronger for males, for older children, for children who are regularly physically active, and for children with regular sleep patterns, and (c) that stronger associations would be found between objectively measured effects than subjectively measured effects. We also investigated whether the relationship between physical activity and sleep in children is bidirectional.

Method

Protocol registration

We prospectively registered this review with the International Prospective Register of Ongoing Systematic Reviews (PROSPERO ID: CRD42017057217) and report our findings according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (See Appendix A.6; 136).

Eligibility criteria

We included articles if they: a) reported results from a sample of 3-13-year-old children (i.e., the study reported a sample mean age between 2.50 to 13.49 years); b) employed a cross-sectional, longitudinal, or experimental design; c) included quantitative measures for physical activity and sleep; and d) quantitatively assessed the relationship between physical activity and sleep. We excluded studies if: a) the sample was drawn from a clinical population (e.g., children with cancer, autism, ADHD, known sleep disorders such as chronic insomnia), unless a typically-developing control group was included; b) the publication was a conference abstract; c) the study exclusively used a qualitative methodology or a case study design; or d) the study was not published in the English language.

Information sources and search

The first author (DA) conducted a systematic search of the databases PubMED, PsychINFO, CINAHL, EMBASE, MEDLINE, SPORTDiscus, SCOPUS, and Cochrane library to identify relevant studies for inclusion in the review. We did not use publication date to restrict the search. The final search was conducted June 6th, 2018. We also checked the reference lists of included studies and relevant review papers for additional articles.

We used variations of the term children (e.g., youth, paediatric, boy, girl), physical activity (e.g., motor activity, physical inactivity, active, exercise), and sleep (e.g., sleep quality, bedtime, wake, time in bed, rapid-eye-movement), identified in the title or abstract, to obtain articles for inclusion in the review. We have included a more detailed list of the search terms in Appendix A.4.

After our initial database searches, we later checked for unpublished data to include in the analyses. We requested unpublished data from known authors and by contacting relevant email listservs. We also checked the ISRCTN registry for unpublished trials. However, no unpublished data was included in this review.

Study selection

The first author (DA) extracted all the records retrieved from the search databases and imported them into Covidence systematic review management software (Veritas Health Innovation, Melbourne), which automatically removed duplicates. DA and a second reviewer (JL, TH, or RH) independently screened each record by title and abstract. We excluded studies at this stage when both reviewers determined that inclusion criteria were not met. DA and a second reviewer (JL, TH, or RH) then assessed the full-text articles for eligibility. We resolved disagreements between reviewers by discussion and included a third reviewer (TS or CL) when necessary. We included the remaining studies in the review and meta-analysis.

Data extraction

The first author (DA) created data extraction forms based on the guidelines proposed by Zaza et al. (137). DA and a second reviewer (JL, TH, or RH) independently extracted relevant study information including: study characteristics (sample size, gender and age of participants, attrition rate, study design, country, first author, and publication year); characteristics of physical activity (duration, volume, type, frequency/regularity, intensity, timing, and measure); characteristics of sleep (duration, timing, quality, variability, efficiency, architecture, and measure), and the study results (effect sizes, confidence intervals, and significance level). Disagreements between reviewers were resolved by discussion and re-examination of the study text. We requested from the authors any effect sizes that were missing from the original published papers.

Risk of bias

We included cross-sectional, longitudinal, and experimental study designs in this review. To assess risk of bias and study quality across diverse study designs, we drew upon three established tools. We combined the 20 items from the appraisal tool for cross-sectional studies (AXIS) (138) with 5 items from the appraisal tool developed for the grading of recommendation, assessment, development and evaluation (GRADE) approach, which is based on the Cochrane collaboration risk of bias tool for randomised trials (139), and added one additional item from the National Heart, Lung, and Blood Institute’s quality assessment tool for observational cohort and cross-sectional studies (140). The final tool consisted of 12 items for risk of bias and 14 items for study quality. We rated each included study with all 26 items. Reviewers responded yes, no, unclear, or not applicable to each item, with "yes" indicating low-risk or high-quality. For use as a moderating variable in the meta-analysis, we stratified responses to give an overall risk of bias score (i.e., high, unclear, low) and a study quality score (i.e., high, moderate, low). For risk of bias, we followed Cochrane guidelines to classify high risk of bias when at least one item was rated as high risk, unclear when at least one item was rated as unclear and none as high risk, and low risk if all items were rated as low risk (141). For study quality items, we decided 80% "yes" indicated high quality, 60-80% indicated moderate quality, and 0-60% indicated low quality. DA and a second reviewer (JL, TH, or RH) independently scored each article for risk of bias and study quality. We resolved disagreements through discussion.

Synthesis of results

We chose the correlation coefficient (r) as the main effect size for this review. Some studies reported standardized regression coefficients (β), unstandardized regression coefficients (*beta*), standardized mean differences (Cohen's d), and odds ratios. We converted all these estimates to correlations. We then transformed correlations into Fisher's z for all analyses and then converted them back to correlations for presentation. Methods and formulas for this process are presented in Appendix A.1 (142-146). When necessary, we reverse coded effect sizes to aid in the interpretation of our results and to combine effect sizes into groups. For our analyses, we coded increases in the following variables as beneficial: all physical activity variables, sleep duration, time in bed, sleep efficiency, sleep quality, deep sleep, and rapid-eye-movement (REM) sleep. We coded decreases in the following variables as beneficial: sleep timing (e.g., earlier bedtime), sleep onset latency, sleep-related problems, daytime tiredness, number of night awakenings, sleep fragmentation, and light sleep.

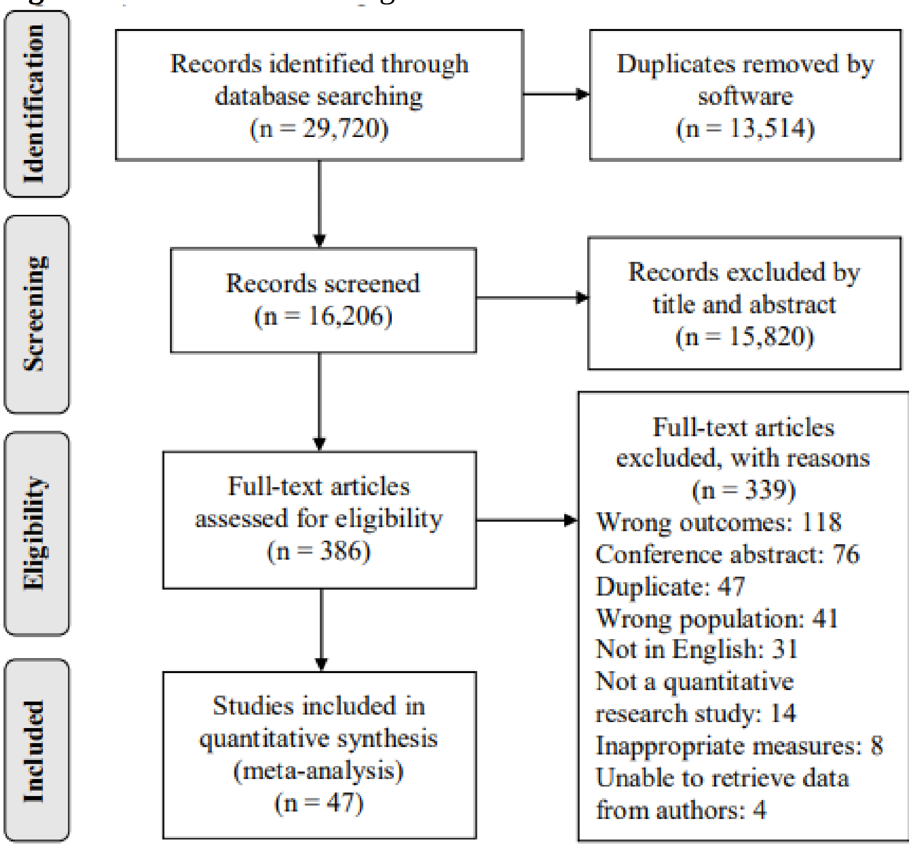
Meta-analysis. We conducted the main analysis and moderator analyses with a multilevel random effects model approach using the meta-analysis package for R (metafor)

(147) in the R environment (version 3.4.4) (148). In this model, we consider the distribution of three variance components at each level (149). Level 3 is the variance between effect sizes of different studies (i.e., variance between studies), Level 2 is the variance of effect sizes within each study (i.e., variance within studies), and Level 1 is the variance of individual effect sizes (i.e., sampling variance). For Level 1, sampling variance is calculated based on study sample size. We chose the random effects model to account for the heterogeneity expected from different populations and procedures used in the included studies.

To examine an overall relationship between physical activity and sleep, we first fit all the data to one overall model. We then extended the model to include pre-determined moderator variables to test whether heterogeneity in the overall model could be explained by various study or effect size characteristics. Finally, we conducted additional outcome variable category analyses on the data, in which we performed separate meta-analyses for each unique association between physical activity variable type and sleep variable type (e.g., moderate physical activity and sleep duration, vigorous physical activity and sleep efficiency). We dummy coded all categorical variables and centred continuous variables around their respective means. Throughout the analyses, we used the *t*-distribution for testing regression coefficients and subsequent confidence intervals and used the restricted maximum likelihood estimation method (150). We used Cochrane's Q to test the assumption of homogeneity among effect sizes. We calculated the I^2 index to test heterogeneity across studies from 0% to 100% with 25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively (151, 152). We assessed the risk of publication bias by visually inspecting contour enhanced funnel plots for asymmetry (153, 154). We considered a p-value of <.05 to be statistically significant.

Moderators. We identified potential moderator variables a priori. These variables were categorised as study characteristics (i.e., outcome variable, measurement methodology, study design, risk of bias, and study quality), participant characteristics (i.e., gender, age, socioeconomic status, and fitness level), and physical activity characteristics (i.e., activity type, time of day, and frequency). Furthermore, we included a variable to test the impact of study direction (i.e., examining the influence of physical activity on sleep, the influence of sleep on physical activity, or without a specified direction). The direction of study outcomes was determined based on the hypothesised direction of the physical activity and sleep relationship in the study. That is, if a study sought to examine the influence of physical activity with sleep as the outcome, then that study was coded as the impact of physical activity on sleep. We used meta-regression analyses to determine whether there was a significant association between these moderating variables and the main outcomes of interest.

Figure 2.1 PRISMA flow diagram



Results

Study Selection

We identified 29,720 records, of which Covidence removed 13,514 duplicates. After screening titles and abstracts, we removed a further 15,820 records. We considered the full-text version of the remaining 386 records against our inclusion criteria. At the final stage, we included 47 studies in the meta-analysis (see Figure 2.1). Inter-rater agreement for all data extracted from included studies was high (*M* = 93.6%, range = 75.5-100%). We resolved any disagreements by discussion.

Study Characteristics

Table 2.1 shows the characteristics of all 47 included articles, representing published studies which reported an association between physical activity and sleep in healthy children. The studies included a total sample of *N* = 62,081 children (53% female) with mean ages between 3.9 to 13.4 years (*M* = 10.00, SD = 2.34). Study sample sizes ranged from *n* = 11 to 9,261 (*M* = 1,592, SD = 2,372) participants. Sixteen studies sampled participants in North America (*n* = 14,508), three in South America (*n* = 5,043), 14 in Europe (*n* = 17,727), four in Asia (*n* = 12,633), seven in Australia or New Zealand (*n* = 5,617), and three were multi-national (i.e., four or more countries; *n* = 6,553).

The studies were mainly cross-sectional in design (*n studies* = 44), with two experimental studies (i.e., one experimentally manipulated exercise to test changes in sleep, the other manipulated sleep), and one 9-month longitudinal study. To measure physical activity, researchers primarily used accelerometers (*n studies* = 26) or questionnaires (*n studies* = 14). One study used both methods. Other methods included time-use-diaries (*n studies* = 3), parent interviews (*n studies* = 1), experimental change in exercise intensity (*n* = 1), and pedometers (*n studies* = 1).

Table 2.1 Study characteristics of included articles

First Author (year)	n	Mean Age	Location	Physical Activity Measured	Method	Sleep Measured	Method	Design	Analysis	Risk of Bias
Adam et al. (2007)	1267	8.9	USA	Time in sports	Time-Use-Diary	Duration, Bedtime, Waketime	Time-Use-Diary	Cross-sectional	Regression, Correlation	High
Aguilar et al. (2015)	196	12.23	Chile	Low-moderate vs. high physical activity score (PAQ)	Questionnaire	Quality	Questionnaire	Cross-sectional	ANOVA	High
Appelhans et al. (2014)	103	10	USA	Moderate-to-vigorous physical activity duration	Accelerometer, Waist-worn	Duration, Bedtime, Waketime	Questionnaire	Cross-sectional	Correlation	Low
Arriscado et al. (2017)	613	11.88	Spain	Physical Activity Questionnaire score	Questionnaire	Duration, Bedtime, Waketime	Questionnaire	Cross-sectional	Correlation	Unclear
Awad et al. (2013)	134	11.5	USA	Moderate physical activity, Vigorous physical activity duration	Questionnaire	Duration, Architecture	At-Home Polysomnography	Cross-sectional	Correlation	Unclear
Bates et al. (2016)	60	11.8	USA	Moderate-to-vigorous physical activity duration	Accelerometer, Waist-worn	Duration, Bedtime, Waketime	Accelerometer, Waist-worn	Cross-sectional	Correlation	Unclear
Borges et al. (2015)	777	10	Portugal	Moderate-to-vigorous physical activity complying days	Accelerometer, Waist-worn	Duration	Questionnaire	Cross-sectional	Regression	High
Brand et al. (2016)	1361	13.4	Switzerland	Low vs. high physical activity Score (PAQ)	Questionnaire	Quality	Questionnaire	Cross-sectional	Mean difference	High
Chaput et al. (2015)	5777	10.4	Multi-national	Moderate-to-vigorous physical activity duration	Accelerometer, Waist-worn	Duration, Efficiency	Accelerometer, Waist-worn	Cross-sectional	Regression	Unclear
Duraccio & Jensen (2017)	131	4.91	USA	Physical activity complying days	Accelerometer, Waist-worn	Duration	Accelerometer, Waist-worn	Cross-sectional	Regression	Unclear
Dworak et al. (2008)	11	12.6	Germany	No exercise vs. moderate/high intensity exercise	Experimental	Duration, Efficiency, Onset latency, Architecture	At-Home Polysomnography	Experiment	Mean difference	High
Ekstedt et al. (2013)	1231	8	Sweden	Moderate-to-vigorous physical activity duration, Total activity counts	Accelerometer, Wrist-worn	Duration, Efficiency, Bedtime, Waketime	Accelerometer, Wrist-worn	Cross-sectional	ANOVA, Correlation	High
Gadermann et al. (2016)	4133	9.7	Canada	Participation in team/individual sports	Questionnaire	Bedtime	Questionnaire	Cross-sectional	Correlation	Unclear
Gaina et al. (2007)	9261	12.8	Japan	Often/seldom/never physical activity participation	Questionnaire	Developing sleepiness	Questionnaire	Cross-sectional	Odds Ratio	High
Garcia-Hermoso et al. (2017)	395	12.1	Chile	Physical Activity Questionnaire score	Questionnaire	Quality	Questionnaire	Cross-sectional	Correlation	High

First Author (year)	n	Mean Age	Location	Physical Activity Measured	Method	Sleep Measured	Method	Design	Analysis	Risk of Bias
Gomes et al. (2017)	6553	10	Multi-national	Moderate-to-vigorous physical activity complying days	Accelerometer, Waist-worn	Duration	Accelerometer, Waist-worn	Cross-sectional	Regression	High
Greever et al. (2017)	55	8.4	USA	Light physical activity, Moderate physical activity, Vigorous physical activity duration	Accelerometer, Wrist-worn	Duration, Sleep Fragmentation, Number of Night awakenings	Accelerometer, Wrist-worn	Cross-sectional	Regression	High
Gupta et al. (2002)	361	13	USA	Total physical activity	Accelerometer, Wrist-worn	Quality	Accelerometer, Wrist-worn	Cross-sectional	Correlation, Regression	Low
Harrex et al. (2017)	439	10.2	New Zealand	Moderate-to-vigorous physical activity duration	Accelerometer, Wrist-worn	Timing	Accelerometer, Wrist-worn	Cross-sectional	Regression	Low
Harrington (2013)	55	8	USA	Light physical activity, Moderate physical activity, Vigorous physical activity percentage, Moderate-to-vigorous physical activity bouts, Steps	Accelerometer, Wrist-worn	Duration	Accelerometer, Wrist-worn	Cross-sectional	Correlation	High
Hart et al. (2016)	37	9.6	USA	Moderate-to-vigorous physical activity percent, Total activity counts	Questionnaire, Accelerometer, Wrist-worn	Decreased vs increased sleep	Accelerometer, Wrist-worn	Experiment	Mean difference	High
Hense et al. (2011)	8542	6	Europe	Moderate-to-vigorous physical activity duration	Accelerometer, Waist-worn	Duration	Questionnaire	Cross-sectional	Regression	Low
Hjorth et al. (2013)	730	10	Denmark	Total physical activity	Accelerometer, Waist-worn	Duration	Accelerometer, Waist-worn	Cross-sectional	Correlation	High
Iwata et al. (2011)	47	5	Japan	Sports lessons	Questionnaire	Efficiency, Bedtime, Waketime	Accelerometer, Wrist-worn	Cross-sectional	Regression	High
Ji et al. (2018)	112	4.5	China	Moderate-to-vigorous physical activity duration	Accelerometer, Wrist-worn	Duration	Accelerometer, Wrist-worn	Cross-sectional	Regression	Low
Jiang et al. (2015)	3213	11.5	China	Leisure-Time physical activity duration	Questionnaire	Duration, Bedtime	Questionnaire	Cross-sectional	Regression	Unclear
Khan et al. (2015)	5560	10.5	Canada	Physical Activity Questionnaire Score	Questionnaire	Duration, Bedtime, Snoring, Sleepiness	Questionnaire	Cross-sectional	Regression	High
Krietsch et al. (2016)	134	9.86	USA	Moderate-to-vigorous physical activity duration	Accelerometer, Arm-worn	Duration	Accelerometer, Arm-worn	Cross-sectional	Regression	Low
Labree et al. (2015)	1943	8.5	The Netherlands	Total physical activity	Questionnaire	Duration	Questionnaire	Cross-sectional	Correlation	High

First Author (year)	n	Mean Age	Location	Physical Activity Measured	Method	Sleep Measured	Method	Design	Analysis	Risk of Bias
Laurson et al. (2014)	674	9.5	USA	Steps	Pedometer	Duration	Questionnaire	Cross-sectional	Correlation	High
Lin et al. (2018a)	433	11.5	Canada	Outdoor active play	Accelerometer, Waist-worn	Duration, Time in bed, Efficiency, Timing	Accelerometer, Waist-worn	Cross-sectional	Regression	Low
Lin et al. (2018b)	5779	10.4	Multi-national	Light physical activity, Moderate-to-vigorous physical activity duration	Accelerometer, Waist-worn	Duration	Accelerometer, Waist-worn	Cross-sectional	Regression	Low
Mcneil et al. (2015)	515	10	Canada	Light physical activity, Moderate physical activity, Vigorous physical activity, Moderate-to-vigorous physical activity duration	Accelerometer, Waist-worn	Duration, Efficiency, Bedtime, Waketime	Accelerometer, Waist-worn	Cross-sectional	Regression	High
Morrissey et al. (2016)	289	11.2	Australia	Light physical activity, Moderate-to-vigorous physical activity duration	Accelerometer, Waist-worn	Sufficient vs. insufficient duration	Questionnaire	Cross-sectional	Regression	High
Nixon et al. (2009)	519	7.3	New Zealand	Vigorous physical activity, Total activity counts	Accelerometer, Waist-worn	Sleep onset latency	Accelerometer, Waist-worn	Cross-sectional	Regression	Unclear
Olds et al. (2011)	1132	11.7	Australia	Moderate-to-vigorous physical activity duration	Time-Use-Diary	Duration	Time-Use-Diary	Cross-sectional	Correlation	Unclear
Ortega et al. (2011)	468	9.5	Estonia, Sweden	Moderate-to-vigorous physical activity, moderate/high activity duration	Accelerometer, Waist-worn	Short vs. long duration	Questionnaire	Cross-sectional	Regression	Low
Pereira et al. (2017)	612	10.5	Portugal	Moderate-to-vigorous physical activity complying days	Accelerometer, Waist-worn	Quality	Questionnaire	Cross-sectional	Regression	Low
Pesonen et al. (2011)	275	8.2	Finland	Total physical activity, Moderate-to-vigorous physical activity, Total activity counts	Accelerometer, Wrist-worn	Duration, Efficiency, Latency, Fragmentation index	Accelerometer, Wrist-worn	Cross-sectional	Regression	Low
Raudsepp (2018)	129	13.2	Estonia	Total physical activity	Questionnaire	Quality	Questionnaire	Longitudinal	Correlation, Regression	High
Sijtsma et al. (2015)	759	3.9	The Netherlands	Outdoor play	Questionnaire	Duration	Questionnaire	Cross-sectional	Correlation	Low
Soric et al. (2015)	276	11.3	Croatia, Slovenia, USA	Moderate physical activity, Vigorous physical activity Moderate-to-vigorous physical activity duration	Accelerometer, Arm-worn	Duration, Time in bed, Efficiency	Accelerometer, Arm-worn	Cross-sectional	Regression	Low

First Author (year)	n	Mean Age	Location	Physical Activity Measured	Method	Sleep Measured	Method	Design	Analysis	Risk of Bias
Stone et al. (2013)	856	11.1	Canada	Light physical activity, Moderate-to-vigorous physical activity duration, Total activity counts	Accelerometer, Waist-worn	Duration	Questionnaire	Cross-sectional	Correlation	Low
Vincent et al. (2017)	65	10.4	Australia	Light physical activity, Moderate-to-vigorous physical activity duration	Accelerometer, Arm-worn	Duration, Time in bed, Efficiency	Accelerometer, Arm-worn	Cross-sectional	Regression	High
Wells et al. (2008)	4452	11	Brazil	Moderate-to-vigorous physical activity duration	Questionnaire	Duration	Questionnaire	Cross-sectional	Regression	Low
Xu et al. (2016)	415, 369	3.5, 5	Australia	Outdoor play	Parent interview	Duration, Bedtime, Efficiency	Parent interview	Cross-sectional	Regression	High
Yu et al. (2011)	2758	4.5	Australia	Total physical activity	Time-Use-Diary	Duration	Time-Use-Diary	Cross-sectional	Regression	Unclear

Note. n = Sample size; mean age in years.

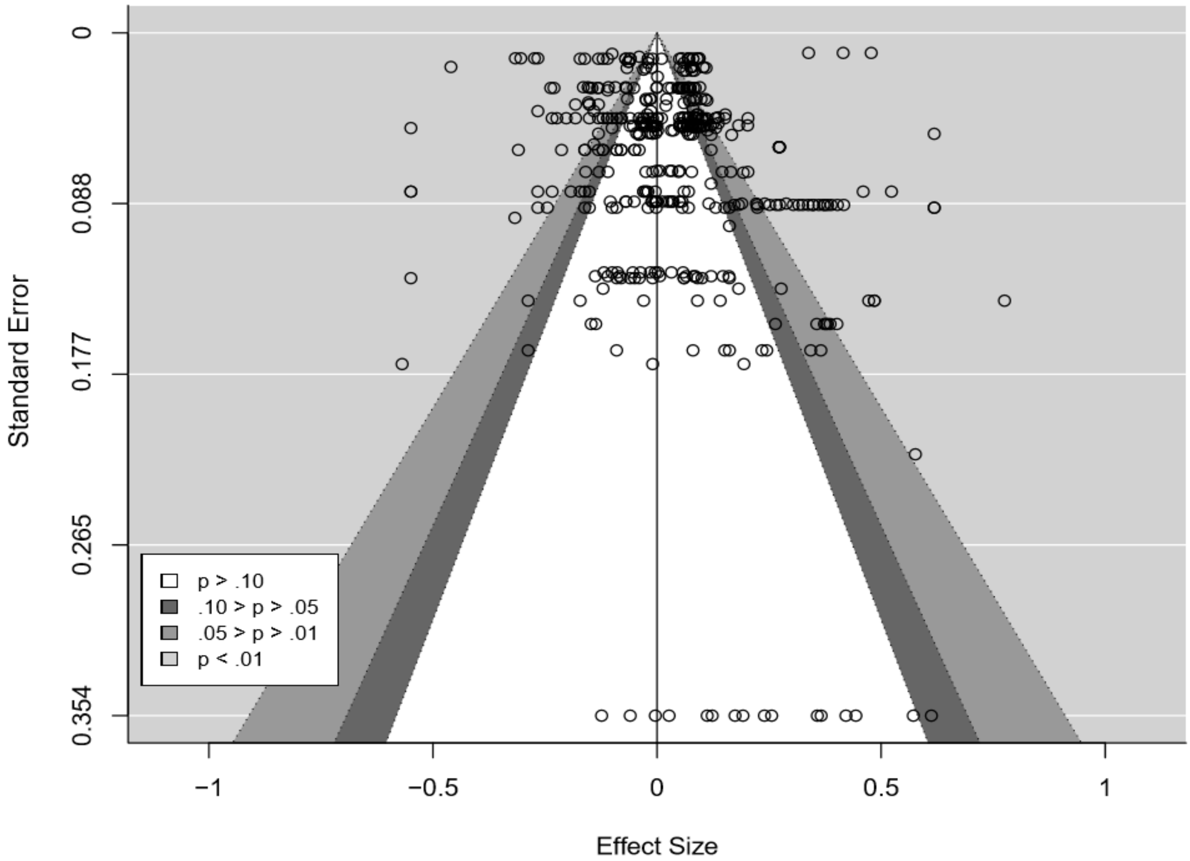
For sleep, accelerometers (*n studies* = 21) and questionnaires (*n studies* = 20) were used most, while some studies used time-use-diaries (*n studies* = 3), parent interviews (*n studies* = 1), and polysomnography (*n studies* = 2). The correlation coefficient was presented in 17 studies. Other effect sizes were converted from studies reporting beta coefficients (β; *n studies* = 28), standardised mean differences (Cohen's *d*; *n studies* = 3), ANOVA (*n studies* = 2), and odds ratios (*n studies* = 1). From the 47 studies, we extracted $k = 451$ effect sizes, ranging from $r = -.51$ to .65.

