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How sleep mediates the relationship between physical activity and mood in adolescents

By

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SUMMARY

Sleep problems and mood difficulties can substantially impact adolescents' lives. Yet, the multiple interrelationships between physical activity, sleep, and mood make physical activity interventions a viable option to prevent and treat these difficulties. This thesis aimed to explore if sleep mediates the 'physical activity - mood' connection; through sleep onset latency (SOL), total sleep time (TST), and sleep timing (chronotype and circadian rhythm timing). The mediations were explored using different designs and measurements throughout the thesis.

The uniqueness of adolescent sleep, and the links between physical activity, sleep, and mood are introduced in **Chapter 1**. The proposed TST mediation emulated the typical beneficial effect of physical activity on sleep and mood; more physical activity → longer TST → better mood. As evening physical activity is often considered detrimental to sleep, this was reflected in the proposed models; more evening physical activity → worse sleep (longer SOL, later sleep timing) → worse mood.

Initial support for the models was found in **Chapter 2** in a large (N = 1,367) cross-sectional sample of adolescents. The data fit the mediation models; more physical activity → better sleep (longer TST, shorter SOL, earlier chronotype) → better mood. The models were significant for the total sample and for girls, but not boys, highlighting potential sex differences. Unexpectedly, evening physical activity (after 6 p.m.) was not linked with worse sleep or mood.

Temporal relationships were assessed in **Chapter 3** with a sample of 19 adolescent girls. Assessments took place over 1 week using objective actigraphy to measure sleep and physical activity, and daily ecological momentary assessments of mood. Chronotype acted as a mediator; more evening physical activity → earlier chronotype → better mood. TST mediations varied from day-to-day. On Wednesday, Friday, and Sunday; more physical activity → shorter TST → mood change. Mood improved on Friday and Sunday, but worsened on Wednesday. Again, evening physical activity (within 3 hours of bedtime) was not detrimental to sleep.

In a laboratory setting, **Chapter 4** assessed the impact of a 5-day physical activity intervention in adolescent boys with a late chronotype. Eighteen boys were randomly allocated to 45 minutes light-intensity treadmill-walking, or 45 minutes sitting. Objective measures assessed sleep (dim light melatonin onset via saliva assay) and physical activity (heart rate monitoring). In this experimental study, the mediation models were not supported. Although morning activity advanced the circadian rhythm (walking group 28-minute circadian advance; sitting group 19-minute delay), mood was not significantly related to sleep or physical activity.

This thesis found evidence that sleep mediates the relationship between physical activity and mood through sleep timing, TST, and SOL. Notable sex differences were found. The mediations were significant in girls, but not in boys. Physical activity’s beneficial effect on sleep and mood indicates that it may prove helpful in the prevention and treatment of sleep and mood difficulties in adolescent girls. The finding that evening physical activity was not detrimental to sleep and mood will be instructive for clinicians providing physical activity recommendations to adolescents.

DECLARATION

I certify that this thesis:

1) does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university
2) and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3) to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signed: MAHeath

Melanie Heath, B. Psych. (Hons.) Date: 03/05/2023

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CHAPTER 1 -

PHYSICAL ACTIVITY, SLEEP, AND MOOD IN ADOLESCENCE: AN EXPLORATION OF COMPLEX CONNECTIONS

1.1 Introduction

Adolescence is a period of dramatic development in a person’s life, and during this time adolescents experience many changes (Towbin et al., 2015). Along with the myriad of new experiences (learning to drive, first job, first romantic relationship) and increasing independence which occurs during this time, the incidence of depression also begins to increase in this age group, particularly in girls (Angold & Costello, 2006). A meta-analysis of depression prevalence (which included studies ranging from current to lifetime prevalence) estimated that the worldwide-pooled prevalence of depression in adolescents is 2.6% (Polanczyk et al., 2015), though in some countries such as the United Kingdom and United States of America this is estimated to be much higher at 7.5% and 11.3% over 12 months, respectively (Goodyer et al., 2017; Mojtabai et al., 2016; Wesselhoeft et al., 2013). Depression - and depressed mood - have a substantial impact on many aspects of the lives of adolescents who experience them. Longitudinal research, systematic reviews, and meta-analyses have found detriments in academic achievement, future mental health, quality of life, and long-term psychosocial outcomes (Bertha & Balázs, 2013; Clayborne et al., 2019; Wickersham et al., 2021). Adolescents also commonly experience sleep difficulties, including the length of time taken to fall asleep (sleep onset latency; (Gradisar et al., 2011; Short, Gradisar, Gill, et al., 2013; Short, Gradisar, Lack, et al., 2013)), not obtaining enough sleep (total sleep time; (Gariepy et al., 2020; Saxvig et al., 2020; Sharman et al., 2017)), and falling asleep later and waking up later than expected by society (late chronotype or delayed circadian rhythm; (Crowley et al., 2018; Roenneberg et al., 2004)). These sleep difficulties also present negative consequences, such as academic difficulties, worse physical health, and a higher likelihood of participating in risk-taking behaviours (Agostini & Centofanti, 2021; Shochat et al., 2014). Due to the substantial impact of depression and poor sleep on adolescents’ lives, it is important that interventions and/or preventative measures are developed to improve outcomes. One common protective factor for both sleep and mood is physical activity in adolescents. Those who participate in more physical activity often have better sleep and report better mood than adolescents who are less active (Brand et al., 2010b; Harris et al., 2017; Kalak et al., 2012). Thus, there is potential for physical activity to be used as a novel prevention or intervention measure for sleep and mood difficulties in adolescents.