Risk of bias

We scored all the included studies for risk of bias. Overall, we rated 22 studies as high risk of bias (i.e., at least one item rated as high risk). The main source of bias was lack of sample size justification for cross-sectional studies. We scored 15 studies as low risk of bias (i.e., all items were rated low risk) and 10 as unclear (i.e., at least one item rated as unclear). We also rated studies according to study quality criteria based on quality of reporting and quality of design. We rated 37 studies as high quality, six studies as moderate quality, and four as low quality.

We assessed risk of bias across studies by visually inspecting the contour-enhanced funnel plot shown in Figure 2.2 (154). While the points on the plot deviate from the funnel shape, the horizontal scatter appears to maintain symmetry. Studies may be missing from the bottom left side of the plot indicating that smaller studies tend to report positive effects. We conducted a trim and fill analysis which indicated asymmetry on both the bottom left side and top left side of the plot (155). We also conducted Egger's test to investigate asymmetry and the test was significant ($z = 5.44$, $p < .001$) (153). While both these analyses indicate publication bias, they also perform poorly with large between-study heterogeneity (156, 157). Therefore, we are unable to conclude whether the asymmetry in the plot is due to heterogeneity between studies or publication bias.

Figure 2.2 Contour-enhanced funnel plot of standard errors with 90%, 95%, and 99% confidence interval lines



Main Analysis

Figure 2.3 shows a caterpillar plot of all 451 effect sizes. Using a multilevel random effects model, we found that the overall association between physical activity and sleep was $r = .02$ (SE = .02). This result was not significantly different from zero (t[450] = .90, $p = .37$) with a 95% confidence interval = -.03 to .07. The I^2 for this model was 97.2%. We performed log-likelihood ratio tests, which indicated significant heterogeneity within studies (33.3%, $p < .001$) and between studies (63.9%, $p < .001$). We then conducted moderator analyses to examine potential sources of this heterogeneity.

Moderator Analysis

Based on the data we were able to extract from the included studies, we applied six moderator variables to our overall model: the direction of study outcomes (i.e., the impact of physical activity on sleep, the impact of sleep on physical activity, or no specified direction), measurement methodology (i.e., objective, subjective, or a mix of both), risk of bias (i.e., low, high, unclear), study quality (i.e., low, moderate, high), gender (i.e., males, females, mixed), and mean age. We tested each hypothesised moderator individually in the model and found that none significantly moderated the overall effect (see Table 2.2).

Figure 2.3 Caterpillar plot of all effect sizes (*r*) with confidence intervals

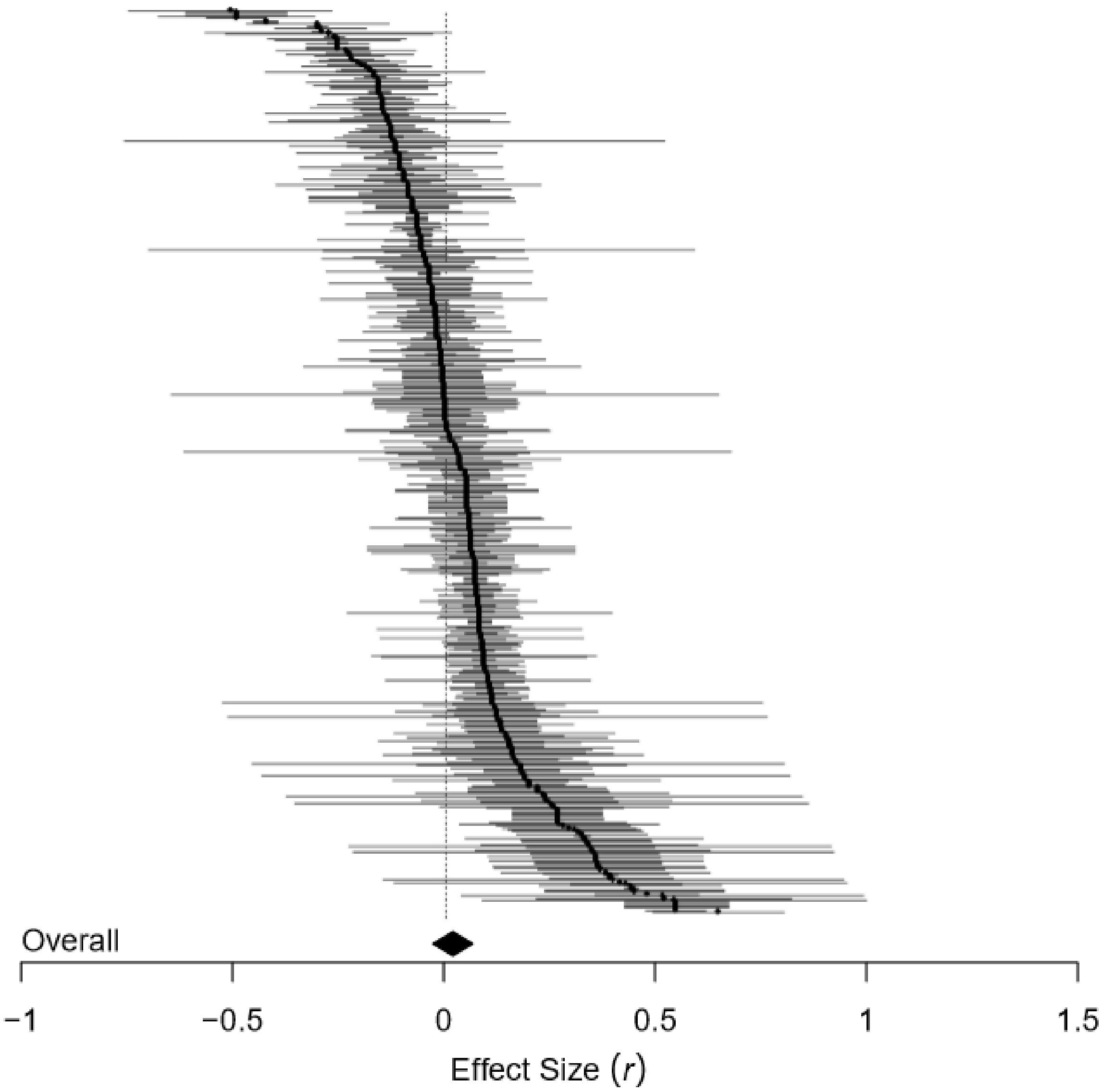


Table 2.2 Moderator analyses of overall association between physical activity and sleep (*n. studies* = 47, *k* = 451)

Moderator Variable	*n. studies*	*k*	Intercept (95%CI)/ *r*(95%CI)	β (95%CI)	*F*(df1, df2)[a]	*p*[b]
Direction of Study Outcomes					*F*(2, 448) = 0.53	.59
Physical Activity Impact on Sleep	19	130	0.01(-0.05, 0.06)			
Sleep Impact on Physical Activity	16	181	0.02(-0.04, 0.07)	0.01(-0.03, 0.05)		
No Direction	22	140	0.04(-0.02, 0.09)	0.03(-0.03, 0.09)		
Gender					*F*(2, 448) = 1.52	.22
Male	9	60	0.02(-0.03, 0.07)			
Female	12	86	0.01(-0.04, 0.06)	-0.01(-0.06. 0.04)		
Mixed	38	305	0.04(-0.01, 0.09)	0.02(-0.05, 0.09)		
Mean Age	47	451	0.03(-0.02, 0.08)	0.01(-0.01, 0.03)	*F*(1, 449) = 1.56	.21
Measurement Methodology					*F*(3, 447) = 0.38	.77
Objective Physical Activity and Objective Sleep	21	277	0.00(-0.07, 0.07)			
Objective Physical Activity and Subjective Sleep	9	29	0.11(-0.09, 0.31)	0.11(-0.10, 0.32)		
Subjective Physical Activity and Subjective Sleep	16	105	0.03(-0.06, 0.11)	0.03(-0.08, 0.14)		
Subjective Physical Activity and Objective Sleep	3	40	0.03(-0.08, 0.14)	0.03(-0.11, 0.16)		
Risk of Bias					*F*(2, 448) = 1.17	.31
Low	14	174	-0.01(-0.09, 0.07)			
High	23	208	0.06(-0.01, 0.13)	0.07(-0.04, 0.18)		
Unclear	10	69	-0.02(-0.12, 0.08)	-0.01(-0.14, 0.12)		
Study Quality					*F*(2, 448) = 0.91	.41
Low	4	54	0.07(-0.09, 0.23)			
Moderate	6	20	0.09(-0.04, 0.23)	0.02(-0.19, 0.23)		
High	37	387	0.01(-0.05, 0.06)	-0.07(-0.23, 0.10)		

Note. *n. studies* = number of studies; *k* = number of effect sizes; *r* = correlation coefficient; CI = confidence interval; β= estimated regression coefficient.

[a] Omnibus test of all regression coefficients in the model.

[b] p-Value of the omnibus test.

* p < .05.

** p < .01

*** p < .001

Categorised Outcome Variable Analyses

While none of the moderators had a significant effect on the overall relationship between physical activity and sleep variables, it was possible that the high levels heterogeneity could be explained by the diverse physical activity and sleep outcomes themselves. In total, studies examined 26 unique sleep outcome variables (e.g., sleep duration, sleep latency, sleep score, sleep disturbances, developing sleepiness) and 24 unique physical activity outcome variables (e.g., number of 5-minute moderate-to-vigorous physical activity bouts, total activity counts/day, physical activity score, vigorous physical activity). We initially planned to test these outcomes as part of the moderation analysis; however, due to considerable variation in outcome variables between studies, we grouped these variables into more manageable variable categories (see Table 2.3). For sleep, we grouped variables based on the five components of sleep health identified by Buysse (i.e., duration, efficiency, timing, quality, and daytime tiredness) (42), and three levels related to sleep architecture (i.e., light, deep, and REM). For physical activity, we included six physical activity categories (i.e., total physical activity, sport and outdoor play, light physical activity, moderate physical activity, vigorous physical activity, and moderate-to-vigorous physical activity). We then investigated the associations between physical activity and sleep by conducting meta-analyses for each physical activity and sleep outcome variable category pairing.

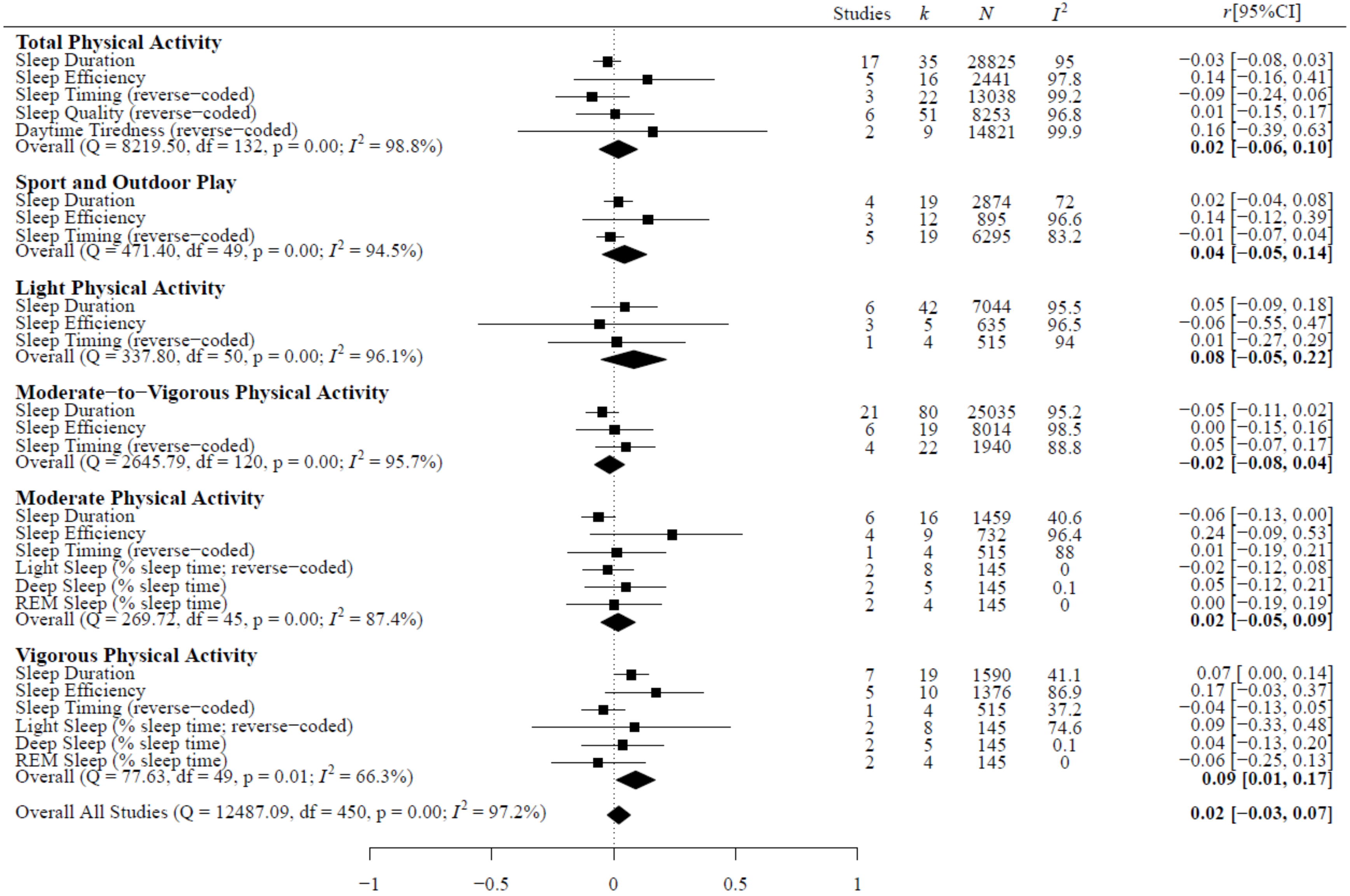
We calculated an individual and overall effect size for each physical activity and sleep variable pairing if there were four or more studies included in the analysis. Figure 2.4 shows the results of the outcome variable category analyses organised by physical activity category. We included Supplementary Figure 2.1 in Appendix A.2 which contains the results with all pairings (i.e., including associations with less than four studies) which shows little difference in results compared to Figure 2.4 (Supplementary Figure 2.2 in Appendix A.3 shows the same results instead organised by sleep category).

Table 2.3 Physical activity and sleep grouped variable categories

Physical Activity Category in Analysis	Physical Activity Specific Variables Extracted from Included Studies
Moderate-to-Vigorous Physical Activity	• Moderate-to-vigorous physical activity duration (accelerometer-derived based on age-specific cut points, metabolic thresholds, or proprietary algorithms) • Number of 5-minute moderate-to-vigorous physical activity bouts (accelerometer-derived based on age specific cut points)
Moderate Physical Activity	• Moderate intensity physical activity duration (accelerometer-derived based on age-specific cut points, metabolic thresholds, or proprietary algorithms)
Vigorous Physical Activity	• Vigorous intensity physical activity duration (accelerometer-derived based on age-specific cut points, metabolic thresholds, or proprietary algorithms) • Participates in vigorous physical activity at least once/week
Light Physical Activity	• Light intensity physical activity duration (accelerometer-derived based on age-specific cut points, metabolic thresholds, or proprietary algorithms)
Total Physical Activity	• Mean activity counts/min • Total activity counts/day • Average activity counts/epoch • Often, seldom, never physical activity participation (self-report) • Total physical activity • Physical activity Score (Physical Activity Questionnaire) • Number of moderate-to-vigorous physical activity complying days • Regular physical activity • Steps/day • Duration leisure time physical activity (after school)
Sport and Outdoor Play	• Runs around outside "a lot" • Sports/day • Hours of sports participation • Participation in individual sports • Participation in team sports • Sport lessons two or more times/week • Outdoor play • Duration of outdoor active play/day

Sleep Category in Analysis	Sleep Specific Variables Extracted from Included Studies
Sleep Duration	• Sleep duration/Total sleep time • Time in bed
Sleep Efficiency	• Sleep efficiency • Sleep onset latency • Number of night awakenings • Sleep fragmentation index (a score derived from the amount of movement and number of awakenings during sleep)
Sleep Timing	• Sleep onset • Sleep offset • Sleep mid-point (All variables coded so that earlier times indicated positive change)
Sleep Quality	• Sleep quality (questionnaire; e.g., The Diet and Lifestyle Questionnaire) • Overall sleep score (self-report questionnaire) • Sleep Self-Report (SSR) subscales: o Quality o Sleep anxiety o Bedtime resistance o Bedtimes routines • Self/Parent-reported sleep disturbances • Self-reported difficulty initiating sleep • Self-reported difficulty maintaining sleep • Snoring
Daytime Sleepiness	• Developing sleepiness • Daytime tiredness
Light Sleep	• Stage 1 sleep • Stage 2 sleep
Deep Sleep	• Stage 3 sleep • Stage 4 sleep
Rapid-Eye-Movement Sleep	• Rapid-eye-movement sleep

Figure 2.4 Associations of sleep outcomes organised by physical activity category

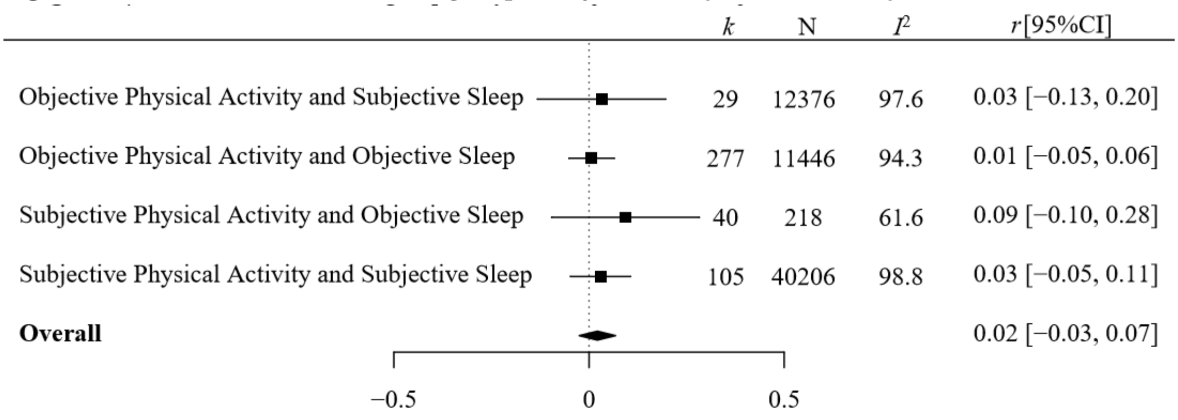


First, we calculated the association between each physical activity category and sleep overall. Only vigorous physical activity had a significant but weak positive association with sleep overall (*r* = .09, CI = .03 - .16). The other physical activity dimensions (i.e., moderate-to-vigorous physical activity, moderate physical activity, light physical activity, total physical activity, and sport and outdoor play) showed small and non-significant associations with sleep overall.

Next, we tested the association between each physical activity category and each sleep category. We found no significant results for total physical activity, sport and outdoor play, light physical activity, moderate physical activity, or moderate-to-vigorous physical activity. We found one small, but statistically significant effect between vigorous physical activity and sleep duration (*r* = .07, CI = .00 - .14) indicating more time spent in vigorous intensity activity was associated with slightly longer sleep duration. No other associations between vigorous physical activity and sleep categories were statistically significant.

We also conducted subgroup analyses based on study measurement methodology (i.e., subjective or objective measures). As shown in Figure 2.5, we found no significant associations within these subgroups, suggesting that measurement methodology differences across the studies did not account for the heterogeneous findings.

Figure 2.5 Effect sizes for 2x2 subgroup analysis of objective vs. subjective measures



Moderators within category analyses. Due to high heterogeneity in the results obtained within many outcome variable category analyses (e.g., moderate-to-vigorous physical activity and sleep duration I^2 = 95.2%), we conducted a series of exploratory moderation analyses on the overall and individual outcome variable models. We chose relationships to explore by considering the number of studies which reported on the association and the size of the I^2 value. We did not examine associations with fewer than four studies for continuous moderators, fewer than four studies for each level of categorical moderators, or associations with a small I^2 (i.e., less than 25%). We tested four moderator variables (i.e., age, risk of bias, study quality, and the direction of study outcomes). We report the full results of the categorical moderation analyses in Supplementary Table 2.2 in Appendix A.5 (we have also included in Supplementary Table 2.2 the number of studies and effect sizes of associations that had too few to be included in the moderation analysis). In summary, we found four significant effects out of the 28 moderator analyses. As the age of children increased, the association between moderate-to-vigorous activity and overall sleep (β = .04, CI = .00 - .08) and the association between total physical activity and sleep quality grew slightly stronger (β = .11, CI = .01 - .22). In contrast to our other findings, the association between vigorous physical activity and sleep became slightly weaker with age (β = -.02, CI = -.05 - .00). Lastly, for moderate-to-vigorous physical activity, studies without a specified direction were more likely to report negative associations than studies that had a hypothesised direction to their analyses (r = -.11, CI = -.20 - -.02).

Discussion

To our knowledge, this is the first meta-analysis to investigate the association between physical activity and sleep in healthy children. We quantitatively examined several different physical activity and sleep outcomes in an overall multilevel meta-analytical model and in individual outcome category meta-analyses. In addition, we investigated whether the findings were moderated by gender, age, direction of association, study design, risk of bias, study quality, year of publication, or measurement methodology. Contrary to our hypotheses, our analyses showed little association between children's physical activity and sleep and insufficient evidence for a bidirectional relationship. The lack of an overall association persisted across all the moderators we tested with only a weak positive association between vigorous intensity physical activity and sleep duration observed in outcome category analyses. Thus, the current evidence shows little support for an association between physical activity and sleep in healthy children. However, high heterogeneity in our analyses and a lack of experimental designs mean that these results point to the need for more and higher quality research.

We found some evidence that children who engaged in more vigorous physical activity had better overall sleep, including longer sleep duration. It may be that beneficial effects from physical activity on sleep are only realised in children when they are active at this high level of intensity (71). There is some evidence in children that, compared with moderate intensity, vigorous physical activity has more beneficial health effects. Owens, Galloway, and Gutin (158), for example, argued in their review that vigorous physical activity has a stronger positive impact on body composition, bone health, and blood pressure than moderate physical activity. However, the associations for vigorous physical activity with overall sleep and sleep duration in our analysis were weak (i.e., r = .09 and .07, respectively) and were synthesised from a small number of studies (i.e., nine and seven studies, respectively). More studies, especially experimental and longitudinal studies, are required to clarify whether vigorous physical activity may constitute an effective tool to improve sleep in children.

In addition to activity intensity, we found some evidence that age may play a moderating role in the relationship between physical activity and sleep. That is, some associations were slightly stronger in older compared with younger children. These findings, while weak and exploratory in our meta-analysis, are supported by findings of another review which showed positive effects of physical activity on sleep in adolescents and young adults (43). A possible explanation for stronger associations with age is that children's time is less regulated by others when they are older. For example, Tashjian, Mullins, and Galván (159), reported greater bedtime autonomy with increasing age in adolescents, which could provide more opportunity for lifestyle factors (e.g., physical activity) to influence variables such as sleep duration and sleep timing compared to children without bedtime autonomy.

Another reason that children's sleep may be less influenced by physical activity compared to adolescents, young adults (43), and adults (124), could be age-related differences in sleep itself. For example, children have different sleep architecture compared to adults. Specifically, children have shorter sleep cycles (i.e., about 60 minutes in children compared to 90 minutes in adults) and spend a larger proportion of the night in rapid-eye-movement sleep (160). These differences may exist because children's nervous system and body are still developing from a young age through maturation which begins around age 11 and 12 for females and males, respectively (161-163). During puberty specifically, the brain and body change rapidly, and hormone levels increase dramatically. Research has shown that the changes associated with puberty have been associated with poorer sleep and reduced physical activity in children (164, 165). A full discussion of the role of developmental processes in the association between physical activity and sleep is beyond the scope of this review; however, child development is a complex process and is likely to impact the physiological mechanisms underlying the association between physical activity and sleep. It may be that the physiological mechanisms are overshadowed by these developmental influences or may have yet to develop at all. While even in adults the underlying mechanism between physical activity and sleep remains unclear, many physiological mechanisms have been proposed including changes to circadian rhythm, body temperature, heart rate, central nervous system, growth hormone secretion, metabolism, immune system, mood, fitness level, and body composition (97, 112, 113, 124). Differences in physiology between children, adolescents and adults may help explain the weak associations found in our meta-analysis; however, little is known about these potential mechanisms in children and further research is needed.

Strengths and Limitations

We conducted a search of eight databases to find all available studies about the association between physical activity and sleep in children. Our approach found 47 relevant studies which reported findings across a substantial number of children worldwide, and a wide range of different measurement methodologies, physical activity outcomes, and sleep outcomes. Our inclusion of such diverse studies introduced issues of heterogeneity in our meta-analysis and influenced the robustness of our findings; however, we used appropriate analytical methods (i.e., multilevel meta-analysis and moderator analyses) to account for such variance within and between included studies. Overall, our approach aimed to provide the most comprehensive data possible for the associations between physical activity and sleep, despite limitations in the included studies or in our methodology.

We identified several limitations in the existing evidence. Included studies measured physical activity and sleep using a wide variety of different tools. While many studies used validated objective measures (i.e., accelerometers), some used single-item questionnaire measures with little validity evidence to assess physical activity or sleep. Our findings show little difference in the associations between objectively-measured outcomes and subjectively-measured outcomes; however, such diversity in measurement methodologies makes between-study comparisons challenging (166). We also aimed to extract data from included studies that indicated the regularity of physical activity; however, this data was not reported, and we were unable to make comparisons between acute and regular physical activity and their impact on sleep. Additionally, only one longitudinal and two experimental studies were included in our review. In contrast, a review of studies focused on associations between adults' physical activity and sleep included 66 experimental studies (124). Cross-sectional studies can be more susceptible to biases (e.g., selection bias, information bias, etc.) and cannot determine causal ordering effects compared to longitudinal and experimental designs. As such, the limited number of studies using high-quality designs in this review means that the quality of the overall body of evidence is low (139). Studies employing high-quality designs using valid measures are needed before we can draw strong conclusions about the association of physical activity and sleep in children.

We also identified several limitations with the methods of this review. First, we were unable to include all possible studies in the review due to missing data. We also excluded studies not published in English, which may have biased our findings. In our analyses, we assumed that shorter sleep duration and less time in bed was detrimental and longer duration was beneficial. However, this is true only to a certain point, as sleeping too long can also negatively impact outcomes of interest (167). We could not account for the possibility of this curvilinear effect in our analysis of sleep duration because the primary studies did not include this information. We also may have encountered ceiling effects by only including studies which sampled typically developing children (i.e., we excluded samples of children with known sleep disorders). By excluding clinical populations, we may have limited the overall association between physical activity and sleep because children with sleep disorders may show greater improvements in sleep from physical activity than typically developing children (97). Lastly physical activity and sleep may be co-dependent due to the time-constrained nature of their participation (i.e., one cannot engage in both activities simultaneously and engaging in one activity could displace time available for other time-dependent activities)

(92, 168, 169). However, few included studies provided the data on all-day time-use and these associations could not be examined in our review. We recommend that future research examining physical activity and sleep should consider methods for accounting for the co-dependent nature of these behaviours (91, 170).

Conclusion

Our aim was to meta-analyse the current literature on physical activity and sleep in healthy children. We found little evidence of an association overall with some weak positive associations between vigorous physical activity and sleep. While further investigation into moderators yielded some significant associations for age and the direction of association, these associations were also weak and were found only within specific categories of the data. Due to high heterogeneity in our models, caution is required when interpreting our findings. The lack of experimental studies found in our review suggests that the overall body of evidence is weak and further research is needed. Current evidence, however, suggests that while physical activity and sleep are important for overall health, physical activity has little association with sleep in otherwise healthy children.

Practice Points

1. Our study suggests that there is little association between physical activity and sleep behaviour in children.
2. Some evidence suggests that vigorous physical activity may have a positive influence on sleep, specifically sleep duration. However, the current findings are weak.
3. Few longitudinal and experimental studies have examined children's physical activity and sleep indicating that the quality of the overall body of evidence is low and results should be interpreted with caution.

Research Agenda

1. There is a need for more high-quality randomised and longitudinal trials to examine the associations between physical activity and sleep in children.
2. Future investigations are also needed which specifically examine the influence of physical activity on children with sleep disorders.

Chapter 3 | Day-to-day and Longer-term Longitudinal Associations between Physical Activity, Sedentary Behaviour, and Sleep in Children

Preface

The study presented in this chapter is currently under review at the academic journal SLEEP (IF = 4.805). I was the first author and contributed the majority of the work on this publication (see Research Portfolio Appendix). Since this chapter is only under review, I have revised some of the text for use in this thesis.

Abstract

Study Objective: Insufficient sleep is common in children and sleep duration has declined over the years. Intervention is needed to improve the sleep behaviour of children. Physical activity is often recommended as a strategy to improve sleep; however, previous research has often shown neutral or even negative results. The objective of this study was to determine the day-to-day and longer-term longitudinal associations between daytime physical activity and night-time sleep.

Methods: We used data from a two-year longitudinal study which included three time points (i.e., baseline, Year 1, and Year 2). Participants were recruited from primary schools and included 1,059 children (50% girls) with a mean age of 8.81-years-old (SD = 0.72) at baseline. Sleep variables included sleep duration, sleep efficiency, time in bed, sleep onset and wake time. Physical activity variables included light, moderate, moderate-to-vigorous, and vigorous physical activity as well as sedentary time. We objectively assessed physical activity and sleep behaviours using the GENEActiv wrist-worn accelerometer over an eight-day period at each timepoint for a potential 21,190 observed days.

Results: We used fixed-effects multilevel models and parallel latent growth curve modelling to examine day-to-day and longer-term associations, respectively. Day-to-day, physical activity and sleep variables were significantly, positively, and bidirectionally associated, except for sleep efficiency which showed little association with physical activity. Longer-term, we found little association between physical activity and sleep variables.

Conclusion: Overall, our findings indicate that there is a day-to-day association between the amount of time spent being physically active and improved sleep. The lack of a longer-term association indicates that a focus on children's daily behaviour may be most appropriate to help children improve sleep and increase physical activity.

Introduction

Inadequate physical activity and insufficient sleep are common in children (11, 12). Moreover, the amount of physical activity and sleep that children obtain has substantially declined over the years (38, 171). These trends are concerning for children's physical and mental well-being and have been linked with obesity, diabetes, cardiovascular disease, depression, poorer cognitive ability, and poorer academic performance when compared to children who are more active and sleep better (42, 68, 92-96). Twenty-four-hour movement behaviour guidelines recommend that children should obtain at least 60 minutes of moderate to vigorous physical activity, break up sedentary time as much as possible, and sleep between 9-11 hours per day (18). Given that many children do not meet these guidelines, investigating ways to improve adherence to the recommendations is warranted.

Recent research has investigated whether one day's participation in one movement behaviour is bidirectionally associated with participation in other movement behaviours (e.g., daytime physical activity and the following night of sleep) (122, 123, 172, 173). In other words, are children more likely to sleep better if they were more active during the day or are children more likely to be more active if they slept better the night before? The few studies that have examined day-to-day movement behaviours in children across one week have reported little (122) or negative (123, 172) associations between objectively measured physical activity and sleep. These findings are consistent with a recent meta-analysis which reported that there is little association between physical activity and sleep in children (128). The meta-analysis (128) also reported only one longer-term longitudinal study had been conducted among children. The one longitudinal study reported a positive association between physical activity and subjectively reported sleep disturbances across a school year (i.e., nine months with three-month lags) in 13-year-old girls (119). A positive longer-term association may suggest that there are habitual adaptations from movement behaviours that are not captured in day-to-day research studies. This discrepancy in findings among day-to-day and longer-term studies may be due to the study designs and measures or the difference in age of the participants. Thus, further research is needed to clarify the possible bidirectional relationship between physical activity and sleep.

The purpose of this study was to objectively examine the relationship between both day-to-day and longer-term (i.e., habitual) physical activity and sleep behaviour in children. Specifically, for day-to-day associations, does daytime physical activity predict improved sleep the following night and does sleep at night predict increased physical activity the following day? For longer-term associations, is there an association between habitual daytime physical activity patterns and habitual night-time sleep behaviour over time?

Methods

This paper is reported following the STROBE statement (174) which is presented in Appendix B.4.

Sample

I used data from the 'Internet-based Professional Learning to help teachers support Activity in Youth' (iPLAY) cluster randomized controlled trial (175). Three cohorts of Grade 3 and 4 children (ages 8-9-years-old) participated in iPLAY over a 3.5-year period. Within each cohort, children's physical activity, sedentary time, and sleep data at three time points over two years (i.e., baseline, 12-months follow-up, and 24-months follow-up) was collected. Data collection occurred between June 2016 and December 2019. Ethical approval to conduct the study was obtained from The NSW Department of Education and the Australian Catholic University Human Research Ethics Committee (Approval # 2014 185N; see Appendix D).

Measures

Daily physical activity, sedentary time, and sleep were measured using the wrist worn GENEActiv triaxial accelerometer (Activinsights, Cambridge, United Kingdom). Participants were asked to wear the accelerometer all day on their non-dominant wrist for a period of eight days with the only exception being during organized contact sports (e.g., rugby) when the device could pose a risk of injury. Data was sampled at a frequency of 87.5 Hz. The GENEActiv accelerometer has been validated for physical activity (176), sedentary time (177), and sleep (60, 61).

I used the R-package GGIR (ver. 1.10-7) in the R environment (ver. 3.6.1) to process the accelerometer data into 5-second epochs (148, 178). GGIR detects non-wear time and calculates physical activity intensities by converting the raw acceleration values into one omnidirectional value of acceleration. I used the Euclidian norm minus one with negative values set to zero (ENMONZ) metric of acceleration. For valid days, I calculated physical activity intensity variables based on ENMONZ value cut-points (176, 177): sedentary activity (0-56.3 mg), light-intensity physical activity (56.3-191.6 mg), moderate-intensity physical activity (191.6-695.8 mg), vigorous-intensity physical activity (greater than 695.8 mg), and moderate-to-vigorous physical activity (greater than 191.6 mg). For sleep detection, GGIR uses estimated change in arm angle relative to the horizontal plane. In this study, a change in arm angle of less than five degrees over a five-minute period was characterized as a possible sleep period (61). GGIR uses a heuristic algorithm based on the distribution of change in z-angle (HDCZA) to detect the total sleep window and any sleep interruptions without the use of a sleep diary (60). With this method, I calculated the following sleep variables: sleep duration (min/night), time in bed (min/night), sleep efficiency (TST/TIB*100), sleep onset (number of hours from previous midnight), and wake time (number of hours from previous day’s midnight). I included a day of participant data if the day had greater than 16 hours of valid wear time (60) and night-time sleep data were present. For the longer-term analyses, I used additional exclusion criteria to include only participants with at least four days, including one weekend day, of valid data defined as at least 16 hours valid wear time (84,

118) and night-time sleep data were present. I included all participants with valid data from at least one timepoint.

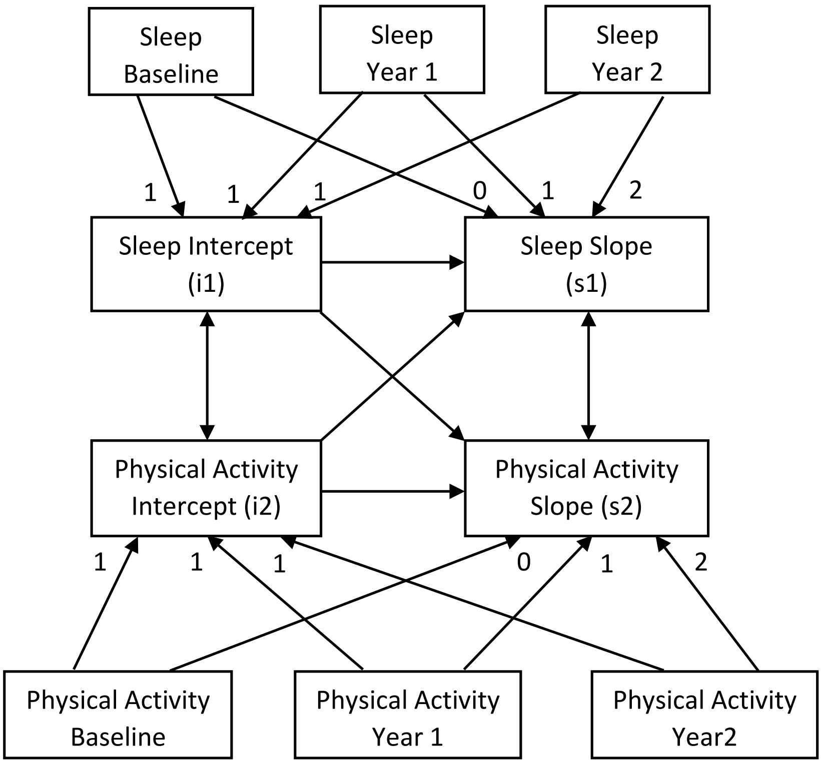
Statistical Analysis

Day-to-day analyses. I used multilevel models with lagged effects using the Linear Models for Panel Data (plm) R-package (179) to test the day-to-day associations between physical activity, sedentary time, and sleep variables. I used fixed-effects models to focus on the within-person variation. That is, fixed-effects models account for all between-person time-invariant variation and allows us to treat each individual as their own control. Therefore, using fixed effects allows us to examine how an individual's behaviour predicts changes in future behaviour.

The two-level models incorporated data from multiple timepoints (Level-1) nested within individuals (Level-2). For each physical activity outcome variable (i.e., light physical activity, moderate physical activity, vigorous physical activity, moderate-to-vigorous physical activity, and sedentary time), either sleep duration, sleep efficiency, time in bed, sleep onset, or wake time was the predictor variable and vice versa. There were, therefore, a total of 50 separate models (i.e., 25 predicting physical activity outcomes and 25 predicting sleep outcomes). To account for the relative and constrained nature of these data in the analyses, I converted physical activity variables from minutes per day to be analysed as proportions of daily wake time spent being active. I used a Bonferroni correction to account for multiple comparisons in the day-to-day analyses and considered a p value of <0.001 to be statistically significant. I controlled for total wear time in all fixed effects models as a within-person time-varying variable. I also controlled for sleep duration in sleep efficiency predicting next day physical activity models.

Longer-term analyses. I used parallel process latent growth curve models to analyse longer-term longitudinal associations between physical activity and sleep (180). Using this analytical method, I compared how changes in one variable over time (i.e., physical activity or sleep) are related to changes in another variable (i.e., sleep or physical activity). In other words, I modelled the trajectory of change in physical activity (i.e., growth process) in parallel with the trajectory of change in sleep. This process allows us to examine how both the intercept and growth of physical activity are related to both the intercept and growth of sleep (see Figure 3.1). Latent growth curve modelling accounts for both between-person and within-person variability to model change. I aggregated data at each time point within individuals by calculating a weighted mean of weekday and weekend data for each variable. For physical activity variables, I defined weekend days as Saturday and Sunday; however, for sleep variables, I defined weekend nights as Friday and Saturday night. All analyses used all available information. I determined model fit using the comparative fit index, root-mean-square error of approximation, and the Tucker-Lewis index (181). For the comparative fit index, values greater than 0.90 and 0.95 demonstrated good and excellent fit, respectively. For the root-mean-square error of approximation, values less than 0.10 and 0.05 demonstrated good fit and excellent fit, respectively. Finally, for the Tucker-Lewis index, a value greater than 0.95 indicated good model fit. Statistical significance was set as $p < .0006$ using a Bonferroni correction. I used the Latent Variable Analysis package (lavaan) within the R environment (ver. 3.6.2) to conduct the analyses (148, 182).

Figure 3.1 Parallel process growth model



Results

Preliminary Analyses

From 1,138 participants, there were 2,876 total participant observations (i.e., eight-day periods), covering a potential 23,008 individual days, across the three timepoints. First, I identified and removed days that did not meet wear time criteria (i.e., less than 16 valid wear time hours). I then calculated the interquartile range for physical activity, sleep variables, and ENMONZ values. I identified extreme outliers (i.e., 3*interquartile range +/- upper/lower quartile) in the data, suggesting accelerometer measurement error. Finally, I removed data for observations with accelerometer calibration errors including those indicated by extreme values. The final study sample consisted of 2,745 observations (i.e., eight-day periods) over three time points (i.e., baseline, 12-month follow-up, and 24-month follow-up) or a potential 21,960 individual days for the day-to-day analyses. I applied additional criteria (i.e., at least four valid days with at least one weekend day) to the data for the habitual analyses. Therefore, the final sample for the habitual analyses consisted of 2,119 observations.

Participant Characteristics

I present the participant characteristics descriptive data of each physical activity and sleep variable for each time point and for the overall sample in Table 3.1. I report the distributions of each variable in Supplementary Figure 3.1 in Appendix B.1. The number of participants declined over time as students moved to different schools, were absent from school during data collection, failed to return the accelerometer, or the accelerometer data was unusable (i.e., failed to record, accelerometer was returned broken, data could not be extracted, etc.).

Table 3.1 Participant characteristics and descriptive data for physical activity and sleep variables (n = number of observed days)

	All (n = 21,960 days)	**Baseline (n = 8,472 days)**	**Year 1 (n = 7,248 days)**	**Year 2 (n= 6,240 days)**
Number of Participant Observations (% male)	2,745 (49%)	1,059 (50%)	906 (49%)	780 (48%)
Age (years)	9.72 ± 1.08	8.81 ± 0.72	9.82 ± 0.71	10.83 ± 0.70
Light Physical Activity (min)	214.00 ± 53.51	220.89 ± 52.51	213.09 ± 53.00	204.35 ± 54.17
Moderate Physical Activity (min)	69.55 ± 31.12	73.72 ± 30.80	69.60 ± 31.58	62.94 ± 29.87
Vigorous Physical Activity (min)	13.34 ± 10.74	14.90 ± 11.11	13.46 ± 10.79	10.73 ± 9.51
Moderate-to-Vigorous Physical Activity (min)	83.14 ± 40.01	88.92 ± 39.79	83.32 ± 40.75	73.82 ± 37.59
Sedentary Time (min)	691.72 ± 126.13	666.54 ± 113.84	698.51 ± 127.29	724.81 ± 135.07
Sleep Duration (min)	455.88 ± 81.83	468.05 ± 72.85	449.27 ± 83.24	444.01 ± 91.14
Sleep Efficiency (%)	86.82 ± 5.67	86.53 ± 5.62	86.81 ± 5.69	87.33 ± 5.69
Time in Bed (min)	529.60 ± 86.71	545.00 ± 74.99	520.72 ± 90.84	515.46 ± 95.07
Sleep Onset (hours)*	22.00 ± 1.33	21.89 ± 1.25	22.01 ± 1.34	22.18 ± 1.43
Wake Time (hours)*	31.11 ± 1.07	31.06 ± 1.02	31.11 ± 1.06	31.20 ± 1.15

Note. Data are presented as mean ± (SD). * = Sleep onset and wake time in hours from the previous day's midnight.

Day-to-day Analyses

I show the results of the fixed effects panel models in Table 3.2 for sleep predicting next day physical activity and Table 3.3 for physical activity predicting the following night's sleep.

Sleep predicting next-day physical activity outcomes. I found statistically significant associations for all the models, except for the sleep efficiency models and the association between sleep duration and moderate physical activity. Increased sleep duration and time in bed both predicted an increase in all physical activity outcomes and a decrease in proportion of time spent sedentary the next day. Similarly, earlier sleep onset and earlier wake time predicted a greater proportion of time spent being active at all intensity levels and a decrease in time spent sedentary the following day.

Table 3.2 Fixed effects models of sleep predicting next-day physical activity outcomes

Predictor	Outcome	Std. Beta	SE	*p* Value
Sleep Duration (min)	Light Physical Activity (% of wake time)	0.032	0.037	<0.001
Sleep Duration (min)	Moderate Physical Activity (% of wake time)	0.022	0.020	0.014
Sleep Duration (min)	Moderate to Vigorous Physical Activity (% of wake time)	0.028	0.026	<0.001
Sleep Duration (min)	Vigorous Physical Activity (% of wake time)	0.045	0.007	<0.001
Sleep Duration (min)	Sedentary Time (% of wake time)	-0.034	0.057	<0.001
Sleep Efficiency (%)[a]	Light Physical Activity (% of wake time)	-0.007	0.010	0.480
Sleep Efficiency (%)[a]	Moderate Physical Activity (% of wake time)	-0.180	0.006	0.061
Sleep Efficiency (%)[a]	Moderate to Vigorous Physical Activity (% of wake time)	-0.019	0.007	0.060
Sleep Efficiency (%)[a]	Vigorous Physical Activity (% of wake time)	-0.012	0.002	0.220
Sleep Efficiency (%)[a]	Sedentary Time (% of wake time)	0.014	0.016	0.187
Time in Bed (min)	Light Physical Activity (% of wake time)	0.039	0.034	<0.001
Time in Bed (min)	Moderate Physical Activity (% of wake time)	0.037	0.019	<0.001
Time in Bed (min)	Moderate to Vigorous Physical Activity (% of wake time)	0.042	0.024	<0.001
Time in Bed (min)	Vigorous Physical Activity (% of wake time)	0.049	0.006	<0.001
Time in Bed (min)	Sedentary Time (% of wake time)	-0.046	0.052	<0.001
Sleep Onset (hours)	Light Physical Activity (% of wake time)	-0.101	0.044	<0.001
Sleep Onset (hours)	Moderate Physical Activity (% of wake time)	-0.094	0.025	<0.001
Sleep Onset (hours)	Moderate to Vigorous Physical Activity (% of wake time)	-0.098	0.032	<0.001
Sleep Onset (hours)	Vigorous Physical Activity (% of wake time)	-0.087	0.008	<0.001
Sleep Onset (hours)	Sedentary Time (% of wake time)	0.114	0.069	<0.001
Wake Time (hours)	Light Physical Activity (% of wake time)	-0.145	0.051	<0.001
Wake Time (hours)	Moderate Physical Activity (% of wake time)	-0.097	0.029	<0.001
Wake Time (hours)	Moderate to Vigorous Physical Activity (% of wake time)	-0.089	0.037	<0.001

Wake Time (hours)	Vigorous Physical Activity (% of wake time)	-0.051	0.010	<0.001
Wake Time (hours)	Sedentary Time (% of wake time)	0.138	0.079	<0.001

Note. All models controlled for accelerometer wear time. [a] = model adjusted for wear time and sleep duration. Statistically significance was set at p <0.001. Effect sizes represent changes in SD units, for example, one SD unit change in sleep duration is associated with a 0.032 SD unit increase in light physical activity.

Physical activity predicting the following night's sleep outcomes. All physical activity variables were statistically significantly associated with the following night's sleep duration, time in bed, and sleep onset. That is, an increase in the proportion of time spent active at any intensity and a decrease in the time spent sedentary were associated with longer sleep duration, longer time in bed, and earlier sleep onset. Physical activity was not associated with sleep efficiency the following night. Physical activity was also generally not associated with the next day's waketime, as only increases in the proportion of time spent in vigorous physical activity was associated with earlier wake times.

Table 3.3 Fixed effects models of physical activity predicting sleep outcomes the following night

Predictor	Outcome	Std. Beta	SE	*p* Value
Light Physical Activity (% of wake time)	Sleep Duration (min)	0.327	0.002	<0.001
Light Physical Activity (% of wake time)	Sleep Efficiency (%)	0.024	0.008	0.003
Light Physical Activity (% of wake time)	Time in Bed (min)	0.271	0.002	<0.001
Light Physical Activity (% of wake time)	Sleep Onset (hours)	-0.163	0.002	<0.001
Light Physical Activity (% of wake time)	Wake Time (hours)	0.000	0.002	0.984
Moderate Physical Activity (% of wake time)	Sleep Duration (min)	0.203	0.004	<0.001
Moderate Physical Activity (% of wake time)	Sleep Efficiency (%)	0.014	0.015	0.087
Moderate Physical Activity (% of wake time)	Time in Bed (min)	0.182	0.004	<0.001
Moderate Physical Activity (% of wake time)	Sleep Onset (hours)	-0.129	0.004	<0.001
Moderate Physical Activity (% of wake time)	Wake Time (hours)	-0.017	0.003	0.075
Moderate to Vigorous Physical Activity (% of wake time)	Sleep Duration (min)	0.195	0.003	<0.001
Moderate to Vigorous Physical Activity (% of wake time)	Sleep Efficiency (%)	0.013	0.012	0.135
Moderate to Vigorous Physical Activity (% of wake time)	Time in Bed (min)	0.179	0.003	<0.001
Moderate to Vigorous Physical Activity (% of wake time)	Sleep Onset (hours)	-0.137	0.003	<0.001
Moderate to Vigorous Physical Activity (% of wake time)	Wake Time (hours)	-0.026	0.002	0.007
Vigorous Physical Activity (% of wake time)	Sleep Duration (min)	0.134	0.012	<0.001
Vigorous Physical Activity (% of wake time)	Sleep Efficiency (%)	0.005	0.044	0.580
Vigorous Physical Activity (% of wake time)	Time in Bed (min)	0.138	0.013	<0.001
Vigorous Physical Activity (% of wake time)	Sleep Onset (hours)	-0.134	0.011	<0.001

Vigorous Physical Activity (% of wake time)	Wake Time (hours)	-0.042	0.009	<0.001
Sedentary Time (% of wake time)	Sleep Duration (min)	-0.294	0.001	<0.001
Sedentary Time (% of wake time)	Sleep Efficiency (%)	-0.021	0.005	0.009
Sedentary Time (% of wake time)	Time in Bed (min)	-0.251	0.002	<0.001
Sedentary Time (% of wake time)	Sleep Onset (hours)	0.164	0.001	<0.001
Sedentary Time (% of wake time)	Wake Time (hours)	0.012	0.001	0.204

Note. All models controlled for accelerometer wear time. Statistically significance was set at p <0.001. Effect sizes represent changes in SD units, for example, one SD unit change in light physical activity is associated with a 0.327 SD unit increase in sleep duration.

Longer-term Analyses

The results of the parallel process growth models (see Figure 3.1) used in the analyses are shown in Table 3.4. Due to errors with convergence among the light physical activity and sedentary time variables, I did not include these models. I report plots for the trajectories of change of all variables in Supplementary Figure 3.2 in Appendix B.2.