In addition to the extensive research which has demonstrated strong connections between physical activity, sleep, and mood (Buecker et al., 2021; Gariépy et al., 2019; Short et al., 2020; Stubbs et al., 2018), there is also evidence within this research base to suggest a more complex model of the ways in which physical activity and sleep can influence mood. The aim of this thesis is to test a set of models, incorporating all three domains, in order to foster a greater understanding of the mechanisms involved in these connections. Due to the unique nature of adolescent sleep (Crowley et al., 2018; Tarokh et al., 2019), this introduction will begin by first exploring the main aspects of adolescent sleep before guiding the reader through the connections between the three domains of physical activity, sleep, and mood. The introduction will provide a more in-depth discussion of the 'sleep – mood' connection, before introducing the important relationships of physical activity with both sleep and mood. In addition to discussion of the relationships between 'sleep – mood', 'physical activity – sleep', and 'physical activity – mood', this introduction will also propose the set of models, which will eventually be tested in the main body of the thesis.

1.2 Typical Sleep and Sleep Difficulties in Adolescents

Typical adolescent sleep looks notably different from that of children and adults. Many biological, cognitive, emotional and social changes occur during adolescence and these changes have a strong impact on their sleep (Owens & Weiss, 2017). Arguably, the most distinguishable change is the slow emergence of a delay in the circadian rhythm (Hagenauer & Lee, 2012; Roenneberg et al., 2004). The circadian rhythm is an endogenous system, which acts as the timekeeper for night and day behaviour in humans (Refinetti & Menaker, 1992). It alters the body's propensity for sleep and wakefulness to ensure that humans sleep during the night and stay awake throughout the day (Refinetti & Menaker, 1992). At the onset of puberty, the circadian rhythm has been shown to delay, and adolescents' bedtime and waketime preferences drift later (Carskadon, 2011; Hagenauer & Lee, 2012; Roenneberg et al., 2004). This delay in sleep timing makes it difficult for adolescents to fall asleep at the time required by societal expectations, and when this physiological drive to sleep later interacts with various behavioural (e.g., evening social activities), societal (e.g., school start times), and psychosocial factors (e.g., increasing study load), this difficulty to fall asleep at a socially-acceptable time is compounded (Crowley et al., 2007; Owens & Weiss, 2017).

Today's adolescents are growing up in a technological landscape which offers challenges and pressures not experienced by previous generations during this life stage (Uhls et al., 2017). Electronics and social media play a large role in adolescents' lives, and with the recent COVID-19 pandemic, adolescent technology use and screen time has increased worldwide (Carroll et al., 2020; López-Bueno et al., 2020; Pietrobelli et al., 2020), an increase which has been seen not only through online learning, but also leisure screen time (Moore et al., 2020; Xiang et al., 2020). Early research generally indicated that adolescents' sleep may be negatively impacted by the use of electronics. A review by Cain and Gradisar (2010) noted that different forms of technology, such as television viewing, and the use of gaming devices and mobile phones, were found to negatively relate to adolescent sleep in multiple ways, including later bedtimes, increased sleep latency, reduced sleep duration, and daytime sleepiness. These same negative impacts on sleep have also been more recently associated with adolescent night-time social media use (Garmy & Ward, 2018; Scott & Woods, 2018; Twenge et al., 2017; van der Schuur et al., 2019). Further to this, a more recent review has also noted connections between more social media use, worse sleep quality, and worse mental health in adolescents (Alonzo et al., 2021). It is important not to dismiss how the late-night use of electronics and social media, and continuing developments in technology, may combine with delayed circadian rhythms to exacerbate adolescents' sleep difficulties.

Another contributing factor to adolescent sleep difficulties is the ability to choose one's own bedtime. Adolescence is a time of increasing independence, and for most adolescents this means at some point choosing their own bedtime. Meta-analytical evidence shows that adolescents who choose their own bedtime select a later bedtime than their peers with parent-set bedtimes (Khor et al., 2021). While this tendency to choose a later bedtime reflects the adolescents' preference to sleep later in accordance with their circadian rhythm (Roenneberg et al., 2004), it is ultimately detrimental, as adolescents with later bedtimes are still required to wake at the same time in the morning as their peers to attend school, resulting in a shorter sleep duration (Crowley et al., 2018). In this way, parent-set bedtimes are protective for adolescent sleep, by ensuring an earlier bedtime and a greater sleep opportunity (Short et al., 2011). For example, Bartel and colleagues' (2015) meta-analysis of protective and risk factors for adolescent sleep identified that parent-set bedtimes had the strongest association with longer total sleep time than any other protective factors, with a mean weighted r of .22. Although this association was small-to-moderate, it was stronger than the second strongest protective factor, sleep hygiene (mean weighted r of .20), or the strongest risk factor, tobacco use (mean weighted r of -.18). In short, the difficulties adolescents' experience in falling asleep, appears to be caused initially by their delayed circadian rhythms, and compounded by later bedtimes, but may be influenced further by protective or risk factors. However, falling asleep is not the only aspect of sleep which can cause issues for adolescents.

Adolescents can also experience difficulties waking up from sleep, as often societal expectations do not permit adolescents to sleep-in later in order to compensate for their delayed sleep onset. Specifically, there is a constant battle between the innate timing of the adolescent circadian rhythm and school start times (Adolescent Sleep Working Group et al., 2014; Owens et al., 2017). School start times vary worldwide, in one study, US adolescents' school start times were 45 minutes earlier than those for Australian adolescents (7:45 a.m. versus 8:30 a.m., respectively; Short et al., 2013). In turn, Australian adolescents obtained 47 minutes more sleep on school nights compared to their US counterparts. Studies also consistently show that adolescents have a longer sleep duration during the school holidays than during the school term (Bei et al., 2014; Hansen et al., 2005; Shen et al., 2021; Szymczak et al., 1993), which again highlights the restrictive impact of school start times on adolescent sleep duration. Recent research has also shown that the move to online schooling during the pandemic increased sleep duration due to the elimination of the time taken to travel to school (Meltzer et al., 2021; Stone et al., 2021). Despite the recommendation that most adolescents need 8-10 hours of sleep, adolescents often obtain much less than this on school nights (Hirshkowitz et al., 2015; Sharman et al., 2017). Indeed, the disparity between adolescent sleep need and their actual sleep duration on school nights can result in attempts to catch up on this sleep on the weekend (Crowley et al., 2018). However, this attempt to relieve sleep debt by sleeping-in on the weekends, although helpful in the short term, becomes detrimental as it allows the circadian rhythm to drift later resulting in even later sleep timing (Crowley & Carskadon, 2010).

In addition to a natural delay in the circadian rhythm, other aspects of typical adolescent sleep also play a role in the sleep difficulties seen in this population. Despite the reductions in sleep duration often seen in adolescents (Keyes et al., 2015), the average adolescent still requires a larger amount of sleep than the average adult (Hirshkowitz et al., 2015). Experimental lab studies have found that adolescents require at least 9 hours of sleep to avoid performance deficits (Carskadon & Acebo, 2002; Lo & Chee, 2020; Short et al., 2018), and the National Sleep Foundation recommends adolescents obtain 8-10 hours of sleep (Hirshkowitz et al., 2015). Despite this, adolescents frequently obtain less hours of sleep than what is recommended (Gradisar et al., 2011; Saxvig et al., 2020; Sharman et al., 2017). As discussed earlier, a number of other factors contribute to the actual hours of sleep obtained by adolescents, and there are many risk factors for shorter adolescent sleep duration, including the use of caffeine, tobacco, computers, phones, exposure to evening light, and negative family environment (Bartel et al., 2015).