Table 3.4 Parallel process latent growth model results

	Moderate Physical Activity (min)			**Moderate-to-Vigorous Physical Activity (min)**			**Vigorous Physical Activity (min)**		
	Std. Est. (r)	Std. Error	p value	Std. Est. (r)	Std. Error	p value	Std. Est. (r)	Std. Error	p value
Sleep Duration (min)									
s2 on i1	0.027	0.037	0.834	0.014	0.043	0.908	-0.009	0.009	0.950
s1 on i2	0.089	0.114	0.783	-0.063	0.087	0.847	-0.381	0.355	0.258
s1 with s2	-0.333	0.004	0.397	-0.246	0.005	0.516	-0.206	0.001	0.706
i1 with i2	-0.118	0.013	0.253	-0.087	0.016	0.387	0.024	0.004	0.814
s1 on i1	0.372	0.174	0.557	0.343	0.172	0.589	0.252	0.166	0.673
s2 on i2	-0.351	0.048	0.007	-0.377	0.045	0.003	-0.516	0.051	0.011
Sleep Efficiency (%)									
s2 on i1	-0.020	0.132	0.783	-0.027	0.165	0.706	-0.015	0.051	0.901
s1 on i2	-0.036	0.005	0.722	-0.034	0.004	0.739	-0.046	0.016	0.686
s1 with s2	-0.021	0.690	0.865	-0.017	0.833	0.887	-0.021	0.199	0.902
i1 with i2	-0.129	4.824	0.072	-0.159	6.009	0.021	-0.233	1.587	0.000*
s1 on i1	-0.341	0.052	0.092	-0.340	0.053	0.096	-0.342	0.054	0.112
s2 on i2	-0.346	0.049	0.011	-0.375	0.047	0.004	-0.524	0.054	0.019
Time in Bed (min)									
s2 on i1	0.007	0.028	0.947	-0.009	0.044	0.940	-0.076	0.584	0.590
s1 on i2	0.048	0.103	0.613	-0.156	0.089	0.650	-0.519	0.007	0.157
s1 with s2	-0.107	0.004	0.367	-0.169	0.005	0.636	0.080	0.077	0.885
i1 with i2	0.024	0.012	0.810	0.103	0.016	0.339	0.313	0.248	0.000*
s1 on i1	-0.302	0.118	0.041	-0.163	0.263	0.861	-0.221	0.246	0.770
s2 on i2	-0.343	0.049	0.013	-0.368	0.047	0.006	-0.485	0.057	0.028
Sleep Onset (hours)									
s2 on i1	-0.119	0.839	0.276	-0.115	0.017	0.249	-0.153	0.284	0.297
s1 on i2	-0.172	0.001	0.499	-0.058	0.063	0.815	0.051	0.005	0.855
s1 with s2	-0.018	0.186	0.958	-0.103	0.004	0.737	0.087	0.058	0.852

i1 with i2	-0.093	1.175	0.279	-0.147	0.025	0.075	-0.282	0.383	0.000*
s1 on i1	-0.190	0.040	0.507	-0.188	0.040	0.520	-0.185	0.041	0.536
s2 on i2	-0.281	0.063	0.166	-0.346	0.059	0.056	-0.536	0.067	0.066
Wake Time (hours)									
s2 on i1	-0.069	0.017	0.535	-0.079	0.020	0.426	-0.157	0.005	0.160
s1 on i2	0.011	0.072	0.921	-0.030	0.053	0.782	-0.148	0.213	0.181
s1 with s2	-0.320	9.656	0.039	-0.238	11.150	0.071	0.016	2.435	0.921
i1 with i2	-0.091	65.374	0.310	-0.104	82.003	0.228	-0.109	21.375	0.198
s1 on i1	-0.321	0.057	0.095	-0.330	0.057	0.081	-0.353	0.057	0.056
s2 on i2	-0.290	0.063	0.137	-0.352	0.057	0.040	-0.520	0.062	0.033

*Statistically significant at p <.0006
i1 = intercept for sleep variable
i2 = intercept for physical activity variable
s1 = slope for sleep variable
s2 = slope for physical activity variable
with = covariance path
on = regression path

For the covariances between change in physical activity and change in sleep over time (s1 with s2), no significant associations were found between any physical activity and sleep variables. The little association found in these results indicated that sleep and physical activity generally did not change together over time.

The covariances between initial physical activity and initial sleep (i1 with i2) showed several significant associations. In contrast to the day-to-day analyses, initial sleep efficiency was negatively associated with initial moderate-to-vigorous physical activity and vigorous physical activity. These results indicate that children with higher sleep efficiency were associated with significantly less moderate-to-vigorous and vigorous physical activity. Initial vigorous physical activity was also associated with significantly longer initial time in bed and earlier initial sleep onset. No other significant associations were found between physical activity variables and sleep variables.

Discussion

This chapter aimed to examine the nature of the relationship between physical activity and sleep in children. I examined both day-to-day and longer-term physical activity and sleep behaviours of children aged 7-12-years-old. This is the first study to investigate both day-to-day and longer-term longitudinal associations within the same sample of children.

The day-to-day findings indicated that physical activity and sleep were significantly and positively related. Increased physical activity, at all intensity levels, was associated with longer sleep duration, longer time in bed, earlier bedtime, and earlier wake time the following night. These associations may also be practically meaningful. For example, a 1% increase (i.e., about 10 minutes) in wake time spent in vigorous physical activity was associated with an increase of about 10 minutes in sleep duration (β = .134), 11 minutes of time in bed (β = .138), 13 minutes earlier sleep onset (β = -.134), and 3 minutes earlier waketime the next day (β = -.042). These same sleep variables were also associated with an increase in time spent being physically active the following day. However, sleep efficiency, as a predictor and as an outcome, showed little association with changes in physical activity or sedentary time.

These positive associations are inconsistent with other similar studies in children. One study reported no day-to-day associations (122), while others have shown negative associations for some physical activity and sleep variables (123, 172). While these studies' samples are similar in age (i.e., 6-12 years-old), the use of one device (albeit different devices) to objectively measure both physical activity and sleep, and measurement days protocol (i.e., 7-8 days), there may be some important differences in methods that impact their findings. For example, each study used different wear time criteria for number of days (e.g., 2-7 days), number of hours/day (e.g., 10-16 hours/day or no criteria), and whether one weekend day was required. Additionally, only one study controlled for wear time in their analyses (122). I used 16 hours/day (60) but included all days meeting that criteria. This protocol allowed my analyses to use all available valid data while controlling for wear time. More research, however, is needed to clarify the optimal wear time criteria for this research or if it varies by device and sleep detection algorithm used (55, 183).

The longer-term findings are also inconsistent with previous research. This study, which is the first longer-term longitudinal investigation of physical activity and sleep in children using device-measured outcomes, found that there is little association between habitual physical activity and sleep behaviours over a two-year period. Raudsepp (119), however, used a similar analysis but employed subjective measures of physical activity and sleep disturbances, found a positive association. That is, increases in reported physical activity was associated with decreases in reported sleep disturbances over nine months. A possible reason for my different findings is the use of objective rather than subjective measures of physical activity and sleep which are susceptible to recall and reporting bias (44).

The day-to-day and longer-term findings seem to be inconsistent with each other. One possible explanation is that day-to-day variation of behaviour is greater than average weekly variation of behaviour across timepoints. To examine this, I compared the average individual standard deviation of physical activity and sleep variables within weeks and within timepoints (see Supplementary Table 3.1 in Appendix B.3). There was less variance within timepoints than within weeks, meaning there was less variance to predict in the longer-term models. More frequent observations may be needed to capture long term variation in physical activity and sleep.

Nevertheless, my findings suggest that these behaviours may need to be emphasized daily to achieve the best health outcomes and supports the clinical recommendation that physical activity may improve sleep behaviour in children (103). My findings also suggest that physical activity and sleep may be reciprocally associated in children (97), and that promoting improvements in one behaviour may have positive implications for the other. Interventions for meeting movement behaviour guidelines, including physical activity and sleep (184), should consider strategies that promote earlier sleep onset, improve consistency of sleep timing, and increase sleep duration and physical activity to improve both physical activity and sleep bidirectionally.

The strengths of this study include the large sample size and the use of both day-to-day data in fixed-effects multilevel models and two-year longitudinal data in parallel process growth models. The fixed-effects models allowed us to specifically examine individual level changes from one day to the next, while parallel process growth modelling allowed me to account for both between- and within-person variation and examine the bidirectional association of physical activity and sleep over a two-year period. Taken together, we get a more complete picture of the relationship between physical activity and sleep in children. I also examined a variety of sleep variables including, duration, efficiency, and timing. Previous research has discussed the need to investigate a variety of sleep dimensions and not just sleep duration (122, 185).

This study also has some limitations. It is unknown how long the appropriate amount of lag between measures should be for long-term longitudinal analyses between physical activity and sleep. Moreover, I have assumed that one-week of accelerometer-derived movement behaviour data is enough to represent habitual movement behaviour for a child at that time. While studies have reported that one-week of data is typically enough to establish reliable estimates of physical activity and sleep (66, 87), it is unknown how stable these estimates are over time. Finally, while accelerometers are considered valid measures of movement behaviours (60, 81, 83) and wrist-worn devices tend to achieve greater wear time compliance (59), some devices malfunctioned during data collection, were lost or broken, or did not meet wear time criteria, resulting in data loss. Therefore, I do not have complete data for all participants at all timepoints which may influence my findings.

Conclusion

This study contributes to a growing body of knowledge of the day-to-day and longer-term relationship between physical activity and sleep in children and provides the first objectively measured longer-term longitudinal study in children. Generally, I found positive associations between day-to-day physical activity and sleep, but little association over time. These findings were largely inconsistent with previous research in this area. Further research is needed to confirm these findings, especially longer-term longitudinal studies. Overall, our findings suggest that day-to-day physical activity and sleep are bidirectionally but weakly associated in children and regular, short-term interventions, which target both behaviours, may be needed to help children sustainably improve sleep and increase physical activity levels.

Chapter 4 | Reliability of GENEActiv Accelerometers for Estimating Physical Activity and Sleep in Children: How Many Days and Hours are Needed?

Preface

This study has not yet been submitted for publication, but I plan to submit soon to the journal of Medicine and Science in Sport and Exercise (IF = 4.478). While I recognise that reliability of estimates is an important issue, I originally planned a different study to include as a chapter of my thesis. The chapter would have examined the validity of the GENEActiv accelerometer to estimate sleep outcomes in children. Briefly, the rationale was that this method has been validated only in older adults (60, 61), but the validity is not known for use with children. I assumed validity for Chapter 3, and the current chapter, based on the adult sample studies and I discuss this limitation in Chapter 5. With the validation study, I experienced slower than anticipated recruitment which lead to data collection being delayed until earlier this year. Then, when restrictions related to the COVID-19 pandemic banned all face-to-face data collection, I could not complete the study before my thesis submission deadline. Nevertheless, I believe this "Plan B" Chapter addresses an important issue and makes a meaningful contribution to the field.

Abstract

Reliable estimates of habitual sleep and physical activity are essential for research that investigates the associations between these behaviours and health outcomes. While the number of days needed and hours/day for estimates of physical activity are generally known, the criteria for sleep estimates are more uncertain. The objective of this study was to identify the number of nights needed to obtain reliable estimates of habitual sleep behaviour in children using the GENEActiv wrist worn accelerometer. The number of days to obtain reliable estimate of physical activity was also examined. Data was used from a two-year longitudinal study that included three waves of measurement at baseline, 12-month follow-up and 24-month follow-up. At each wave, children wore an accelerometer for potentially 8 days 24 hours/day. The sample included all observations for a total of 2,745 children (51% girls) between the ages of 7-12-years-old (mean = 9.8 years, SD = 1.1 year) with at least one day of valid accelerometer data from any wave of data collection. Reliability estimates were calculated for sleep duration, sleep efficiency, sleep onset, wake time, time in bed, light physical activity, moderate physical activity, moderate-to-vigorous physical activity, vigorous physical activity, and sedentary time. Intraclass correlations and the Spearman Brown prophecy formula were used to determine the nights and days needed for reliable estimates. Estimates varied depending on the outcome of interest. I found that between 3 and 5 nights were needed to achieve acceptable reliability (ICC = 0.7) in sleep outcomes and physical activity outcomes required between 3 and 4 days. Future studies examining habitual movement behaviours, such as sleep and physical activity, should consider these criteria when designing their studies and prepare strategies to improve wear time compliance to ensure reliable estimates are obtained.

Introduction

Accelerometers are valuable devices for measuring free-living movement behaviours, such as physical activity (186) and sleep (51). These devices can provide detailed information about 24-hour behaviour across several days, are feasible for large scale studies, and are less prone to biases and error compared to time-use-diaries which require participant recall (44, 55, 81, 82). While estimates for the number of days to achieve reliable physical activity estimates are generally known (84-87, 187, 188), few studies have examined how many days are needed to reliably estimate habitual sleep using accelerometers (64-66). Reliable estimates of habitual sleep and physical activity are essential for research that investigates the associations between these behaviours and health outcomes.

Most studies examining how many days are required to estimate habitual physical activity report that 2-7 days are appropriate depending on the activity intensity, type of accelerometer, and position of wear (87). Some studies also indicate that one or two weekend days are required as well (84-86, 187, 188). Still, a recent review of accelerometer use in youth physical activity studies showed a wide range of criteria have been applied in this research. The review reported eight different minimum wear day criteria ranging between 1-10 days have been used (87). However, a rough consensus appears to be a 7-day protocol to achieve a 4-day minimum of valid days.

The few studies that have reported reliabilities for sleep outcomes in children show that sleep variables may typically need more days than physical activity outcomes to achieve acceptable reliability. Ridgers et al. (65), using the Sensewear armband worn on the upper arm, found the 6 and 7 nights were needed to achieve moderate reliability in sleep duration and time in bed in 8-11-year-old children. Taylor et al. (66), reported 4-7 nights were needed to achieve moderate reliability for sleep duration, sleep efficiency, sleep onset, and wake time for 7-year-old children when employing actigraphy on the hip. Meanwhile, Acebo et al. (64), reported that 3-6 nights are acceptable for 5-year-olds for the same sleep outcomes when measured using actigraphy on the wrist. Wrist-worn devices have been shown to promote greater wear time compliance than the hip which may lead to more reliable estimates (59).

There is considerable difference in recommended number of nights across these previous studies which has important implications for research measurement protocols. Furthermore, none of the studies applied inclusion criteria to their sleep data, instead considering a night valid when there is data recorded (64, 65). Finally, there are no studies that have examined the reliability of sleep estimates using the GENEActiv wrist worn accelerometer. The GENEActiv accelerometer is relatively new but increasingly popular amongst movement behaviours researchers (189). Therefore, given the limited and varied findings for reliabilities of sleep outcomes, the lack of inclusion criteria applied to sleep estimates in previous research, and the unknown reliability of using the GENEActiv accelerometer in children, further examination of the reliability of physical activity and sleep estimates in children is warranted.

Purpose

The purpose of this study was to investigate the optimal number of nights and valid percentage per night needed to obtain reliable estimates of habitual sleep behaviour (i.e., sleep duration, sleep efficiency, time in bed, sleep onset, and wake time) using accelerometry in children. I also investigated the number of days and hours per day needed to obtain reliable estimates of habitual weekly physical activity and sedentary time.

Methods

Participants

The data comes from the ‘Internet-based Professional Learning to help teachers support Activity in Youth’ (iPLAY) cluster randomized controlled trial (175). Data were collected from primary school children starting in Grade 3 and 4 with follow-up data collection in the following two years (i.e., one-year follow-up and two-year follow-up). For each data collection, the participants wore an accelerometer for eight days. The initial sample included 1,217 children at baseline, 1,027 children at one-year follow-up, and 925 children at two-year follow-up for a total of 3,169 observations or a possible 25,352 monitored days. The Australian Catholic University Research Ethics Committee approved the study (Approval # 2014 185N) and written consent was obtained from all parents/guardians prior to participation (see Appendix D). Data collected occurred between July 2016 and December 2019.

Accelerometer Data

Daily sleep and physical activity were measured using the wrist worn GENEActiv triaxial accelerometer (Activinsights, Cambridge, United Kingdom). I distributed accelerometers to consenting students during their school day and asked teachers to collect the devices immediately after the scheduled monitoring period (i.e., eight days). I asked participants to only remove the accelerometer during contact sports when the device could be a risk of injury, otherwise that the device should be worn on their non-dominant wrist 24 hours/day. The accelerometers were set to sample at a frequency of 87.5 Hz and data were stored in 5-second epochs.

I extracted the accelerometer data using the GENEActiv PC Software (ver. 3.3) and processed and analysed the data using R-package GGIR (ver. 1.10-7; 178) in the R environment (ver. 3.6.1; 148). GGIR was developed for GENEActiv accelerometers and uses raw acceleration ENMONZ values (i.e., Euclidian norm minus one with negative values set to zero) with validated cut-points to determine intensity of physical activity (176, 177). I measured the following physical activity variables: sedentary activity (0-56.3 mg), light-intensity physical activity (56.3-191.6 mg), moderate-intensity physical activity (191.6-695.8

mg), vigorous-intensity physical activity (greater than 695.8 mg), and moderate-to-vigorous physical activity (greater than 191.6 mg).

For sleep detection, GGIR identifies periods of sustained inactivity where there is a smaller change in arm angle than a predefined threshold (61). In this study, I defined the threshold parameters as a change in arm angle of five degrees over a five-minute period (60). These thresholds have shown good accuracy for sleep detection compared to polysomnography, the gold-standard sleep measure. I measured the following sleep variables: sleep duration, sleep efficiency, time in bed, sleep onset, and wake time.

GGIR also estimates non-wear time for periods of sustained low acceleration. This is determined by the characteristics of 15-minute blocks within a 60-minute window or by the value range of raw acceleration. That is, blocks are classified as non-wear time when the standard deviation of a window is less than 13mg or the value range is less than 50mg for at least two of the three axes of acceleration. GGIR can then impute this missing data based on average ENMONZ values from similar timepoints on other days. GGIR provides two estimates to determine valid wear time: number of valid hours and fraction of the night invalid (%). In this study, I converted the fraction night invalid variable to reflect percentage night valid (i.e., I converted fraction night invalid = .25 to 75% valid). I used valid hours and percentage night valid as criteria for the reliability scores to present ranges of reliability when including 1-24 hours/day of valid data for physical activity variables and 50-100% valid nights for sleep variables. I included all returned accelerometers with extractable data in the analysis.

Statistical Analysis

I conducted all analyses using R (ver. 3.6.3; 148). To assess reliability, I calculated intraclass correlation coefficients (ICC2) using two-way mixed effects, absolute agreement, single measurement models (190) using the R-package psych (191) for all included variables.

The ICC is a common method to assess the agreement of measures ranging from 0 to 1.0 where 1.0 indicates perfect reliability or that the variation is all between-subject variation and not within-subjects. ICC values less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9, and greater than 0.9 can be interpreted as poor, moderate, good, and excellent reliability, respectively (192).

I calculated single measurement ICC values, or single day ICC values, for all combinations of inclusion criteria. That is, for physical activity, I calculated a single day ICC for hourly increments starting at a minimum of 1 hour to a maximum of 24 hours of wear time for every two, three, four, five, six, and seven valid days of data. I randomly sampled days from participants meeting the criteria. For example, I calculated one single day ICC value for the criteria of 10 hours/day by taking the average ICC value of six ICC values from 2-7 randomly sample days. In addition, because the days were randomly sampled which resulted in slight variations in ICC values, I repeated the random sampling five times and used the average value. This method was repeated for each criteria and each variable and has been used previously for other recent reliability studies (65, 193). For sleep variable ICC values, I used a similar process; however, I instead used six criteria for percentage night valid from 50, 60, 70, 80, 90, and 100% from 2-7 randomly sampled days of valid data.

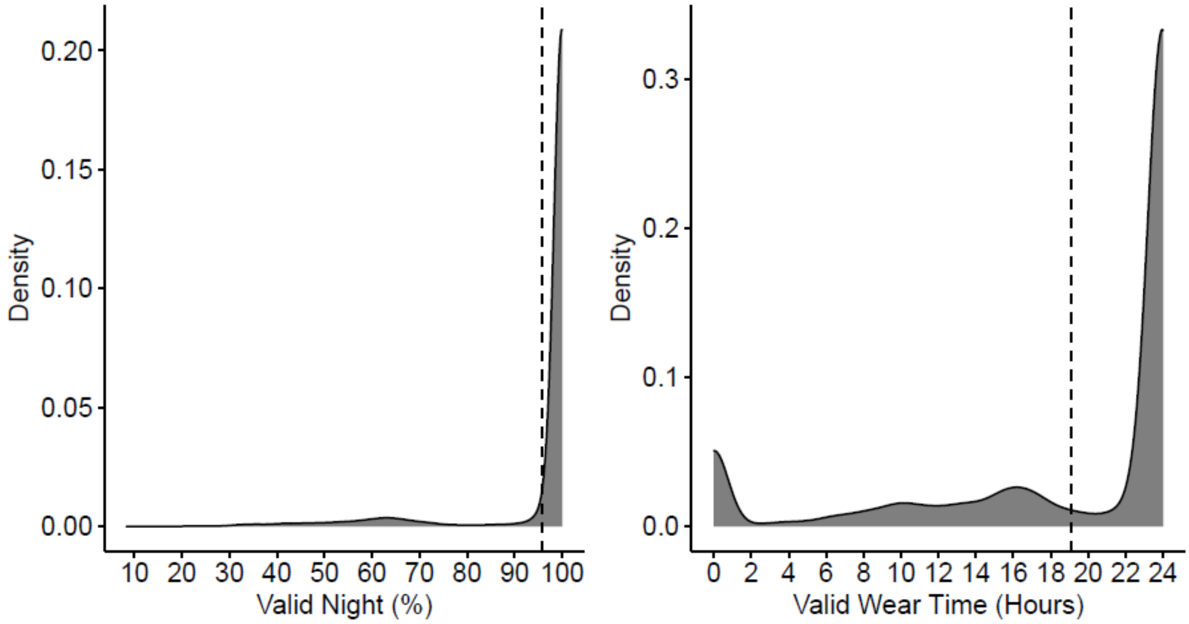
I then used the single day ICC values with the Spearman-Brown prophecy formula to determine the number of valid measurement days needed to obtain reliability scores of 0.7, 0.8, and 0.9 (194).

Results

Preliminary Analyses

First, I checked the data for calibration errors and device malfunction. I found extreme outliers (i.e., 3*interquartile range +/- upper/lower quartile) for all outcome variables and for ENMONZ values of acceleration suggesting device error and I removed these cases. I present the distributions of sleep and physical activity outcomes in Appendix C.1 Supplementary Figure 4.1. The final sample consisted of 2,745 children (51% girls) between the ages of 7-12-years-old (mean = 9.8 years, SD = 1.1 year) with at least one day of valid accelerometer data. I then examined the valid wear time and percentage night valid criteria. I show the density plots for each criterion variable in Figure 4.1. This sample showed very good accelerometer wear time compliance. The average wear time/day was 19.1 hours (SD = 7.9 hours) and the average percentage night valid was 95.8% (SD = 1.3%).

Figure 4.1 Density plots of the distributions for the sleep criterion percentage night valid (left) and the physical activity criterion for valid wear time (right).
----- = average value



Physical Activity Outcomes

I present the single day ICC values, number of days needed to achieve 0.7, 0.8, and 0.9 reliability scores for the physical activity and sedentary time outcomes, and the number of participants in the sample that met reliabilities of 0.7 and 0.8 in Table 4.1. There was little variation in single day ICC values across all valid wear time criteria for each outcome. Single day ICC values only consistently improved with increased wear time for vigorous physical activity and, for the other variables, tended to be the weakest by a small margin between 13-16 hours of wear time.

Table 4.1 ICC values and number of days needed to achieve 0.7, 0.8, and 0.9 reliability estimates for physical activity and sedentary time outcomes

Minimum Wear Time Criteria (Hours)	Single Day ICC	95% CI	Number of days to achieve reliabilities of			Number (%) of children meeting reliabilities of	
			0.7	0.8	0.9	0.7	0.8
Light Physical Activity							
1	0.47	0.45, 0.49	2.6	4.5	10.1	2646 (96.4)	2475 (90.2)
2	0.47	0.45, 0.49	2.6	4.5	10.2	2646 (96.4)	2475 (90.2)
3	0.47	0.45, 0.49	2.6	4.5	10.1	2639 (96.1)	2472 (90.1)
4	0.47	0.45, 0.49	2.6	4.5	10.2	2639 (96.1)	2472 (90.1)
5	0.47	0.45, 0.49	2.7	4.5	10.2	2639 (96.1)	2471 (90.0)
6	0.47	0.45, 0.49	2.6	4.5	10.2	2639 (96.1)	2469 (89.9)
7	0.46	0.44, 0.48	2.7	4.7	10.5	2639 (96.1)	2469 (89.9)
8	0.45	0.43, 0.47	2.8	4.8	10.9	2639 (96.1)	2468 (89.9)
9	0.44	0.42, 0.46	3.0	5.1	11.5	2639 (96.1)	2332 (85.0)
10	0.44	0.42, 0.46	3.0	5.1	11.4	2639 (96.1)	2332 (85.0)
11	0.44	0.42, 0.46	2.9	5.0	11.3	2637 (96.1)	2466 (89.8)
12	0.44	0.43, 0.46	2.9	5.0	11.3	2637 (96.1)	2466 (89.8)
13	0.44	0.42, 0.46	3.0	5.1	11.4	2637 (96.1)	2332 (85.0)
14	0.44	0.42, 0.46	3.0	5.2	11.6	2637 (96.1)	2332 (85.0)
15	0.43	0.41, 0.45	3.1	5.2	11.8	2565 (93.4)	2332 (85.0)
16	0.43	0.41, 0.45	3.1	5.3	11.9	2564 (93.4)	2330 (84.9)
17	0.43	0.41, 0.45	3.0	5.2	11.7	2635 (96.0)	2330 (84.9)
18	0.44	0.42, 0.46	3.0	5.1	11.5	2634 (96.0)	2329 (84.8)
19	0.44	0.42, 0.46	3.0	5.1	11.5	2634 (96.0)	2329 (84.8)
20	0.45	0.43, 0.47	2.9	5.0	11.2	2634 (96.0)	2463 (89.7)
21	0.45	0.43, 0.47	2.8	4.9	11.0	2634 (96.0)	2462 (89.7)
22	0.45	0.43, 0.47	2.8	4.9	10.9	2634 (96.0)	2462 (89.7)
23	0.46	0.43, 0.48	2.8	4.8	10.7	2633 (95.9)	2462 (89.7)
24	0.46	0.44, 0.48	2.8	4.7	10.6	2633 (95.9)	2462 (89.7)
Moderate Physical Activity							
1	0.47	0.45, 0.49	2.6	4.5	10.2	2649 (96.5)	2479 (90.3)
2	0.47	0.45, 0.49	2.6	4.5	10.1	2649 (96.5)	2479 (90.3)
3	0.47	0.45, 0.49	2.7	4.5	10.2	2642 (96.2)	2476 (90.2)
4	0.46	0.45, 0.48	2.7	4.6	10.4	2642 (96.2)	2476 (90.2)
5	0.46	0.45, 0.48	2.7	4.6	10.4	2642 (96.2)	2475 (90.2)
6	0.46	0.44, 0.48	2.7	4.7	10.5	2642 (96.2)	2473 (90.1)
7	0.46	0.44, 0.48	2.8	4.7	10.6	2642 (96.2)	2473 (90.1)
8	0.45	0.43, 0.47	2.8	4.9	11.0	2642 (96.2)	2472 (90.1)
9	0.45	0.43, 0.46	2.9	5.0	11.2	2642 (96.2)	2472 (90.1)
10	0.45	0.43, 0.46	2.9	5.0	11.2	2642 (96.2)	2472 (90.1)
11	0.44	0.42, 0.46	3.0	5.1	11.5	2640 (96.2)	2337 (85.1)
12	0.43	0.42, 0.45	3.0	5.2	11.7	2640 (96.2)	2337 (85.1)
13	0.43	0.41, 0.45	3.1	5.3	11.9	2567 (93.5)	2337 (85.1)
14	0.43	0.41, 0.45	3.1	5.3	11.9	2567 (93.5)	2337 (85.1)

15	0.43	0.41, 0.45	3.1	5.3	12.0	2567 (93.5)	2337 (85.1)
16	0.43	0.41, 0.45	3.1	5.3	11.8	2566 (93.5)	2335 (85.1)
17	0.43	0.41, 0.45	3.0	5.2	11.7	2638 (96.1)	2335 (85.1)
18	0.44	0.42, 0.46	3.0	5.1	11.5	2637 (96.1)	2334 (85.0)
19	0.44	0.42, 0.46	2.9	5.0	11.4	2637 (96.1)	2467 (89.9)
20	0.44	0.42, 0.46	3.0	5.1	11.5	2637 (96.1)	2334 (85.0)
21	0.44	0.42, 0.46	2.9	5.0	11.3	2637 (96.1)	2466 (89.8)
22	0.44	0.42, 0.47	2.9	5.0	11.3	2637 (96.1)	2466 (89.8)
23	0.44	0.42, 0.46	3.0	5.1	11.4	2636 (96.0)	2332 (85.0)
24	0.44	0.42, 0.46	2.9	5.0	11.4	2636 (96.0)	2466 (89.8)
Moderate to Vigorous Physical Activity							
1	0.46	0.45, 0.48	2.7	4.6	10.4	2649 (96.5)	2479 (90.3)
2	0.46	0.44, 0.48	2.7	4.7	10.5	2649 (96.5)	2479 (90.3)
3	0.46	0.44, 0.48	2.7	4.7	10.5	2642 (96.2)	2476 (90.2)
4	0.46	0.45, 0.48	2.7	4.6	10.4	2642 (96.2)	2476 (90.2)
5	0.46	0.44, 0.48	2.7	4.7	10.6	2642 (96.2)	2475 (90.2)
6	0.46	0.44, 0.48	2.8	4.7	10.6	2642 (96.2)	2473 (90.1)
7	0.45	0.44, 0.47	2.8	4.8	10.8	2642 (96.2)	2473 (90.1)
8	0.45	0.43, 0.47	2.8	4.9	10.9	2642 (96.2)	2472 (90.1)
9	0.45	0.43, 0.47	2.9	5.0	11.1	2642 (96.2)	2472 (90.1)
10	0.44	0.42, 0.46	3.0	5.1	11.4	2642 (96.2)	2337 (85.1)
11	0.44	0.42, 0.46	3.0	5.1	11.6	2640 (96.2)	2337 (85.1)
12	0.43	0.41, 0.45	3.1	5.3	11.8	2568 (93.6)	2337 (85.1)
13	0.43	0.41, 0.45	3.1	5.3	11.9	2567 (93.5)	2337 (85.1)
14	0.43	0.41, 0.45	3.1	5.3	12.0	2567 (93.5)	2337 (85.1)
15	0.43	0.41, 0.45	3.1	5.2	11.8	2567 (93.5)	2337 (85.1)
16	0.43	0.41, 0.45	3.1	5.3	11.9	2566 (93.5)	2335 (85.1)
17	0.44	0.42, 0.46	3.0	5.1	11.6	2638 (96.1)	2335 (85.1)
18	0.44	0.42, 0.46	3.0	5.1	11.4	2637 (96.1)	2334 (85.0)
19	0.44	0.42, 0.46	2.9	5.0	11.3	2637 (96.1)	2467 (89.9)
20	0.44	0.42, 0.46	3.0	5.1	11.4	2637 (96.1)	2334 (85.0)
21	0.44	0.42, 0.46	2.9	5.0	11.3	2637 (96.1)	2466 (89.8)
22	0.45	0.43, 0.47	2.9	5.0	11.2	2637 (96.1)	2466 (89.8)
23	0.44	0.42, 0.46	3.0	5.1	11.4	2636 (96.0)	2332 (85.0)
24	0.44	0.42, 0.47	2.9	5.0	11.3	2636 (96.0)	2466 (89.8)
Vigorous Physical Activity							
1	0.39	0.37, 0.41	3.6	6.2	14.0	2570 (93.6)	2144 (78.1)
2	0.39	0.37, 0.41	3.6	6.2	14.0	2570 (93.6)	2144 (78.1)
3	0.39	0.37, 0.41	3.6	6.2	13.9	2569 (93.6)	2142 (78.0)
4	0.40	0.38, 0.41	3.6	6.1	13.7	2569 (93.6)	2142 (78.0)
5	0.39	0.37, 0.41	3.6	6.2	14.0	2569 (93.6)	2142 (78.0)
6	0.39	0.37, 0.41	3.6	6.2	13.9	2569 (93.6)	2139 (77.9)
7	0.39	0.38, 0.41	3.6	6.1	13.8	2569 (93.6)	2139 (77.9)
8	0.39	0.37, 0.41	3.6	6.2	13.9	2569 (93.6)	2129 (77.6)
9	0.39	0.37, 0.41	3.6	6.2	14.0	2569 (93.6)	2129 (77.6)
10	0.40	0.38, 0.42	3.5	6.1	13.7	2569 (93.6)	2129 (77.6)

11	0.40	0.39, 0.42	3.4	5.9	13.3	2568 (93.6)	2328 (84.8)
12	0.41	0.39, 0.43	3.4	5.9	13.2	2568 (93.6)	2328 (84.8)
13	0.41	0.39, 0.43	3.4	5.8	13.0	2567 (93.5)	2328 (84.8)
14	0.42	0.40, 0.44	3.3	5.6	12.6	2567 (93.5)	2328 (84.8)
15	0.42	0.40, 0.44	3.3	5.6	12.6	2567 (93.5)	2328 (84.8)
16	0.42	0.40, 0.44	3.2	5.4	12.2	2566 (93.5)	2326 (84.7)
17	0.43	0.41, 0.45	3.0	5.2	11.7	2637 (96.1)	2326 (84.7)
18	0.44	0.42, 0.46	3.0	5.1	11.4	2636 (96.0)	2325 (84.7)
19	0.44	0.42, 0.46	3.0	5.1	11.6	2636 (96.0)	2325 (84.7)
20	0.44	0.42, 0.46	2.9	5.0	11.3	2636 (96.0)	2462 (89.7)
21	0.44	0.42, 0.46	2.9	5.0	11.3	2636 (96.0)	2461 (89.7)
22	0.45	0.42, 0.47	2.9	5.0	11.2	2636 (96.0)	2461 (89.7)
23	0.44	0.42, 0.46	3.0	5.1	11.4	2635 (96.0)	2323 (84.6)
24	0.44	0.42, 0.46	3.0	5.1	11.4	2635 (96.0)	2323 (84.6)
Sedentary Time							
1	0.42	0.40, 0.44	3.2	5.4	12.3	2318 (84.4)	2045 (74.5)
2	0.43	0.41, 0.45	3.1	5.4	12.1	2318 (84.4)	2045 (74.5)
3	0.42	0.40, 0.44	3.2	5.4	12.2	2317 (84.4)	2045 (74.5)
4	0.42	0.41, 0.44	3.2	5.4	12.2	2317 (84.4)	2045 (74.5)
5	0.43	0.41, 0.45	3.1	5.3	12.0	2317 (84.4)	2045 (74.5)
6	0.43	0.41, 0.45	3.1	5.3	12.0	2317 (84.4)	2045 (74.5)
7	0.43	0.41, 0.44	3.2	5.4	12.2	2317 (84.4)	2045 (74.5)
8	0.43	0.41, 0.45	3.1	5.4	12.0	2317 (84.4)	2043 (74.4)
9	0.42	0.40, 0.44	3.2	5.5	12.3	2317 (84.4)	2043 (74.4)
10	0.42	0.40, 0.44	3.2	5.6	12.5	2317 (84.4)	2043 (74.4)
11	0.41	0.39, 0.43	3.4	5.8	13.0	2317 (84.4)	2043 (74.4)
12	0.40	0.38, 0.42	3.4	5.9	13.3	2317 (84.4)	2043 (74.4)
13	0.40	0.38, 0.42	3.5	6.0	13.6	2316 (84.4)	2042 (74.4)
14	0.39	0.37, 0.41	3.6	6.3	14.1	2316 (84.4)	1805 (65.8)
15	0.37	0.35, 0.39	4.0	6.8	15.3	2316 (84.4)	1805 (65.8)
16	0.35	0.33, 0.37	4.3	7.4	16.6	2191 (79.8)	1114 (40.6)
17	0.35	0.33, 0.37	4.4	7.5	16.8	2191 (79.8)	1114 (40.6)
18	0.36	0.34, 0.38	4.1	7.0	15.8	2191 (79.8)	1805 (65.8)
19	0.37	0.35, 0.40	3.9	6.7	15.1	2316 (84.4)	1805 (65.8)
20	0.38	0.36, 0.40	3.8	6.5	14.6	2316 (84.4)	1805 (65.8)
21	0.39	0.36, 0.41	3.7	6.4	14.3	2316 (84.4)	1805 (65.8)
22	0.39	0.37, 0.41	3.6	6.2	14.0	2316 (84.4)	1805 (65.8)
23	0.40	0.37, 0.42	3.6	6.1	13.7	2316 (84.4)	1805 (65.8)
24	0.41	0.38, 0.43	3.4	5.8	13.1	2316 (84.4)	2039 (74.3)

To achieve acceptable reliabilities of 0.7 and 0.8 for light, moderate, and moderate-to-vigorous physical activity, 3-4 and 5-6 days were needed, respectively. Similarly, vigorous physical activity required 3-4 days to achieve a reliability of 0.7 but needed 5-7 days to achieve 0.8. Sedentary time required the most days, needing 4-5 days and 6-8 days for reliabilities of 0.7 and 0.8, respectively.

Nearly all of the sample met criteria for moderate reliability of 0.7 across all minimum wear time hours (i.e., light physical activity 93.4-96.4%, moderate physical activity 93.5-96.5%, moderate-to-vigorous physical activity 93.5-96.5%, vigorous physical activity 93.5-96.0%, and sedentary time 79.8-84.4%), indicating high wear time compliance within the sample.

Sleep Outcomes

I present the single day ICC values, number of days needed to achieve 0.7, 0.8, and 0.9 reliability scores for sleep outcomes, and the number of participants in the sample that met reliabilities of 0.7 and 0.8 in Table 4.2. The was little variation between the lowest percentage night valid and the highest; however, the single day ICC values tended to increase slightly as the criteria increased for all sleep outcomes.

Sleep duration and wake time for all percent night valid criteria required 5 and 8 nights to achieve reliabilities of 0.7 and 0.8, respectively. Time in bed with 100% night valid needed 4 and 7 nights to achieve acceptable reliabilities. For sleep onset to achieve acceptable reliabilities of 0.7 and 0.8, 4 and 6 nights were needed but at 100% night valid 3 days were enough at the 0.7 level. I found sleep efficiency needed the least nights of all the sleep outcomes, requiring 3 nights with 90% or more night valid and 5 nights with 100% valid data to achieve reliabilities of 0.7 and 0.8, respectively. Across all sleep outcomes, the range of participants meeting criteria for a reliability of 0.7 was 60.9-80.7%.

Table 4.2 ICC values and number of days needed to achieve 0.7, 0.8, and 0.9 reliability estimates for sleep outcomes

Night Valid Criteria (%)	Single Day ICC	95% CI	No. of days to achieve reliabilities of			No. (%) of children meeting reliabilities of	
			0.7	0.8	0.9	0.7	0.8
Sleep Duration							
50	0.33	0.31, 0.35	4.7	8.0	18.0	2094 (76.3)	1022 (37.2)
60	0.34	0.32, 0.36	4.5	7.6	17.2	2063 (75.2)	1002 (36.5)
70	0.34	0.32, 0.36	4.5	7.7	17.4	2027 (73.8)	970 (35.3)
80	0.34	0.32, 0.36	4.5	7.7	17.4	2013 (73.3)	953 (34.7)
90	0.35	0.33, 0.37	4.4	7.5	16.8	1995 (72.7)	922 (33.6)
100	0.36	0.34, 0.38	4.1	7.1	16.0	1849 (67.4)	515 (18.8)
Sleep Efficiency							
50	0.41	0.39, 0.43	3.4	5.8	13.0	2152 (78.4)	1891 (68.9)
60	0.41	0.39, 0.43	3.3	5.7	12.8	2140 (78.0)	1881 (68.5)
70	0.42	0.40, 0.44	3.2	5.4	12.2	2126 (77.4)	1870 (68.1)
80	0.43	0.41, 0.45	3.1	5.3	12.0	2120 (77.2)	1863 (67.9)
90	0.44	0.42, 0.46	3.0	5.1	11.5	2214 (80.7)	1849 (67.4)
100	0.46	0.44, 0.48	2.7	4.6	10.4	2153 (78.4)	1848 (67.3)
Time in Bed							
50	0.33	0.31, 0.35	4.7	8.0	18.1	2097 (76.4)	1082 (39.4)
60	0.34	0.32, 0.36	4.5	7.6	17.2	2080 (75.8)	1072 (39.1)
70	0.35	0.33, 0.37	4.3	7.4	16.6	2045 (74.5)	1044 (38.0)
80	0.36	0.34, 0.38	4.2	7.2	16.1	2031 (74.0)	1031 (37.6)
90	0.36	0.34, 0.38	4.1	7.0	15.8	2012 (73.3)	1643 (59.9)
100	0.37	0.35, 0.40	3.9	6.7	15.1	2025 (73.8)	1219 (44.4)
Sleep Onset							
50	0.43	0.41, 0.45	3.1	5.4	12.1	2034 (74.1)	1792 (65.3)
60	0.42	0.40, 0.44	3.3	5.6	12.6	2011 (73.3)	1775 (64.7)
70	0.42	0.40, 0.44	3.3	5.6	12.6	1952 (71.1)	1731 (63.1)
80	0.42	0.40, 0.44	3.2	5.5	12.3	1941 (70.7)	1714 (62.4)
90	0.42	0.40, 0.45	3.2	5.4	12.2	1931 (70.3)	1698 (61.9)
100	0.44	0.42, 0.46	3.0	5.1	11.5	1964 (71.5)	1478 (53.8)
Wake Time							
50	0.33	0.31, 0.35	4.7	8.1	18.1	1928 (70.2)	-
60	0.33	0.31, 0.36	4.6	8.0	17.9	1894 (69.0)	951 (34.6)
70	0.33	0.31, 0.36	4.7	8.0	18.0	1839 (67.0)	928 (33.8)
80	0.34	0.32, 0.36	4.5	7.7	17.3	1826 (66.5)	915 (33.3)
90	0.34	0.32, 0.37	4.5	7.6	17.2	1812 (66.0)	887 (32.3)
100	0.35	0.32, 0.37	4.4	7.6	17.0	1672 (60.9)	500 (18.2)

Discussion

The purpose of this study was to investigate the numbers nights needed to achieve reliable estimates sleep duration, sleep efficiency, time in bed, sleep onset, and wake time in children using the GENEActiv accelerometer. I also investigated the number of days that needed to reliably estimate habitual light physical activity, moderate physical activity, moderate-to-vigorous physical activity, vigorous physical activity, and sedentary time. I found that the numbers of days needed to obtain reliable estimates varied by outcome variable and by inclusion criteria. Broadly, I found that 4 days, for almost all valid hour criteria, would be enough to achieve moderate reliability (i.e., 0.7) for all physical activity and sedentary time outcomes. For moderately reliable estimates of habitual sleep behaviour, I found that 5 nights are needed.

There was little variation in single day ICC values across minimum valid hour criteria in physical activity variable. Other studies have shown a pattern whereby increased wear time criteria resulted in larger ICC values (65, 195). Meaning that increased valid hours required less days to achieve acceptable reliability. In this study, only vigorous physical activity showed this pattern. Still, the ICC values tended to be similar in size to previous studies (65, 195) and overall my findings for physical activity fit the general consensus that 4 days of valid data are needed for reliable estimates (87). Sedentary time tended to have lower ICC values compared to the physical activity outcomes, indicating that there is more variability in sedentary time across days which resulted in 4-5 days being required. This is more days than reported by Dillon et al. (84) but similar to other studies (85, 196).

Single day ICC values for sleep outcomes increased in size as percent night valid criteria became more stringent; however, sleep ICC values tended to be smaller than those for physical activity. Consequently, more nights are needed for reliable estimates of habitual sleep behaviour than for habitual physical activity. Sleep efficiency and sleep onset showed stronger ICC values (range = 0.41-0.46) compared to sleep duration, time in bed, and wake time (range = 0.33-0.37). The findings for sleep duration and time in bed required less days to achieve acceptable reliability (i.e., 4-5 nights) compared to Ridgers et al. (65) and Acebo et al. (64), who reported 6-7 nights are needed for sleep duration and time in bed. Sleep efficiency and sleep onset also needed fewer nights (i.e., 3-4 nights) than has been stated by Taylor et al. (66), who reported 4-7 nights are needed. Wake time in this study, however, required more nights (i.e., 5 nights compared to 2-4 nights). For all sleep outcomes, the reliability was best when using the valid night criteria of 100%.

Children in this sample were less likely to have valid sleep data and meet criteria for reliable data compared to the physical activity outcomes. For example, for reliabilities of 0.7, most of the sample met even the most stringent wear time criterion (i.e., 24 hours/day wear time) with between 84.4% and 96% of children included. Sleep, on the other hand, under the same most stringent criteria (i.e., 100% valid night data) included 60.9-78.4% of the sample. Furthermore, even at a reliability of 0.8 most children with 24 hours/day of wear time were still included (i.e., 74.3% for sedentary time to 89.8% for moderate to vigorous physical activity). However, sample sizes for some sleep outcomes drop considerably when 100% valid night criteria and reliabilities of 0.8 were considered (i.e., 18.8% for sleep duration and 18.1% for wake time). Researchers need to consider the effect that level of reliability and movement behaviour inclusion criteria have on sample size when considering their measurement protocols. The reliability criterion of 0.7 is widely used and considered acceptable for this research to both reduce participant burden and maximise participant retention (197).

There was very little difference in physical activity ICC values from 1 to 24 hours (e.g., ICC for at least 1 hour/day light physical activity was 0.47 while 24 hours/day was 0.46). This may be due to the high wear time compliance in this sample which resulted in little variation at lower hours of wear time. Regardless, I do not recommend that one hour of wear time is sufficient to estimate habitual physical activity. Rather, I have presented all available data so that researchers can make informed decisions for their study protocols that are founded on evidence and theory. Previous research has commonly used a minimum of 8-10 hours to define a valid day (87).

A key strength of this study is the use of sleep inclusion criteria. No other studies have used an inclusion criterion for their sleep estimates other than "has data". This is important because it provides an indication of the quality of the sleep estimates being used in the analyses. I have also examined a variety of daily movement behaviours and several dimensions of sleep. Another strength of the study is the large sample size with high accelerometer wear time compliance which potentially provided more generalisable and precise results than smaller studies with poorer wear time. Notwithstanding these strengths, one limitation of my study is that I did not specifically examine the inclusion of weekend days. Some studies have reported that weekend days are required for reliable estimates (87), while others have stated that the inclusion of weekend data is not necessary (198). My analyses, however, randomly sampled valid days and nights which included weekends. Therefore, I cannot determine whether a weekend day is needed for reliable estimates. Another limitation is that the window of time that these estimates reliably predict is unknown. That is, five days of sleep behaviour data provides a reliable estimate of habitual sleep for a given week, but I do not know if it is reliable for a month or longer. More research is needed to determine the measurement protocol needed to estimate longer periods of habitual activity.

Conclusion

This study examined the number of nights and days needed to reliably estimate habitual 24-hour movement behaviours using the GENEActiv accelerometer. The findings from this study suggest that 5 nights of valid sleep data would provide acceptable reliability for habitual sleep behaviour. I also found that at least 4 days of valid data would provide acceptable reliability for habitual physical activity and sedentary time, across all minimum daily wear time criteria. Researchers should account for the effect that various inclusion criteria may have on study sample size and consider adjustments to their study designs or strategies for improving wear time compliance to achieve an acceptable level of reliability.

Chapter 5 | General Discussion

Review of Thesis Objectives

In this thesis, my primary objective was to examine the relationship between physical activity and sleep in children. I also aimed to investigate the direction of the relationship and the number of nights needed to obtain reliable estimates of habitual sleep behaviour. In Chapters 2-4, I presented three studies designed to meet these objectives and contribute to the body of evidence in child sleep research. In Chapter 2, I synthesised the current literature with the first systematic review and meta-analysis of the relationship between physical activity and sleep in children. In Chapter 3, I reported the results of the first longer-term longitudinal study in children using objectively measured physical activity and sleep outcomes. And, in Chapter 4, I provided future researchers with criteria for the number of nights of monitoring that are required to obtain reliable estimates of habitual sleep when using accelerometers.

The meta-analysis I presented in Chapter 2 aimed to consolidate all previous evidence for the association between physical activity and sleep in children. Previous meta-analyses of this relationship have only been conducted among adults and adolescents (43, 124). Those meta-analyses found significant positive associations between physical activity and sleep. My meta-analysis in children, however, found an inconsistent relationship and overall little evidence for an association (128). The meta-analysis included 47 studies which represented 62,081 children (53% girls) between 3-13-years-old from across the world. I found an overall association of $r = 0.02$ (95%CI = -0.03 to 0.07). When examining a variety of different physical activity and sleep outcomes, vigorous physical activity was the only physical activity outcome that showed a weak but positive significant association with sleep overall ($r = 0.09$, 95% CI = 0.01 to 0.17) and sleep duration, specifically ($r = 0.07$, 95% CI = 0.00 to 0.14). Another important finding of the review was that very few high-quality longitudinal or experimental studies had investigated this association in children. This gap in the research indicated that the overall body of evidence may be lacking, and additional high-quality research should be conducted.

To address this limitation of low-quality research that I identified in the meta-analysis and to further examine the direction of the relationship between physical activity and sleep, I conducted a two-year longitudinal study (Chapter 3). Only one longitudinal study had been conducted previously among 129 secondary school-aged girls over one school year. The study found a long-term association between increased self-reported physical activity and decreased ratings of sleep problems (119). In my two-year longitudinal study, I used objective measures of physical activity and sleep with a much larger sample of 1,059 children. I examined several physical activity and sleep outcomes for day-to-day (i.e., within timepoints) associations and longer-term (i.e., across timepoints) associations. Day-to-day, I found evidence for a bidirectional relationship between light-, moderate-, moderate-to-vigorous-, and vigorous-intensity physical activity and sleep duration, time in bed, sleep onset, and wake time. Stated simply, physical activity during the day improved sleep at night and sleep at night improved physical activity the following day. However, for habitual physical activity and sleep across timepoints, I found there was little association in either direction.

For estimates of habitual physical activity and sleep outcomes, I needed to know how many days would be required to obtain reliable values. For physical activity, the general consensus among researchers appears to be that a minimum of 4 days is needed (87). Sleep, however, does not have generally accepted consensus. Therefore, I conducted a reliability study (Chapter 4) to determine the number of nights needed to obtain reliable estimates of sleep behaviour. I found that sleep efficiency and sleep onset needed 3-4 nights, time in bed needed 4-5 nights, and sleep duration and wake time needed 5 nights each.

In Chapter 3, I used the criteria of at least 4 nights of sleep data for the longer-term longitudinal analysis. However, the reliability study in Chapter 4 found that 5 nights are needed for some sleep variables. Therefore, I conducted a sensitivity analysis to address this discrepancy. I used the new criteria of 5 nights and repeated the parallel process latent growth curve modelling analysis. I present the results of this sensitivity analysis in Supplementary Table 5.1 in Appendix E (see Table 3.4 in Chapter 3 for comparison). I found that there was very little difference in the results, thereby indicating that the new criteria did not significantly influence the findings of Chapter 3.

Implications

Overall, the goal of this thesis was to understand the relationship between physical activity and sleep in children. Knowing how these behaviours interact is important because engaging in each of these behaviours has important implications for a variety of health outcomes (8, 9). However, due to the constraints of how we can spend our time each day, it may be that spending more time being active takes away from time spent sleeping. While an individual may increase physical activity and benefit from the positive health outcomes associated with physical activity, they may also be decreasing their sleep duration which exposes them to the poor health outcomes associated with short sleep duration. Alternatively, these behaviours could support one another in a virtuous circle where increased physical activity leads to improved sleep that night and improved sleep that night encourages increased physical activity the next day. The findings of this thesis, specifically Chapter 2 (meta-analysis) and Chapter 3 (longitudinal study), showed no evidence for the former hypothesis and some supporting evidence for the latter alternative. While the associations I found between physical activity and sleep in children may be weaker than the associations reported in older populations (43, 124), these behaviours do seem to be bidirectionally associated. The results of Chapter 2 and Chapter 3 together suggest that increased daytime physical activity is associated with improved night-time sleep. Vigorous physical activity was the only outcome that showed a significant association in my meta-analysis and showed strong and positive day-to-day associations with most sleep outcomes measured in Chapter 3. Therefore, vigorous physical activity may be particularly important for this association in children. This finding is supported by research that shows that vigorous physical activity (as opposed to light and moderate intensity physical activity) may be necessary for some health benefits to manifest (71). Clinical recommendations often propose increased physical activity as a means improve sleep and prevent sleep disorders (103, 113, 114). Based on the findings of this thesis, these recommendations may consider emphasising an increase in vigorous activity to achieve the best outcome. Furthermore, guidelines for daily movement behaviours may place a greater emphasis on obtaining daily vigorous physical activity in children (15).

In the reliability study (Chapter 4), I found the number of nights that are needed to obtain reliable estimates of different dimension of habitual sleep. In addition to the number of nights, inclusion criteria are needed to determine if a night is valid. With physical activity outcomes for example, researchers typically require a certain number of days and hours of valid wear time for data to be included. Most commonly, this criteria is 4 or more days with ranges between at least 8 and 10 hours/day (87). However, in sleep studies a specific sleep criterion is not typically used or specified. In Chapter 4, I used the percentage of the night reported as valid by GGIR for sleep outcome inclusion criteria. Other sleep studies, however, have simply used the same criteria for sleep as they do for physical activity outcomes or have applied no minimum wear time criteria for sleep outcomes (64, 65, 199). Some recent sleep studies in children have reported using the minimum total sleep period criterion of at least 160 minutes to define a valid night (200, 201), although it is not clear how this cut-off was determined and represents only a small portion of a full night of data. This lack of valid night criteria, therefore, requires the researchers to rely on the sleep detection algorithm used to provide valid estimates, which may or may not be appropriate, but this is not clear nor transparent. In my reliability study, I found that single day intraclass correlation (ICC) values increased as the percentage of the night increased from 50% to 100% valid. This increase in ICC values demonstrates that sleep inclusion criteria may be important in determining the quality of included sleep data. Future sleep studies should consider and report the inclusion criteria for valid sleep data used in their studies so that the decisions being applied to raw sleep data are transparent.

Strengths

This thesis had several strengths that support the internal validity and generalisability of the included studies. In the systematic review and meta-analysis, I aggregated the current evidence of studies that have examined the association between physical activity and sleep. As mentioned previously, this was the first systematic review and meta-analysis to focus on the association in children specifically. I conducted the meta-analysis using best practices including pre-registration of the study protocol and following the PRISMA statement for guidelines on reporting systematic reviews and meta-analyses (136, 202). To ensure the search for studies was comprehensive, I kept the inclusion criteria broad so that as many studies as possible could be considered. I included a range of study designs and a wide variety of possible physical activity and sleep outcomes. Using this approach, I identified 47 relevant studies that represented several different countries from around the world. These methods ensured that the review was thorough and helped reduce potential areas of bias.

Another key strength of this thesis was the use of objective measures which may provide more reliable estimates of physical activity and sleep than subjective measures (77, 78, 203, 204). Subjective measures may be especially problematic for children self-reporting their physical activity and sleep where they may report only what was most recent or what they believe is most appropriate (44, 205). I used the GENEActiv accelerometer which is a wrist-worn and waterproof device which can be worn all day for weeks on a single charge. An advantage of the wrist location is that it tends to achieve greater wear time compliance compared to hip or waist devices (59, 84). By using this device, children needed to remove the device less often and as shown in Chapter 4, the wear time compliance in my studies was very good. Furthermore, the GENEActiv has been validated for use with physical activity in adults and children (176, 177) and for sleep in samples of adults (60, 61).

Another strength was the large sample size of children in Chapter 3 and Chapter 4 (N = 1,059 at baseline data collection). The sample was also collected from a range of low to high socioeconomic and urban to rural communities which helps increase the generalisability of my findings. Furthermore, it can be difficult, time-consuming, and costly to concurrently collect accelerometry data from such a large sample. The fact that this much accelerometer data was collected and included in the analyses of these chapters is a significant strength of this research.

A final strength of this thesis is that each included study built on the study that came before it. That is, while conducting the meta-analysis, I was able to identify gaps in the current literature and use this information to inform the methods of my longitudinal study. In turn, while conducting the longitudinal study, it became evident that the criteria applied to accelerometer data for physical activity outcomes was much more established than the criteria for sleep outcomes. This contrast directly informed the necessity for additional reliability data for sleep studies using accelerometers and I was able to address this gap in Chapter 4. By identifying gaps and using these gaps to inform methodological decisions in my thesis, I strengthened and improved the impact of my thesis overall and of each included study.

Limitations

This thesis also has some limitations. While the use of accelerometers is a strength of this thesis, the lack of subjective measures in Chapter 3 is also a weakness. Some aspects of sleep may only be measurable using subjective measures (e.g., sleep quality, sleep disturbances, or daytime tiredness) and could play an important role in understanding the whole picture of the association between physical activity and sleep (206, 207). Buysse (42), in his definition of sleep health, described the construct of sleep quality or satisfaction as the subjective rating of poor or good sleep. While subjective sleep quality has shown some association with other objective dimensions of sleep, such as slow wave sleep or deep sleep (42), it may play an important role on its own. For example, in an experiment with young adults, participants were arbitrarily told that they had good or poor sleep and it was shown that those assigned the poor condition performed worse on cognitive functioning tests than those assigned to the good condition (208). This study shows the importance of subjective perceptions of sleep quality. It may be that objective measures and subjective measures used in conjunction are needed to make a comprehensive assessment of sleep and the associations with physical activity or other outcomes. I was unable to include subjective measures of sleep as sleep was not an outcome of the iPLAY intervention (i.e., the larger project from which data for Chapters 3 and 4 were drawn) and there was little room for additional items in the already lengthy questionnaire for children. However, future research should incorporate both types of instruments in their measurement of sleep outcomes.

An additional limitation comes from the accelerometers themselves. While in most cases participants wore and returned the accelerometer as instructed, there were still some cases where the accelerometer was either not worn enough, not returned, or malfunctioned. For schools involved in the research study (iPLAY) described in Chapters 3 and 4, a loss rate of less than 10% per data collection wave was considered acceptable. While the overall loss rate throughout the course of the iPLAY intervention was only 4% of devices (n = 106), this is still a considerable financial burden and loss of data. In addition, some accelerometers that were returned experienced recording malfunctions where they either recorded no data or there was calibration error causing impossible values of acceleration. One strategy, that was not followed in the iPLAY program, is to screen data immediately upon return for wear time compliance and valid data and then, if any issues are found, ask the participant to wear the device again (87). The amount of valid data retained in our study was still large; however, future research studies could prepare strategies to mitigate losses and encourage device return rates.

The GENEActiv accelerometer also lacks specific sleep validation data for use with children. To date, the only studies that have validated these devices against polysomnography (i.e., the gold-standard sleep measure) have been conducted in adults (60, 61). However, because the algorithm I used to score sleep is based on arm movement and there is no evidence to suggest that children move their arms differently during sleep than adults, I have assumed that this method is still suitable. Nevertheless, validation studies should be conducted for each population of interest and each device used to estimate sleep (55). As stated in the preface to Chapter 4, I originally planned to conduct a validation study in children. This study was underway; however, due to slow recruitment and restrictions on face-to-face data collection associated with the COVID-19 pandemic, the study was postponed, and I was unable to include it in this thesis.

Lastly, Chapter 3 and 4 use the same data source. While it was a large sample size and efforts were made to include participants with diverse socioeconomic backgrounds, the sample still comes largely from a mostly healthy and wealthy western country. Thus, the findings of this thesis may not be generalisable to all children from other cultures o r countries. In addition, the health status data of participants was not collected, nor specifically, whether participants had chronic conditions including sleep disorders. Furthermore, in my meta-analysis in Chapter 2, I excluded studies that examined children with sleep disorders or other known chronic conditions. Not examining the association between physical activity and sleep in children with known conditions may be another important limitation of this thesis. Those with sleep disorders, specifically, are often recommended to engage in exercise as a non-pharmacological intervention to treat their disorder and they may show greater improvements in sleep from increased physical activity than their otherwise healthy counterparts (97). Therefore, ceiling effects from using only seemingly healthy participants may limit the generalisability and strength of my findings.

Future Research

As stated in the meta-analysis in Chapter 2, research examining the association between physical activity and sleep lack in high-quality studies, such as longitudinal and experimental designs. I conducted a longitudinal study in Chapter 3; however, additional studies are still needed to improve the quality of the overall body of evidence. Future longitudinal studies should consider increasing the frequency of follow-up measurements and the duration of the overall study. These studies could follow participants from childhood into adolescence to examine whether movement behaviour patterns in childhood affect the patterns of behaviour in later years. To date, two longer-term longitudinal studies have been conducted in children. One study employed subjective measures and found positive associations (119). The other (Chapter 3), used objective measures and found little association. Additional studies are needed to clarify the long-term associations between physical activity and sleep and these studies should employ both subjective and objective measures.

While the studies conducted in this thesis provide evidence for bidirectional day-to-day associations between physical activity and sleep, there is still very little that we understand about the underlying mechanisms. In line with the restorative theory of sleep (24), it may be that sleep is a time of restoration and daytime physical activity produces fatigue which encourages the body to sleep to recover. And, that when the body is more restored from a good night of sleep, people are more likely to feel energised and be active the following day. Still, the physiological mechanisms that drive this are unclear. There is little evidence relating to possible mechanisms and further research is needed (102). Experimental studies that modify the amount of physical activity and sleep obtained and explore the change in various physiological systems could be quite informative. For example, studies have shown that the circadian rhythm (i.e., the body's internal clock) can be estimated by measuring gene expression from blood or hair follicle samples (209, 210). Experimental studies could examine whether certain amounts of physical activity result in positive shifts in circadian rhythm which could relate to more regular and improved sleep. Understanding the underlying mechanisms can improve our understanding of how movement behaviours relate and may inform broader questions about why we need to sleep in the first place.

Conclusion

The findings of this thesis have contributed to the body of literature on the relationship between physical activity and sleep behaviour in children. In Chapter 2, I synthesised the current literature and found little overall association and no significant moderating variables, but vigorous physical activity showed some weak but positive associations with overall sleep and sleep duration. The review also identified an important gap that few studies in the body of evidence have employed high-quality study designs. In Chapter 3, I addressed this gap by conducting a longitudinal study. I found that objectively measured daytime physical activity was positively and bidirectionally associated with the following night of sleep, but longer-term showed little association across a two years period. In Chapter 4, I showed that 5 valid nights are enough nights of monitoring to obtain reliable estimates of habitual sleep behaviour including sleep duration, sleep efficiency, time in bed, sleep onset, and wake time.

Overall, more experimental and longitudinal studies using both objective and subjective measures are still needed to confirm these findings; however, this thesis shows that there is likely a positive bidirectional relationship in children. Increased physical activity can help children sleep better at night and better sleep at night can help children be more active the next day.

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Research Portfolio Appendix

Meta-Analysis (chapter 2)

The meta-analysis in Chapter 2 has been published in Sleep Medicine Reviews. The published copy is available here:

Antczak D, Lonsdale C, Lee J, Hilland T, Duncan MJ, Del Pozo Cruz B, et al. "Physical activity and sleep are inconsistently related in healthy children: A systematic review and meta-analysis." Sleep Medicine Reviews. (2020): 51:101278.

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Devan Antczak

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Ryan Hulteen

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[redacted]

Borja del Pozo Cruz

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[redacted]

Philip Parker

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[redacted]

Chris Lonsdale

Physical Activity and Sleep Longitudinal Study (chapter 3)

The paper in Chapter 3 is currently under review at Sleep (IF = 4.805) with reference number SLEEP-2020-0652. Proof of submission is attached below.

ID	TITLE	CREATED	SUBMITTED
SLEEP-2020-0652	Day-to-day and Longer-term Longitudinal Associations between Physical Activity, Sedentary Behavior, and Sleep in Children View Submission Cover Letter	23-Jul-2020	28-Jul-2020 view receipt

I acknowledge that my contribution to the paper is 80%. [redacted] Devan Antczak

I acknowledge that my contribution to the paper is 5%. [redacted] Taren Sanders

I acknowledge that my contribution to the paper is 5%. [redacted] Borja del Pozo Cruz

I acknowledge that my contribution to the paper is 5%. [redacted] Philip Parker

I acknowledge that my contribution to the paper is 5%. [redacted] Chris Lonsdale

Appendix A (Chapter 2)| Meta-Analysis Supplementary Material

Appendix A.1 Effect Size Calculations

We outline here the method and formulas used in this meta-analysis to convert effect sizes to correlations. When authors reported unstandardised coefficients, we used formula (1) from Bring to standardise *beta* coefficients:[1]

$$\beta = beta \times \left(\frac{SD_{independent}}{SD_{dependent}}\right). \tag{1}$$

We used formula (2) from Cohen to standardise mean differences:[2]

$$Cohen's\ d = \frac{M_1 - M_2}{SD_{pooled}}\ . \tag{2}$$

To harmonies the effect sizes across all studies, we converted them all to correlation coefficients using formula (3) for standardised regression coefficients:[3]

$$r = \beta + .05\lambda\ . \tag{3}$$

In formula (3), λ is 1 if β is non-negative and 0 if β is negative. Standardised mean differences were converted to *r* using formula (4):[4]

$$r = \sqrt{\frac{d^2}{d^2 + 4}}\ . \tag{4}$$

A standardised beta coefficient can be converted to correlation if it is in the range of -.50 to .50.[3] Beta coefficients outside of this range were included in the meta-analysis at the maximum allowable value (n=8). To convert odds ratios, we first converted the odds ratio to Cohen's *d* using formula (5):

$$LogOddsRatio = d\ \frac{\pi}{\sqrt{3}}\ , \tag{5}$$

and then we used formula (2) to convert this into a correlation.[5] Lastly, in accordance with Borenstein et al,[5] we transformed the correlations into Fisher's z and calculated a variance for each effect for meta-analysis using formulas (6) and (7):

$$z = 0.5 \times \ln\left(\frac{1+r}{1-r}\right), \tag{6}$$

$$V_z = \frac{1}{n-3}\ . \tag{7}$$

We then converted the meta-analysis' summary effects and confidence intervals back to correlation coefficients for presentation using formula (8):

$$r = \frac{e^{(2\times z)} - 1}{e^{(2\times z)} + 1}\ . \tag{8}$$

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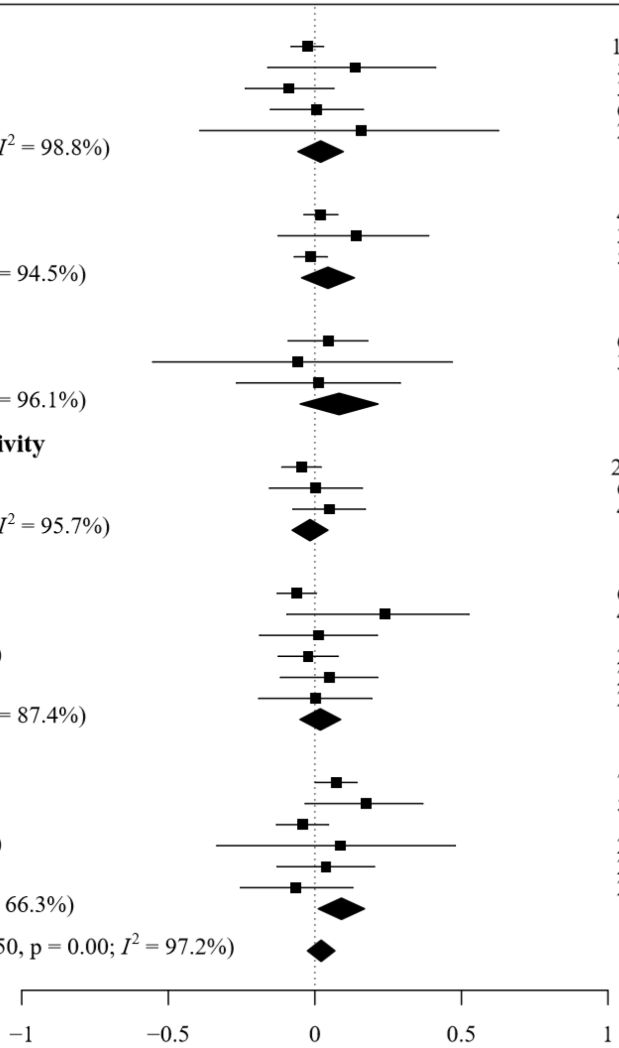
Appendix A.2 Associations of Sleep Outcomes Organised by Physical Activity Category

Supplementary Figure 2.1 Associations of sleep outcomes organized by physical activity category

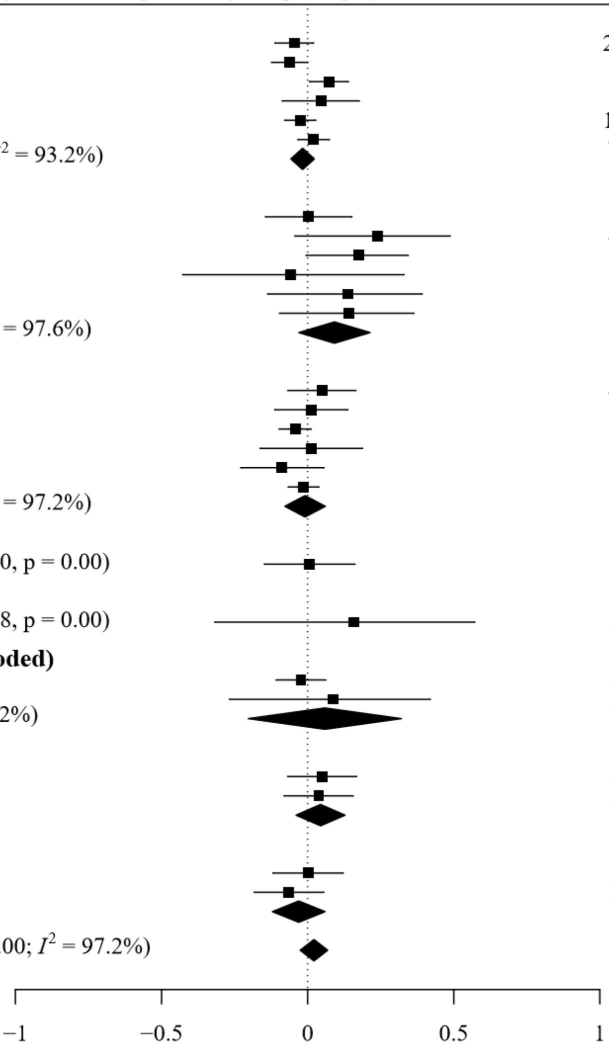


	Studies	k	N	I^2	r[95%CI]
Total Physical Activity					
Sleep Duration	17	35	28825	95	−0.03 [−0.08, 0.03]
Sleep Efficiency	5	16	2441	97.8	0.14 [−0.16, 0.41]
Sleep Timing (reverse−coded)	3	22	13038	99.2	−0.09 [−0.24, 0.06]
Sleep Quality (reverse−coded)	6	51	8253	96.8	0.01 [−0.15, 0.17]
Daytime Tiredness (reverse−coded)	2	9	14821	99.9	0.16 [−0.39, 0.63]
Overall (Q = 8219.50, df = 132, p = 0.00; I^2 = 98.8%)					**0.02 [−0.06, 0.10]**
Sport and Outdoor Play					
Sleep Duration	4	19	2874	72	0.02 [−0.04, 0.08]
Sleep Efficiency	3	12	895	96.6	0.14 [−0.12, 0.39]
Sleep Timing (reverse−coded)	5	19	6295	83.2	−0.01 [−0.07, 0.04]
Overall (Q = 471.40, df = 49, p = 0.00; I^2 = 94.5%)					**0.04 [−0.05, 0.14]**
Light Physical Activity					
Sleep Duration	6	42	7044	95.5	0.05 [−0.09, 0.18]
Sleep Efficiency	3	5	635	96.5	−0.06 [−0.55, 0.47]
Sleep Timing (reverse−coded)	1	4	515	94	0.01 [−0.27, 0.29]
Overall (Q = 337.80, df = 50, p = 0.00; I^2 = 96.1%)					**0.08 [−0.05, 0.22]**
Moderate−to−Vigorous Physical Activity					
Sleep Duration	21	80	25035	95.2	−0.05 [−0.11, 0.02]
Sleep Efficiency	6	19	8014	98.5	0.00 [−0.15, 0.16]
Sleep Timing (reverse−coded)	4	22	1940	88.8	0.05 [−0.07, 0.17]
Overall (Q = 2645.79, df = 120, p = 0.00; I^2 = 95.7%)					**−0.02 [−0.08, 0.04]**
Moderate Physical Activity					
Sleep Duration	6	16	1459	40.6	−0.06 [−0.13, 0.00]
Sleep Efficiency	4	9	732	96.4	0.24 [−0.09, 0.53]
Sleep Timing (reverse−coded)	1	4	515	88	0.01 [−0.19, 0.21]
Light Sleep (% sleep time; reverse−coded)	2	8	145	0	−0.02 [−0.12, 0.08]
Deep Sleep (% sleep time)	2	5	145	0.1	0.05 [−0.12, 0.21]
REM Sleep (% sleep time)	2	4	145	0	0.00 [−0.19, 0.19]
Overall (Q = 269.72, df = 45, p = 0.00; I^2 = 87.4%)					**0.02 [−0.05, 0.09]**
Vigorous Physical Activity					
Sleep Duration	7	19	1590	41.1	0.07 [0.00, 0.14]
Sleep Efficiency	5	10	1376	86.9	0.17 [−0.03, 0.37]
Sleep Timing (reverse−coded)	1	4	515	37.2	−0.04 [−0.13, 0.05]
Light Sleep (% sleep time; reverse−coded)	2	8	145	74.6	0.09 [−0.33, 0.48]
Deep Sleep (% sleep time)	2	5	145	0.1	0.04 [−0.13, 0.20]
REM Sleep (% sleep time)	2	4	145	0	−0.06 [−0.25, 0.13]
Overall (Q = 77.63, df = 49, p = 0.01; I^2 = 66.3%)					**0.09 [0.01, 0.17]**
Overall All Studies (Q = 12487.09, df = 450, p = 0.00; I^2 = 97.2%)					**0.02 [−0.03, 0.07]**

Appendix A.3 Associations of Physical Activity Outcomes Organised by Sleep Category

Supplementary Figure 2.2 Associations of physical activity outcomes organized by sleep category

	Studies	*k*	*N*	I^2	*r*[95%CI]
Sleep Duration					
Moderate−to−Vigorous Physical Activity	21	80	25035	95.2	−0.05 [−0.11, 0.02]
Moderate Physical Activity	6	16	1459	40.6	−0.06 [−0.12, −0.00]
Vigorous Physical Activity	7	19	1590	41.1	0.07 [0.01, 0.14]
Light Physical Activity	6	42	7044	95.5	0.05 [−0.09, 0.18]
Total Physical Activity	17	35	28825	95	−0.03 [−0.08, 0.03]
Sport and Outdoor Play	4	19	2874	72	0.02 [−0.03, 0.07]
Overall (Q = 2545.35, df = 210, p = 0.00; I^2 = 93.2%)					**−0.02 [−0.06, 0.02]**
Sleep Efficiency					
Moderate−to−Vigorous Physical Activity	6	19	8014	98.5	0.00 [−0.14, 0.15]
Moderate Physical Activity	4	9	732	96.4	0.24 [−0.04, 0.49]
Vigorous Physical Activity	5	10	1376	86.9	0.17 [−0.00, 0.34]
Light Physical Activity	3	5	635	96.5	−0.06 [−0.43, 0.33]
Total Physical Activity	5	16	2441	97.8	0.14 [−0.14, 0.39]
Sport and Outdoor Play	3	12	895	96.6	0.14 [−0.10, 0.36]
Overall (Q = 1586.43, df = 70, p = 0.00; I^2 = 97.6%)					**0.09 [−0.03, 0.21]**
Sleep Timing (reverse−coded)					
Moderate−to−Vigorous Physical Activity	4	22	1940	88.8	0.05 [−0.07, 0.16]
Moderate Physical Activity	1	4	515	88	0.01 [−0.11, 0.14]
Vigorous Physical Activity	1	4	515	37.2	−0.04 [−0.10, 0.01]
Light Physical Activity	1	4	515	94	0.01 [−0.16, 0.19]
Total Physical Activity	3	22	13038	99.2	−0.09 [−0.23, 0.06]
Sport and Outdoor Play	5	19	6295	83.2	−0.01 [−0.07, 0.04]
Overall (Q = 2211.54, df = 74, p = 0.00; I^2 = 97.2%)					**−0.01 [−0.08, 0.06]**
Sleep Quality (reverse−coded)					
Total Physical Activity (Q = 686.34, df = 50, p = 0.00)	6	51	8253	96.8	0.01 [−0.15, 0.16]
Daytime Tiredness (reverse−coded)					
Total Physical Activity (Q = 3885.61, df = 8, p = 0.00)	2	9	14821	99.9	0.16 [−0.32, 0.57]
Light Sleep (% sleep time; reverse−coded)					
Moderate Physical Activity	2	8	145	0	−0.02 [−0.11, 0.06]
Vigorous Physical Activity	2	8	145	0.1	0.09 [−0.27, 0.42]
Overall (Q = 8.61, df = 15, p = 0.90; I^2 = 62%)					**0.06 [−0.20, 0.32]**
Deep Sleep (% sleep time)					
Moderate Physical Activity	2	5	145	0	0.05 [−0.07, 0.17]
Vigorous Physical Activity	2	5	145	74.6	0.04 [−0.08, 0.16]
(Q = 0.95, df = 9, p = 1.00)I^2 = .1%)					**0.04 [−0.04, 0.13]**
REM Sleep (% sleep time)					
Moderate Physical Activity	2	4	145	0.1	0.00 [−0.12, 0.12]
Vigorous Physical Activity	2	4	145	0	−0.06 [−0.18, 0.06]
(Q = 3.42, df = 7, p = 0.84)I^2 = 1.6%)					**−0.03 [−0.12, 0.06]**
All Studies (Q = 12487.09, df = 450, p = 0.00; I^2 = 97.2%)					**0.02 [−0.03, 0.07]**



Appendix A.4 Database Search Terms and Strategy

Children	Sleep	Physical Activity
Child*	Sleep*	“Motor (in)activity”
Youth	Bedtime*	“Physical (in)activity”
Pediatric*	Polysomnography	Exercis*
Paediatric*	Insomnia	Fitness
Student*	“Time in bed”	Sedentary
Pupil*	Wake*	Sport*
Boy*	Awake*	Recreation
Girl*	Waking	Lifestyle
Preschool*	REM	Acceleromet*
Toddler*	“rapid eye movement”	Actigraph*
Adolesc*	“sleep quality”	“Physically (in)active”
Teen*	“sleep timing”	Sitting
Pubescent	“sleep latency”	Steps
prepubescent	“sleep efficiency”	Walk*
juvenile	“sleep duration”	Walking
“young person”	“sleep hygiene”	Run
“young persons”	“sleep medicine”	running
“young people”	“sleep satisfaction”	Bicycle
	“sleep health”	Bicycling
	“sleep time”	Bike
	“sleep onset”	Biking
	“sleep diary”	“Active transport”
	“sleep diaries”	“active transportation”
	“sleep log”	“Active transit”
		“Active travel”
		Commut*
		“Active commuting”
		“Active living”
		“Active-living”

Include Relevant Mesh Headings/Terms from Specific Database
(Child* OR Youth OR Pediatric* OR Paediatric* OR Student* OR Pupil* OR Boy* OR Girl* OR Preschool* OR Toddler* OR Adolesc* OR Teen* OR “young person” OR pubescent OR prepubescent OR juvenile OR “young persons” OR “young people”)
AND
(Sleep* OR Bedtime* OR Polysomnography OR Insomnia OR “Time in bed” OR wake* OR awake* OR waking OR REM OR “rapid eye movement” OR “sleep quality” OR “sleep timing” OR “sleep latency” OR “sleep efficiency” OR “sleep duration” OR “sleep hygiene” OR “sleep medicine” OR “sleep satisfaction” OR “sleep health” OR “sleep time” OR “sleep onset” OR “sleep diary” OR “sleep diaries” OR “sleep log”)
AND
(“Motor activity” OR “Motor inactivity” OR “Physical activity” OR “Physical inactivity” OR Exercis* OR Fitness OR Sedentary OR Sport* OR Recreation OR Lifestyle OR Sitting OR Steps OR Acceleromet* OR Actigraph* OR “Physically active” OR “Physically inactive” OR Walk* OR Walking OR run OR running OR Bicycle OR Bicycling OR Bike OR Biking OR “Active transport” OR “active transportation” OR “Active transit” OR “Active travel” OR Commut* OR “Active commuting” OR “Active living” OR “Active-living”)

Example Database Search – MEDLINE

1. (MH "Child") OR (MH "Child, Preschool")
2. TI (Child* OR Youth OR Pediatric* OR Paediatric* OR Student* OR Pupil* OR Boy* OR Girl* OR Preschool* OR Toddler* OR Adolesc* OR Teen* OR “young person” OR pubescent OR prepubescent OR juvenile OR “young persons” OR “young people”) OR AB (Child* OR Youth OR Pediatric* OR Paediatric* OR Student* OR Pupil* OR Boy* OR Girl* OR Preschool* OR Toddler* OR Adolesc* OR Teen* OR “young person” OR pubescent OR prepubescent OR juvenile OR “young persons” OR “young people”)
3. (MH "Sleep") OR (MH "Sleep Deprivation") OR (MH "Sleep, REM") OR (MH "Sleep Stages") OR (MH "Polysomnography")
4. TI (Sleep* OR Bedtime* OR Polysomnography OR Insomnia OR “Time in bed” OR wake* OR awake* OR waking OR REM OR “rapid eye movement” OR “sleep quality” OR “sleep timing” OR “sleep latency” OR “sleep efficiency” OR “sleep duration” OR “sleep hygiene” OR “sleep medicine” OR “sleep satisfaction” OR “sleep health” OR “sleep time” OR “sleep onset” OR “sleep diary” OR “sleep diaries” OR “sleep log”) OR AB (Sleep* OR Bedtime* OR Polysomnography OR Insomnia OR “Time in bed” OR wake* OR awake* OR waking OR REM OR “rapid eye movement” OR “sleep quality” OR “sleep timing” OR “sleep latency” OR “sleep efficiency” OR “sleep duration” OR “sleep hygiene” OR “sleep medicine” OR “sleep satisfaction” OR “sleep health” OR “sleep time” OR “sleep onset” OR “sleep diary” OR “sleep diaries” OR “sleep log”)
5. (MH "Motor Activity") OR (MH "Locomotion") OR (MH "Exercise") OR (MH "Running") OR (MH "Swimming") OR (MH "Walking") OR (MH "Physical Fitness") OR (MH "Recreation")
6. TI (“Motor activity” OR “motor inactivity” OR “Physical activity” OR “physical inactivity” OR Exercis* OR Fitness OR Sedentary OR Sport* OR Recreation OR Lifestyle OR Sitting OR Steps OR Acceleromet* OR Actigraph* OR “Physically active” OR “physically inactive” OR Walk* OR Walking OR “Active transport” OR “active transportation” OR “Active transit” OR “Active travel” OR Commut* OR “Active commuting” OR run OR running OR Bicycle OR Bicycling OR Bike OR Biking OR “Active living” OR “Active-living”) OR AB (“Motor activity” Or “motor inactivity” OR “Physical activity” OR “physical inactivity” OR Exercis* OR Fitness OR Sedentary OR Sport* OR Recreation OR Lifestyle OR Sitting OR Steps OR Acceleromet* OR Actigraph* OR “Physically active” OR “physically inactive” OR Walk* OR Walking OR “Active transport” OR “active transportation” OR “Active transit” OR “Active travel” OR Commut* OR “Active commuting” OR run OR running OR Bicycle OR Bicycling OR Bike OR Biking OR “Active living” OR “Active-living”)
7. 1 OR 2
8. 3 OR 4
9. 5 OR 6
10. 7 AND 8 AND 9

Appendix A.5 Table of Results of Categorical Moderator Analysis

Supplementary Table 2.1 Results of continuous and categorical moderator analyses within outcome variable categories

Moderator Variables	n. studies	k	Intercept (95%CI)/ *r*(95%CI)	β (95%CI)	*F*(df1, df2)[a]	*p*[b]
(1) Moderate-to-Vigorous Physical Activity and Sleep Overall	21	121				
Age	21	121	0.003 (-0.057, 0.064)	0.04 (0.004, 0.076)*	*F*(1, 119) = 4.74	.031*
Study Design					NA	
Cross-Sectional	20	120	NA			
Longitudinal	1	1	NA			
Experimental	0	0	NA			
Risk of Bias					*F*(2, 118) = 0.454	0.636
Low	11	71	-0.001 (-0.088, 0.086)			
High	7	33	-0.009 (-0.122, 0.103)	-0.008 (-0.151, 0.134)		
Unclear	3	17	NA			
Study Quality					NA	
High	18	96	NA			
Moderate	1	1	NA			
Low	2	25	NA			
Direction of Association					*F*(2, 118) = 0.284	0.753
No Specified Direction	7	25	-0.008 (-0.102, 0.086)			
Sleep on Physical Activity	6	59	-0.009 (-0.08, 0.063)	-0.001 (-0.104, 0.103)		
Physical Activity on Sleep	8	37	-0.033 (-0.109, 0.044)	-0.025 (-0.13, 0.081)		
(2) Moderate Physical Activity and Sleep Overall	7	46				
Age	7	46	0.011 (-0.077, 0.098)	0.013 (-0.064, 0.09)	*F*(1, 44) = 0.119	0.732
Study Design					NA	
Cross-Sectional	6	38	NA			
Longitudinal	1	8	NA			
Experimental	0	0	NA			
Risk of Bias					NA	
Low	2	13	NA			
High	4	18	NA			
Unclear	1	15	NA			
Study Quality					NA	
High	5	37	NA			
Moderate	1	1	NA			
Low	1	8	NA			
Direction of Association					NA	
No Specified Direction	3	17	NA			
Sleep on Physical Activity	2	20	NA			
Physical Activity on Sleep	2	9	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
(3) Vigorous Physical Activity and Sleep Overall	9	50				
Age	9	50	0.043 (-0.003, 0.088)	-0.024 (-0.045, -0.003)*	$F(1, 48) = 5.234$	.027*
Study Design					NA	
Cross-Sectional	8	42	NA			
Longitudinal	1	8	NA			
Experimental	0	0	NA			
Risk of Bias					NA	
Low	5	37	NA			
High	1	1	NA			
Unclear	2	12	NA			
Study Quality					NA	
High	6	38	NA			
Moderate	2	4	NA			
Low	1	8	NA			
Direction of Association					NA	
No Specified Direction	3	17	NA			
Sleep on Physical Activity	2	20	NA			
Physical Activity on Sleep	4	13	NA			
(4) Light Physical Activity and Sleep Overall	7	51				
Age	7	51	0.073 (-0.075, 0.221)	-0.06 (-0.201, 0.08)	$F(1, 49) = 0.74$	0.394
Study Design					NA	
Cross-Sectional	7	51	NA			
Longitudinal	0	0	NA			
Experimental	0	0	NA			
Risk of Bias					NA	
Low	1	30	NA			
High	5	19	NA			
Unclear	1	2	NA			
Study Quality					NA	
High	5	50	NA			
Moderate	1	1	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	3	4	NA			
Sleep on Physical Activity	2	29	NA			
Physical Activity on Sleep	2	18	NA			
(5) Total Physical Activity and Sleep Overall	24	133				
Age	24	133	0.022 (-0.059, 0.102)	0.007 (-0.026, 0.041)	$F(1, 131) = 0.18$	0.672
Study Design					NA	
Cross-Sectional	22	111	NA			
Longitudinal	1	2	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Experimental	1	20	NA			
Risk of Bias					$F(2, 130) = 0.52$	0.596
Low	13	97	-0.062 (-0.252, 0.127)			
High	4	20	0.048 (-0.055, 0.151)	0.11 (-0.106, 0.326)		
Unclear	5	16	0.008 (-0.167, 0.184)	0.071 (-0.187, 0.329)		
Study Quality					NA	
High	17	106	-0.006 (-0.101, 0.09)			
Moderate	5	13	0.131 (-0.05, 0.313)	0.137 (-0.068, 0.342)		
Low	2	14	NA			
Direction of Association					$F(2, 130) = 0.619$	0.54
No Specified Direction	14	66	0.029 (-0.059, 0.118)			
Sleep on Physical Activity	7	41	0.039 (-0.065, 0.143)	0.01 (-0.084, 0.104)		
Physical Activity on Sleep	9	26	-0.01 (-0.11, 0.09)	-0.04 (-0.135, 0.056)		
(6) Sport and Outdoor Play and Sleep Overall	6	50				
Age	6	50	0.034 (-0.099, 0.167)	-0.004 (-0.037, 0.029)	$F(1, 48) = 0.069$	0.793
Study Design					NA	
Cross-Sectional	6	50	NA			
Longitudinal	0	0	NA			
Experimental	0	0	NA			
Risk of Bias					NA	
Low	2	25	NA			
High	3	23	NA			
Unclear	1	2	NA			
Study Quality					NA	
High	6	50	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	4	11	NA			
Sleep on Physical Activity	1	12	NA			
Physical Activity on Sleep	3	22	NA			
(7) Moderate-to-Vigorous Physical Activity and Sleep Duration	21	80				
Age	21	80	-0.028 (-0.097, 0.041)	0.03 (-0.007, 0.068)	$F(1, 78) = 2.565$	0.113
Study Design					NA	
Cross-Sectional	20	79	NA			
Experimental	1	1	NA			
Longitudinal	0	0	NA			
Risk of Bias					$F(2, 77) = 1.625$	0.204
Low	10	57	-0.028 (-0.115, 0.058)			
High	7	16	-0.01 (-0.125, 0.106)	0.019 (-0.126, 0.163)		
Unclear	3	7	NA	NA		
Study Quality					NA	

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
High	17	72	NA			
Moderate	1	1	NA			
Low	2	7	NA			
Direction of Association					F(2, 77) = 7.006	.002**
No Specified Direction	7	14	-0.11 (-0.198, -0.023)*			
Sleep on Physical Activity	10	41	-0.033 (-0.11, 0.045)	0.078 (0.012, 0.143)*		
Physical Activity on Sleep	7	25	-0.007 (-0.084, 0.071)	0.103 (0.038, 0.169)**		
(8) Moderate-to-Vigorous Physical Activity and Sleep Efficiency	6	19				
Age	6	19	0.057 (-0.121, 0.236)	0.06 (-0.053, 0.173)	F(1, 17) = 1.26	0.277
Study Design					NA	
Cross-Sectional	6	19	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	2	10	NA			
High	3	7	NA			
Unclear	1	2	NA			
Study Quality					NA	
High	5	16	NA			
Moderate	0	0	NA			
Low	1	3	NA			
Direction of Association					F(2, 16) = 1.9	0.182
No Specified Direction	1	1	NA			
Sleep on Physical Activity	4	8	0.148 (-0.061, 0.357)			
Physical Activity on Sleep	4	10	-0.079 (-0.263, 0.105)	0.151 (-0.449, 0.751)		
(9) Moderate-to-Vigorous Physical Activity and Sleep Timing	4	22				
Age	4	22	0.082 (-0.019, 0.183)	0.061 -0.007, 0.129)	F(1, 20) = 3.481	0.077
Study Design					NA	
Cross-Sectional	4	22	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	1	4	NA			
High	2	10	NA			
Unclear	1	8	NA			
Study Quality					NA	
High	2	8	NA			
Moderate	0	0	NA			
Low	2	14	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Direction of Association					NA	
No Specified Direction	2	10	NA			
Sleep on Physical Activity	3	10	NA			
Physical Activity on Sleep	1	2	NA			
(10) Moderate Physical Activity and Sleep Duration	6	16				
Age	6	16	-0.061 (-0.141, 0.018)	0.008 (-0.07, 0.087)	$F(1, 14) = 0.049$	0.828
Study Design					NA	
Cross-Sectional	5	15	NA			
Experimental	1	1	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	2	9	NA			
High	3	4	NA			
Unclear	1	3	NA			
Study Quality					NA	
High	5	15	NA			
Moderate	0	0	NA			
Low	1	1	NA			
Direction of Association					NA	
No Specified Direction	2	4	NA			
Sleep on Physical Activity	2	10	NA			
Physical Activity on Sleep	2	2	NA			
(11) Moderate Physical Activity and Sleep Efficiency	4	9				
Age	4	9	0.223 (-0.172, 0.617)	0.047 (-0.258, 0.353)	$F(1, 7) = 0.133$	0.726
Study Design					NA	
Cross-Sectional	3	7	NA			
Experimental	1	2	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	1	4	NA			
High	3	5	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	2	6	NA			
Moderate	1	1	NA			
Low	1	2	NA			
Direction of Association					NA	
No Specified Direction	1	1	NA			
Sleep on Physical Activity	2	6	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Physical Activity on Sleep	1	2	NA			
(12) Moderate Physical Activity and Sleep Timing	1	4				
Age	1	4	NA		NA	
Study Design					NA	
Cross-Sectional	1	4	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	4	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	1	4	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	0	0	NA			
Sleep on Physical Activity	1	4	NA			
Physical Activity on Sleep	0	0	NA			
(13) Moderate Physical Activity and Light Sleep	2	8				
Age	2	8	NA		NA	
Study Design					NA	
Cross-Sectional	1	6	NA			
Experimental	1	2	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	2	NA			
Unclear	1	6	NA			
Study Quality					NA	
High	1	6	NA			
Moderate	0	0	NA			
Low	1	2	NA			
Direction of Association					NA	
No Specified Direction	1	6	NA			
Sleep on Physical Activity	0	0	NA			
Physical Activity on Sleep	1	2	NA			
(14) Moderate Physical Activity and Deep Sleep	2	5				
Age	2	5	NA		NA	

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Study Design					NA	
Cross-Sectional	1	3	NA			
Experimental	1	2	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	2	NA			
Unclear	1	3	NA			
Study Quality					NA	
High	1	3	NA			
Moderate	0	0	NA			
Low	1	2	NA			
Direction of Association					NA	
No Specified Direction	1	3	NA			
Sleep on Physical Activity	0	0	NA			
Physical Activity on Sleep	1	2	NA			
(15) Moderate Physical Activity and REM Sleep	2	4				
Age	2	4	NA		NA	
Study Design					NA	
Cross-Sectional	1	3	NA			
Experimental	1	1	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	1	NA			
Unclear	1	3	NA			
Study Quality					NA	
High	1	3	NA			
Moderate	0	0	NA			
Low	1	1	NA			
Direction of Association					NA	
No Specified Direction	1	3	NA			
Sleep on Physical Activity	0	0	NA			
Physical Activity on Sleep	1	1	NA			
(16) Vigorous Physical Activity and Sleep Duration	7	19				
Age	7	19	0.053 (-0.006, 0.113)	-0.025 (-0.05, 0.001)	$F(1, 17) = 4.134$	0.058
Study Design					NA	
Cross-Sectional	6	18	NA			
Experimental	1	1	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	3	4	NA			
High	2	9	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Unclear	2	6	NA			
Study Quality					NA	
High	5	15	NA			
Moderate	1	3	NA			
Low	1	1	NA			
Direction of Association					NA	
No Specified Direction	2	4	NA			
Sleep on Physical Activity	2	10	NA			
Physical Activity on Sleep	3	5	NA			
(17) Vigorous Physical Activity and Sleep Efficiency	5	10				
Age	5	10	0.209 (-0.078, 0.497)	0.018 (-0.133, 0.169)	$F(1, 8) = 0.075$	0.79
Study Design					NA	
Cross-Sectional	4	8	NA			
Experimental	1	2	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	1	4	NA			
High	3	5	NA			
Unclear	1	1	NA			
Study Quality					NA	
High	3	7	NA			
Moderate	1	1	NA			
Low	1	2	NA			
Direction of Association					NA	
No Specified Direction	1	1	NA			
Sleep on Physical Activity	2	6	NA			
Physical Activity on Sleep	2	3	NA			
(18) Vigorous Physical Activity and Sleep Timing	1	4				
Age	1	4	NA		NA	
Study Design					NA	
Cross-Sectional	1	4	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	4	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	1	4	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	

Moderator Variables	n. studies	k	Intercept (95%CI)/ *r*(95%CI)	β (95%CI)	*F*(df1, df2)[a]	*p*[b]
No Specified Direction	0	0	NA			
Sleep on Physical Activity	1	4	NA			
Physical Activity on Sleep	0	0	NA			
(19) Vigorous Physical Activity and Light Sleep	2	8				
Age	2	8	NA		NA	
Study Design					NA	
Cross-Sectional	1	6	NA			
Experimental	1	2	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	2	NA			
Unclear	1	6	NA			
Study Quality					NA	
High	1	6	NA			
Moderate	0	0	NA			
Low	1	2	NA			
Direction of Association					NA	
No Specified Direction	1	6	NA			
Sleep on Physical Activity	0	0	NA			
Physical Activity on Sleep	1	2	NA			
(20) Vigorous Physical Activity and Deep Sleep	2	5				
Age	2	5	NA		NA	
Study Design					NA	
Cross-Sectional	1	3	NA			
Experimental	1	2	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	2	NA			
Unclear	1	3	NA			
Study Quality					NA	
High	1	3	NA			
Moderate	0	0	NA			
Low	1	2	NA			
Direction of Association					NA	
No Specified Direction	1	3	NA			
Sleep on Physical Activity	0	0	NA			
Physical Activity on Sleep	1	2	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
(21) Vigorous Physical Activity and REM Sleep	2	4				
Age	2	4	NA		NA	
Study Design					NA	
Cross-Sectional	1	3	NA			
Experimental	1	1	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	1	NA			
Unclear	1	3	NA			
Study Quality					NA	
High	1	3	NA			
Moderate	0	0	NA			
Low	1	1	NA			
Direction of Association					NA	
No Specified Direction	1	3	NA			
Sleep on Physical Activity	0	0	NA			
Physical Activity on Sleep	1	1	NA			
(22) Light Physical Activity and Sleep Duration	6	42				
Age	6	42	0.047 (-0.099, 0.192)	0.018 (-0.139, 0.175)	$F(1, 40) = 0.056$	0.814
Study Design					NA	
Cross-Sectional	6	42	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	2	32	NA			
High	4	10	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	6	42	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	2	3	NA			
Sleep on Physical Activity	4	22	NA			
Physical Activity on Sleep	2	17	NA			
(23) Light Physical Activity and Sleep Efficiency	3	5				
Age	3	5	NA		NA	
Study Design					NA	
Cross-Sectional	3	5	NA			
Experimental	0	0	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	3	5	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	2	4	NA			
Moderate	1	1	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	1	1	NA			
Sleep on Physical Activity	2	3	NA			
Physical Activity on Sleep	1	1	NA			
(24) Light Physical Activity and Sleep Timing	1	4				
Age	1	4	NA		NA	
Study Design					NA	
Cross-Sectional	1	4	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	1	4	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	1	4	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	0	0	NA			
Sleep on Physical Activity	1	4	NA			
Physical Activity on Sleep	0	0	NA			
(25) Total Physical Activity and Sleep Duration	17	35				
Age	17	35	-0.036 (-0.098, 0.027)	-0.011 (-0.036, 0.015)	$F(1, 33) = 0.693$	0.411
Study Design					NA	
Cross-Sectional	16	33	NA			
Experimental	1	2	NA			
Longitudinal	0	0	NA			
Risk of Bias					$F(2, 32) = 0.914$	0.411
Low	3	7	NA			
High	10	18	-0.043 (-0.12, 0.033)			
Unclear	4	10	0.035 (-0.074, 0.145)	0.097 (-0.073, 0.266)		
Study Quality					NA	
High	12	25	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Moderate	3	5	NA			
Low	2	5	NA			
Direction of Association					$F(2, 32) = 0.813$	0.453
No Specified Direction	9	15	-0.056 (-0.13, 0.018)			
Sleep on Physical Activity	5	9	0.001 (-0.089, 0.09)	0.057 (-0.048, 0.161)		
Physical Activity on Sleep	6	11	-0.002 (-0.084, 0.08)	0.054 (-0.046, 0.154)		
(26) Total Physical Activity and Sleep Efficiency	5	16				
Age	5	16	0.162 (-0.269, 0.592)	0.012 (-0.162, 0.186)	$F(1, 14) = 0.023$	0.881
Study Design					NA	
Cross-Sectional	5	16	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	2	10	NA			
High	2	4	NA			
Unclear	1	2	NA			
Study Quality					NA	
High	3	12	NA			
Moderate	1	1	NA			
Low	1	3	NA			
Direction of Association					NA	
No Specified Direction	3	5	NA			
Sleep on Physical Activity	3	5	NA			
Physical Activity on Sleep	3	6	NA			
(27) Total Physical Activity and Sleep Timing	3	22				
Age	3	22	NA		NA	
Study Design					NA	
Cross-Sectional	3	22	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	2	18	NA			
Unclear	1	4	NA			
Study Quality					NA	
High	2	16	NA			
Moderate	0	0	NA			
Low	1	6	NA			
Direction of Association					NA	
No Specified Direction	1	2	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Sleep on Physical Activity	2	14	NA			
Physical Activity on Sleep	2	6	NA			
(28) Total Physical Activity and Sleep Quality	6	51				
Age	6	51	-0.177 (-0.387, 0.032)	0.114 (0.009, 0.219)*	F(1, 49) = 4.728	.035*
Study Design					NA	
Cross-Sectional	5	31	NA			
Experimental	0	0	NA			
Longitudinal	1	20	NA			
Risk of Bias					NA	
Low	1	3	NA			
High	5	48	NA			
Unclear	0	0				
Study Quality					NA	
High	4	44	NA			
Moderate	2	7	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	4	41	NA			
Sleep on Physical Activity	2	7	NA			
Physical Activity on Sleep	2	3	NA			
(29) Total Physical Activity and Daytime Tiredness	2	9				
Age	2	9	NA		NA	
Study Design					NA	
Cross-Sectional	2	9	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	0	0	NA			
High	2	9	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	2	9	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	1	3	NA			
Sleep on Physical Activity	1	6	NA			
Physical Activity on Sleep	0	0	NA			
(30) Sport and Outdoor Play and Sleep Duration	4	19				

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
Age	4	19	0.005 (-0.082, 0.092)	-0.007 (-0.029, 0.014)	$F(1, 17) = 0.517$	0.482
Study Design					NA	
Cross-Sectional	4	19	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	2	13	NA			
High	2	6	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	4	19	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	3	5	NA			
Sleep on Physical Activity	1	6	NA			
Physical Activity on Sleep	2	8	NA			
(31) Sport and Outdoor Play and Sleep Efficiency	3	12				
Age	3	12	NA		NA	
Study Design					NA	
Cross-Sectional	3	12	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	1	6	NA			
High	2	6	NA			
Unclear	0	0	NA			
Study Quality					NA	
High	3	12	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	1	2	NA			
Sleep on Physical Activity	1	3	NA			
Physical Activity on Sleep	2	7	NA			
(32) Sport and Outdoor Play and Sleep Timing	5	19				
Age	5	19	-0.016 (-0.104, 0.072)	-0.004 (-0.03, 0.023)	$F(1, 17) = 0.086$	0.773
Study Design					NA	
Cross-Sectional	5	19	NA			
Experimental	0	0	NA			
Longitudinal	0	0	NA			
Risk of Bias					NA	
Low	1	6	NA			

Moderator Variables	n. studies	k	Intercept (95%CI)/ r(95%CI)	β (95%CI)	F(df1, df2)[a]	p[b]
High	3	11	NA			
Unclear	1	2	NA			
Study Quality					NA	
High	5	19	NA			
Moderate	0	0	NA			
Low	0	0	NA			
Direction of Association					NA	
No Specified Direction	2	4	NA			
Sleep on Physical Activity	1	3	NA			
Physical Activity on Sleep	3	12	NA			

Note. *n. studies* = number of studies; *k* = number of effect sizes; *r* = correlation coefficient; CI = confidence interval; β= estimated regression coefficient; NA = not applicable, indicating that the association did not have enough studies to conduct the moderator analysis defined as at least 5 studies for continuous moderators and at least 4 studies for each level of categorical moderators.

[a] Omnibus test of all regression coefficients in the model.

[b] p-Value of the omnibus test.

* p < .05

** p < .01

*** p < .001

Appendix A.6 PRISMA Checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	1
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	5
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	5
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	5
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	5
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	6
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	6
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	6
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	7
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	7
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	7
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	8

		consistency (e.g., I^2) for each meta-analysis.	
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	7
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	9
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	10
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	10
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	11
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	11
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	11
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	11
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	12,14,16
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	17
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	18
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	19
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	20

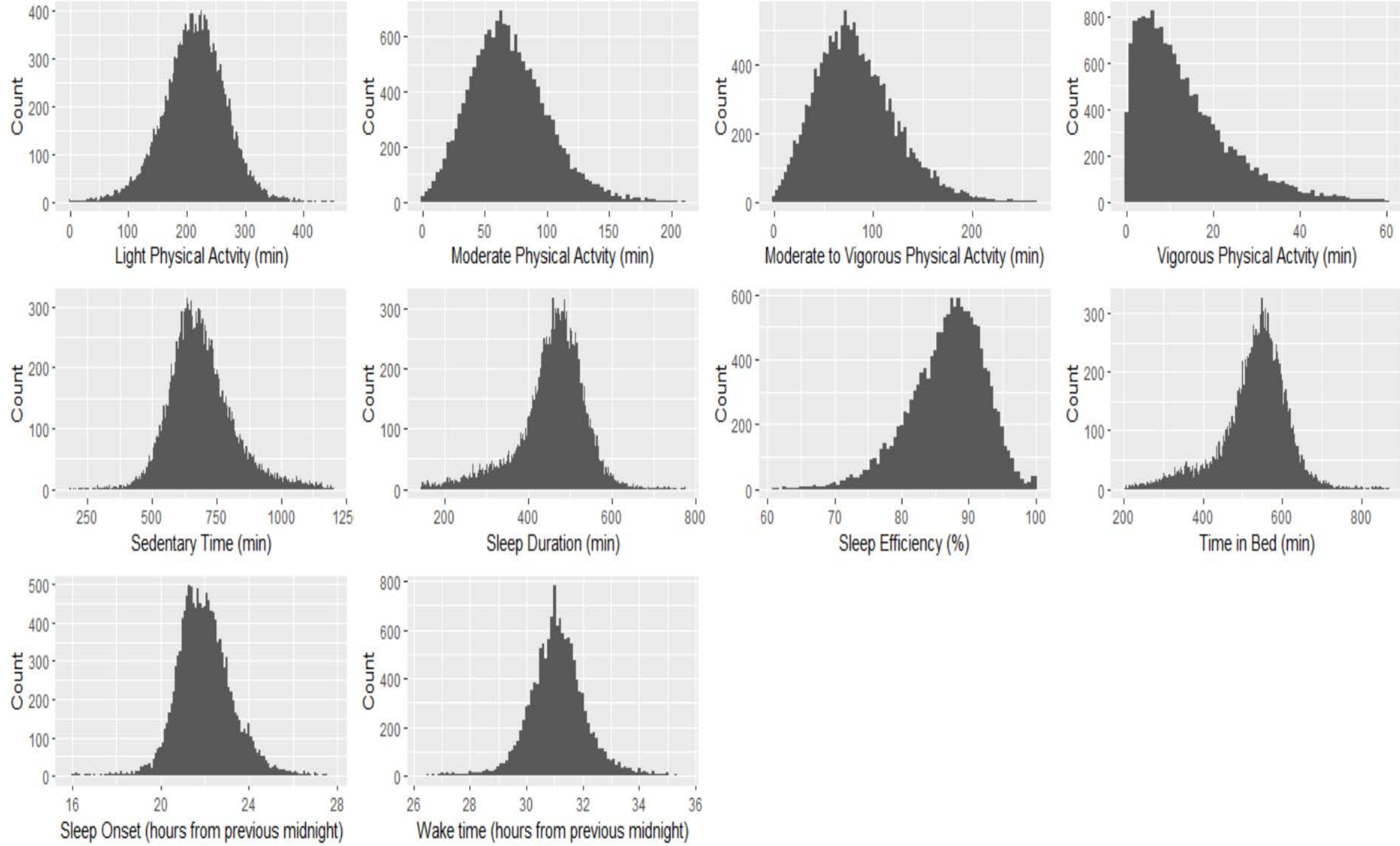
From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit: **www.prisma-statement.org**.

Appendix B (Chapter 3) | Longitudinal Study Supplementary Material

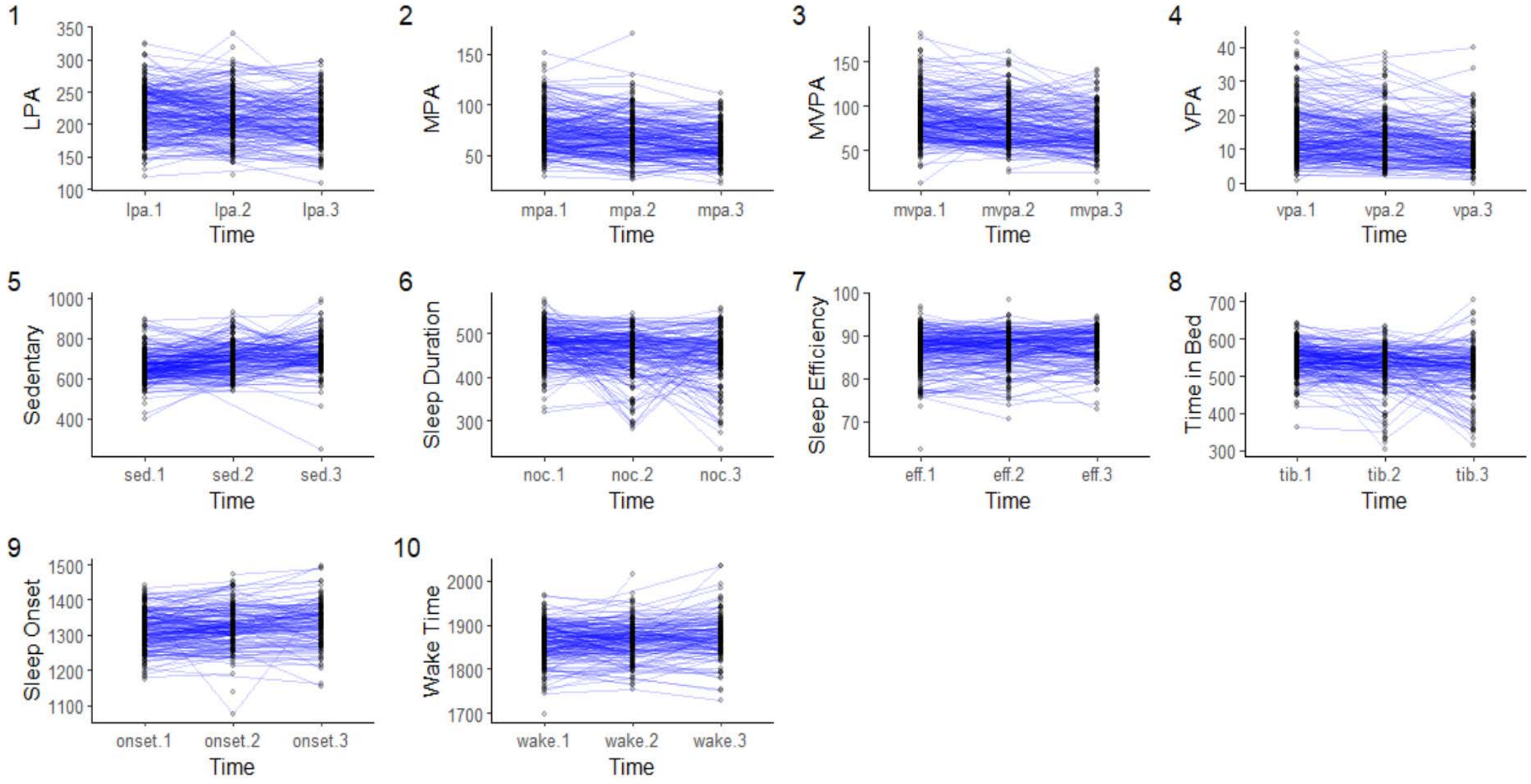
Appendix B.1 Distributions of physical activity and sleep variables

Supplementary Figure 3.1 Distributions of physical activity and sleep variables



Appendix B.2 Trajectories of change in physical activity and sleep variables at Baseline, Year 1, and Year 2

Supplementary Figure 3.2 Trajectories of change in physical activity and sleep variables at Baseline, Year 1, and Year 2



Appendix B.3 Comparisons of Day-to-Day and Longer-Term Variation

Supplementary Table 3.1 Average individual SDs within weeks (i.e., day-to-day) vs. within timepoints (i.e., longer-term)

	Day to Day	Longer Term
Light Physical Activity (min)	37.13	19.90
Moderate Physical Activity (min)	21.55	10.78
Moderate-to-Vigorous Physical Activity (min)	27.57	13.59
vigorous Physical Activity (min)	7.06	3.40
Sedentary Time (min)	91.39	55.67
Sleep Duration (min)	57.83	35.13
Sleep Efficiency (%)	3.91	1.79
Time in Bed (min)	59.97	40.35
Sleep Onset (min)	50.93	25.56
Wake Time (min)	44.64	20.60

Appendix B.4 STROBE Statement—Checklist of items that should be included in reports of cohort studies

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract (*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	1,3
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	4
Objectives	3	State specific objectives, including any prespecified hypotheses	5
Methods			
Study design	4	Present key elements of study design early in the paper	5
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	5
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up (*b*) For matched studies, give matching criteria and number of exposed and unexposed	5
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	5-6
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	5-6
Bias	9	Describe any efforts to address potential sources of bias	6
Study size	10	Explain how the study size was arrived at	6
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	6
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding (*b*) Describe any methods used to examine subgroups and interactions (*c*) Explain how missing data were addressed (*d*) If applicable, explain how loss to follow-up was addressed (*e*) Describe any sensitivity analyses	7
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed (b) Give reasons for non-participation at each stage (c) Consider use of a flow diagram	8
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	9

		(b) Indicate number of participants with missing data for each variable of interest (c) Summarise follow-up time (eg, average and total amount)	
Outcome data	15*	Report numbers of outcome events or summary measures over time	9
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included (*b*) Report category boundaries when continuous variables were categorized (*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	10
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	na
Discussion			
Key results	18	Summarise key results with reference to study objectives	11
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	13
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	11-12
Generalisability	21	Discuss the generalisability (external validity) of the study results	13
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	na

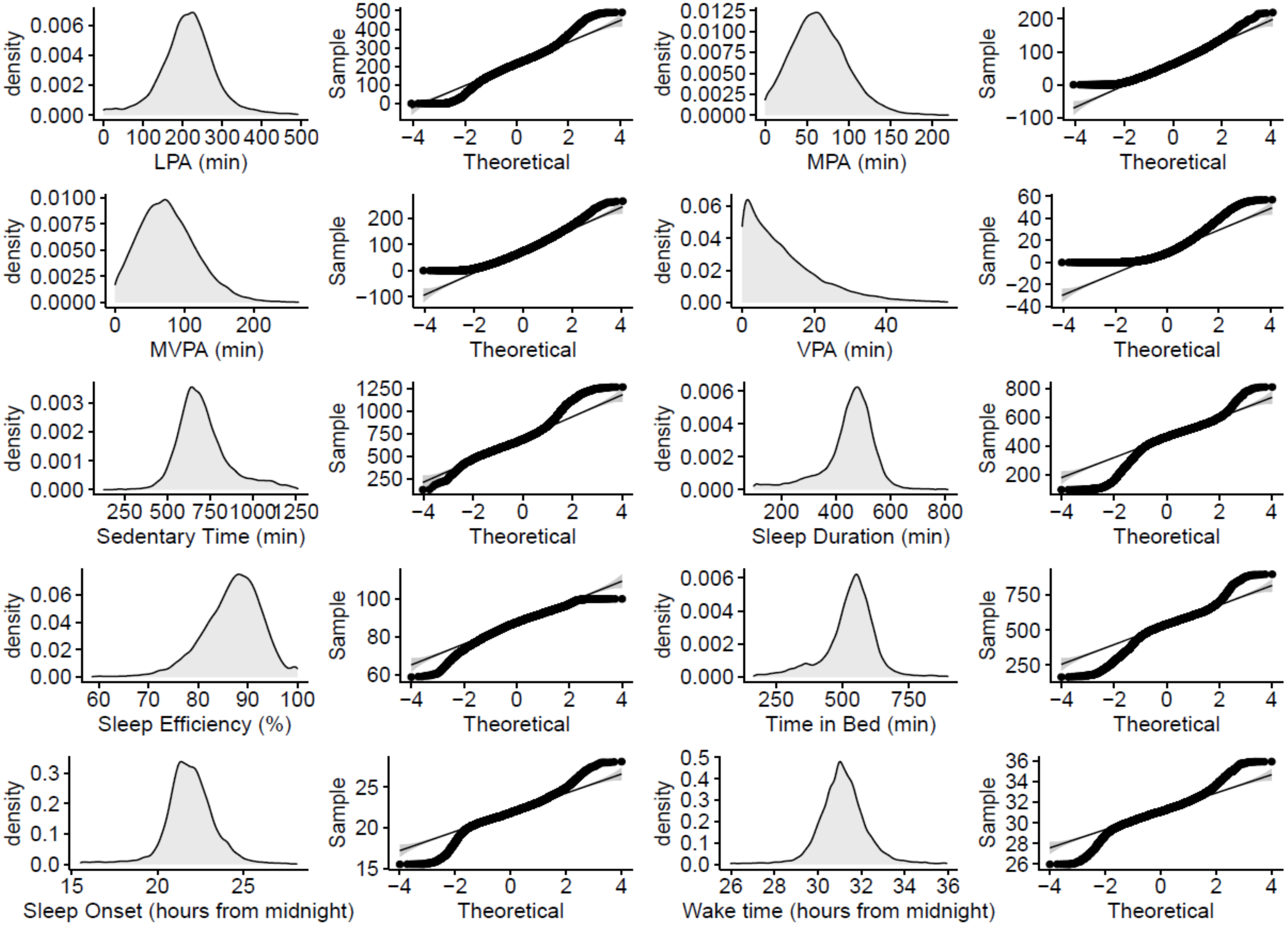
*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at http://www.strobe-statement.org.

Appendix C (Chapter 4) | Reliability Study Supplementary Material

Appendix C.1 Distributions of sleep and physical activity variables

Supplementary Figure 4.1 Distributions of sleep and physical activity variables



Appendix D | Ethics Information for the iPLAY Study

Appendix D.1 Evidence of Ethics Approval

2014 185N Modification approved

Ms Pratigya Pozniak <pratigya.pozniak@acu.edu.au>

Tue 4/5/2016 2:20 PM

Research - Schools

To:Chris Lonsdale <Chris.Lonsdale@acu.edu.au>;

Cc:Pratigya Pozniak <Pratigya.Pozniak@acu.edu.au>;

Dear Christopher,

Ethics Register Number : 2014 185N
Project Title : A Cluster Randomised Controlled Trial of a School-based Physical Activity Intervention in At-risk Communities. (Primary school project: Evidenced based Physical Activity Promotion in NSW Primary Schools)
End Date : 31/12/2016

Thank you for submitting the request to modify form for the above project.

The Chair of the Human Research Ethics Committee has approved the following modification(s):

1. Scaling up: The study originally approved under HREC Registration number 2014 185N has been awarded further funding from the NHMRC to scale-up the project. As a result of the additional funding, the nature of the study has changed from a randomised controlled trial (RCT) involving 20 schools to now also include 180 schools in a dissemination study with a pre-post design. The intervention in the RCT and dissemination will be identical. Most other procedures will also be the same, except in the dissemination study no objective measures will be collected. The researchers will, therefore, not supply children in dissemination study schools with accelerometers to wear for a week, nor will they measure fitness, blood pressure and fundamental movement skills. Students, teachers and principals in dissemination schools will only be required to complete the pre and post intervention questionnaires during class time. In effect, the project now contains three 'levels' of assessment.
2. Passive vs Active Consent: Request to seek passive consent for all dissemination study schools (540-720 classes from 180 schools) and for students in the main sample of the RCT who will not be asked to provide heart rate, blood pressure or fundamental movement skill assessments.
3. Attention control: Introduce an attention control intervention for the 10 schools in the control arm of the RCT.

We wish you well in this ongoing research project.

Kind regards,
Ms Pratigya Pozniak

Ethics Officer | Research Services
Office of the Deputy Vice Chancellor (Research)

Appendix D.2 iPLAY Information Letter and Consent Form

Professor Chris Lonsdale
Institute for Positive Psychology and Education
Australian Catholic University
33 Berry Street, PO Box 968
North Sydney NSW 2059.
Phone: (02) 9701 4642

TEACHER INFORMATION STATEMENT

Dear Teacher,

Your school is participating in a research project conducted by Australian Catholic University, called iPLAY. This project is funded and supported by the NSW Department of Education and the National Health and Medical Research Council and will evaluate the effectiveness of a professional learning intervention targeting primary school teachers. The research involves developing teachers' skills and strategies to improve sport and PE lessons and increase students' physical activity and health. These improvements are expected to increase students' engagement, motivation, behaviour and learning as well as improve teachers' confidence.

Who is carrying out the study?
This project is being conducted by Professor Chris Lonsdale (Chief Investigator) from Australian Catholic University and Professor David Lubans from the University of Newcastle.

What does the study involve?

Overview
Baseline assessment will occur once we receive consent. The baseline assessment involves a 5 minute online questionnaire for teachers. The intervention will take place over 3 terms, with the post-intervention assessment occurring 12 months and 24 months after the original baseline assessment.

As part of the research project we are interested in the link between teachers' experiences at work and their days absent from work. We would like to contact the Human Resources Department of the NSW Department of Education (DoE) and/or your principal to obtain information about your days absent from work over the duration of the study. We will seek information for all teachers in the study and link it with their survey responses in a confidential manner. Neither the DoE nor your principal will have access to your survey responses. Information gained during the study may be published, but no information will be used in any way that reveals your identity.

The intervention will involve all teachers completing a 2-hour face-to-face workshop, online learning modules and 3 mentoring sessions over 4 terms.

How much time will the study take?
Teacher questionnaires will be completed online and will require 5 minutes (x 3 time points).
Professional Development Intervention: Teachers will participate in a 2-hour workshop and complete 4 hours of online self-paced learning modules. In addition, there are three one hour mentor sessions, each with 1 hour of preparation and lesson reflections. One of mentoring sessions will be with a specialist mentor, one with a peer and one as a group mentoring session. Action plans and resources are available through our website and mobile app.
Total: 14 hours of professional development.

Will the study benefit me?
Teachers
All teachers who take part in the study will receive 14 hours of BOSTES registered TPL at '*Proficient*' level. There will be extra hours offered at '*Highly Accomplished*' for up to 3 iPLAY leaders in each school. Teachers participating in the study will have access to the iPLAY website and mobile app which have been designed to build capacity to teach sport and physical activity in your school.

Participating teachers are expected to improve the quality of their teaching, resulting in increased motivation and engagement for students. Thus, you may benefit from greater job satisfaction.

Students
The professional development training course is designed to help teachers create a more stimulating learning environment. As a result, students may benefit from higher quality teaching, resulting in more enjoyable sport and P.E lessons. Compared with usual practice, the iPLAY intervention aims to produce positive effects on students' moderate-to-vigorous physical activity levels, fundamental movement skills, physical health and subjective well-being. Also, there is evidence that students who are more physically active are also more engaged with school and have greater academic performance.

Will the study involve any discomfort for me?
No discomfort is expected.

How is this study being paid for?
The study is funded by the NSW Department of Education and the National Health and Medical Research Council.

Will anyone else know the results? How will the results be disseminated?
The researchers will keep confidential any personal information provided by teachers. Once the data has been collected, de-identified using a coding system, and entered into an electronic data file, questionnaires and other data collection sheets will be destroyed. The electronic data files will be retained for at least 5 years, but no individual will be identifiable in published reports.

At the end of the study, each principal and teacher will be sent a report describing the main results. Individual results will not be provided to all students, but will be available upon request by a parent or student. Scholarly reports, such as journal articles, will also be published. All reports will be published in general terms and will not allow the identification of individual schools.

Can I withdraw from the study?
A decision regarding your school's participation in the study has been made by your principal. If you agree to participate, you can choose to stop participation at any time. A decision not to participate or end involvement in the study will not jeopardise your relationship with the Australian Catholic University or the University of Newcastle. Withdrawal from this study will not result in any action against you or your school; this is a purely voluntary research activity.

Can I tell other people about the study?
You are welcome to discuss the study with others and invite principals and teachers from other government-funded primary schools to contact the research team if they wish to learn more about the study.

What if I require further information?
If you would like further information please do not hesitate to contact Professor Chris Lonsdale at admin@iplay.org.au or 9701 4732. Thank you for considering this invitation

What if I have a complaint?
This study has been approved by the Australian Catholic University Human Research Ethics Committee. The approval number is 2014185N if you have any complaints or reservations about the ethical conduct of this research, you may contact the Ethics Committee on 02 9739 2519 or via email: res.ethics@acu.edu.au. Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

[redacted]

Professor Chris Lonsdale
Institute for Positive Psychology and Education
Australian Catholic University
Phone: (02) 9701 4642
chris.lonsdale@acu.edu.au

Professor Chris Lonsdale
Institute for Positive Psychology and Education
Australian Catholic University
33 Berry Street, PO Box 968
North Sydney NSW 2059.
Phone: (02) 9701 4642

Research Project:
Evidenced-based Physical Activity Promotion in NSW Primary Schools
Chief Investigators: A/Prof Chris Lonsdale and Prof David Lubans

TEACHER CONSENT FORM

I acknowledge that:

I have read the teacher information sheet and have been given the opportunity to discuss the information and my involvement in the project with the researchers via telephone or email.

The procedures required for the project and the time involved have been explained to me, and any questions I have about the project have been answered to my satisfaction.

I understand that my involvement is confidential and that the information gained during the study may be published, but no information will be used in any way that reveals my identity.

I understand that my participation in this study is voluntary. I can withdraw my school from the study at any time, without penalty.

I consent to being involved in:
1. The completion of professional development
2. Answering questionnaires (5 mins x 3 time points over 3 year period)
3. The DoE and/or my principal providing information about my days absent during the consented 3 year period.
Please cross out any activity for which you do not provide consent.

Name of school:	*Teacher's name:*
Mobile: *Stage/Class:*	*DET Email:*
Signature:	*Date:*
NESA teacher No:	

Please sign the consent form and return to the research team at admin@iplay.org.au

This study has been approved by the Australian Catholic University Human Research Ethics Committee. The Approval number is: 2014185N.
Manager, Ethics c/o Office of the Deputy Vice Chancellor (Research), Australian Catholic University, North Sydney Campus
PO Box 968. NORTH SYDNEY, NSW 2059 Ph.: 02 9739 2519 Fax: 02 9739 2870Email: res.ethics@acu.edu.au
Any issues you raise will be treated in confidence and investigated fully, and you will be informed of the outcome.

Institute for Positive Psychology & Education

ACU
AUSTRALIAN CATHOLIC UNIVERSITY

Appendix E | Discussion Sensitivity Analysis

Supplementary Table 5.1 Sensitivity analysis for parallel process latent growth model results with minimum 5 days of valid data rather than 4 days

	Moderate Physical Activity (min)			**Moderate-to-Vigorous Physical Activity (min)**			**Vigorous Physical Activity (min)**		
	Std. Estimate (r)	Std. Error	p value	Std. Estimate (r)	Std. Error	p value	Std. Estimate (r)	Std. Error	p value
Sleep Duration (min)									
s2 on i1	0.071	0.030	0.524	0.053	0.036	0.608	0.021	0.008	0.865
s1 on i2	0.040	0.104	0.898	-0.102	0.081	0.747	-0.390	0.333	0.234
s1 with s2	-0.243	0.004	0.510	-0.168	0.005	0.635	-0.071	0.001	0.882
i1 with i2	-0.129	0.013	0.181	-0.098	0.016	0.297	0.012	0.004	0.903
s1 on i1	0.161	0.129	0.767	0.131	0.128	0.807	0.052	0.125	0.917
s2 on i2	-0.342	0.049	0.008 *	-0.374	0.046	0.003 *	-0.522	0.050	0.006 *
Sleep Efficiency (%)									
s2 on i1	-0.013	0.135	0.858	0.044	2.513	0.575	0.013	0.050	0.905
s1 on i2	-0.051	0.005	0.623	0.007	2.348	0.951	-0.045	0.016	0.699
s1 with s2	-0.014	0.714	0.914	-0.023	1.035	0.856	-0.076	0.191	0.639
i1 with i2	-0.114	4.729	0.112	-0.147	6.019	0.035 *	-0.220	1.617	0.002 *
s1 on i1	-0.314	0.054	0.138	-0.307	0.838	0.213	-0.314	0.056	0.161
s2 on i2	-0.342	0.050	0.010 *	-0.373	35.036	0.027 *	-0.526	0.054	0.015 *
Time in Bed (min)									
s2 on i1	0.000	0.023	0.998	-0.021	0.034	0.831	-0.086	0.443	0.464
s1 on i2	0.026	0.100	0.775	-0.158	0.084	0.585	-0.422	0.006	0.151
s1 with s2	-0.065	0.004	0.585	-0.085	0.005	0.801	0.165	0.071	0.737
i1 with i2	0.017	0.013	0.845	0.091	0.016	0.342	0.278	0.257	0.002 *
s1 on i1	-0.359	0.091	0.004 *	-0.456	0.169	0.462	-0.458	0.161	0.370
s2 on i2	-0.353	0.049	0.007 *	-0.378	0.047	0.003 *	-0.499	0.055	0.016 *
Sleep Onset (hours)									
s2 on i1	-0.101	0.840	0.341	-0.089	0.017	0.370	-0.107	0.283	0.461
s1 on i2	-0.198	0.001	0.400	-0.113	0.063	0.640	0.011	0.005	0.969
s1 with s2	-0.002	0.178	0.995	-0.020	0.004	0.945	0.307	0.049	0.426
i1 with i2	-0.091	1.157	0.281	-0.149	0.025	0.069	-0.285	0.389	0.001 *
s1 on i1	-0.248	0.037	0.356	-0.251	0.038	0.361	-0.246	0.039	0.391
s2 on i2	-0.276	0.064	0.160	-0.341	0.060	0.058	-0.537	0.068	0.062
Wake Time (hours)									
s2 on i1	-0.051	0.017	0.625	-0.057	0.02	0.554	-0.124	0.004	0.24
s1 on i2	-0.043	0.071	0.694	-0.081	0.054	0.452	-0.184	0.222	0.103
s1 with s2	-0.263	9.746	0.067	-0.195	11.306	0.123	0.074	2.502	0.626
i1 with i2	-0.092	64.855	0.302	-0.107	81.947	0.214	-0.11	21.489	0.194
s1 on i1	-0.337	0.057	0.072	-0.346	0.057	0.06	-0.368	0.057	0.042 *
s2 on i2	-0.297	0.061	0.097	-0.357	0.056	0.027 *	-0.531	0.061	0.021 *

i1 = intercept for sleep variable
i2 = intercept for physical activity variable
s1 = slope for sleep variable
s2 = slope for physical activity variable
with = correlation path
on = regression path