Further to this, there is also some research to indicate that the accumulation of homeostatic sleep pressure is slower in adolescents. Similar to the circadian rhythm, homeostatic sleep pressure also regulates sleep, however unlike the circadian rhythm, homeostatic sleep pressure is independent of time of day (Borbély et al., 2016). In the homeostatic sleep pressure process, sleep propensity increases in relation to the amount of time which has already been spent awake or asleep (Borbély et al., 2016). That is, the longer a person is awake the stronger the drive is to sleep - and the longer a person has been asleep, the stronger the drive is to wake (Borbély et al., 2016). There is evidence to indicate that homeostatic sleep pressure may accumulate slower during mid-adolescence (Tanner stage 5, 13.9±1.2 years), thus further contributing to the delayed onset of sleep in this population (Agostini & Centofanti, 2021; Taylor et al., 2005).

The difficulties adolescents experience with their sleep can have serious consequences. Research has shown a myriad of negative outcomes from obtaining insufficient sleep (Owens & Weiss, 2017). Systematic reviews of the consequences faced by adolescents with inadequate sleep find that it affects overall health, with reduced health-promoting behaviours and increased rates of back pain, cardiovascular risk, and insulin resistance, it also increased body weight and caloric intake, resulting in higher rates of overweight and obese adolescents (Agostini & Centofanti, 2021; Shochat et al., 2014). Adolescents with insufficient sleep are also found to have a higher likelihood of participating in risk-taking behaviours, including smoking, alcohol and drug use, sexual activity, susceptibility to unintentional injuries, and serious suicidal ideation (Agostini & Centofanti, 2021;

Goldstein & Franzen, 2020; Shochat et al., 2014). There is also evidence that reduced adolescent sleep duration negatively impacts school and academic performance (Agostini & Centofanti, 2021; Curcio et al., 2006; Dewald et al., 2010; Shochat et al., 2014).

1.3 Sleep and Mood

One of the most common and potentially devastating consequences of insufficient sleep in adolescents is an increase in depression symptoms. A review by Crouse et al. (2021) demonstrated that depressive symptoms and depression diagnoses are often associated with delayed circadian timing in adolescents and young adults. This circadian timing delay being one to which adolescents are particularly biologically vulnerable, as previously discussed (Carskadon, 2011; Hagenauer & Lee, 2012; Roenneberg et al., 2004). It is therefore unsurprising that sleep problems and depression or low mood are closely connected in adolescents (Clarke & Harvey, 2012). There is a higher likelihood of developing a mood disorder in adolescence and adulthood if an individual has a history of poor sleep (Scott et al., 2021). Although, the relationship between low mood and poor sleep has been well established in the adult population (Baglioni et al., 2011; Harvey, 2011), there is less research into this relationship in adolescents, nevertheless evidence can be seen in independent studies from around the globe (Shochat et al., 2014). In Shochat's systematic review, the relationship between poor sleep and low mood in adolescents is consistently found across prospective and cross-sectional study designs and in cohorts ranging in size from 280 to 100,000 adolescents.

Evidence for the association between sleep and mood appears to be bidirectional. For example, a study of the daily associations between sleep and mood in 286 adolescents found that worse mood (reduced positive affect and higher negative affect) during the day predicted worse sleep quality that night, and poorer sleep quality also predicted worse mood (reduced positive affect and higher negative affect) the next day (van Zundert et al., 2015). In 2014, Lovato and Gradisar conducted a meta-analysis to investigate the directionality of the sleep-mood relationship. Upon summarising the available causal research of the relationship between sleep and depressed mood in adolescents, less evidence was found to suggest that depression occurs prior to poor sleep (3 studies), and more evidence supported poor sleep predicting the onset of depression (7 studies; Lovato & Gradisar). Indeed, a recent longitudinal study of 4,951 early adolescents (aged 9-10 years) found that sleep disturbance predicted depression at 1 year follow-up (Goldstone et al., 2020). Similar results have also been seen on a temporal level, Reddy and colleagues (2017) found just one night of short sleep significantly reduced positive affect the next day in a sample of 42 adolescents (13-17 years).

The relationship between sleep and mood in adolescents is complex, as there are numerous situations in which the unique characteristics of adolescent sleep interact with the challenges of their life stage to impact their sleep. There are variety of ways in which this can happen, some of which will be explored in more detail later in the chapter. However, the ‘sleep – mood’ connection is notable as the relationship between restricted sleep and low mood can be seen in many studies, through general mood disturbance (Shochat et al., 2014; Sullivan & Ordiah, 2018), and in worsened mood following a night of short sleep (Fuligni et al., 2019; Reddy et al., 2017; Short & Louca, 2015). This is concerning, as in addition to this increase in low mood, adolescents with restricted sleep also find it more difficult to regulate negative emotions (Baum et al., 2014; Watling et al., 2017). As such, not only are adolescents with insufficient sleep experiencing a greater amount of negative emotions, they are also at a disadvantage when attempting to control them - thus compounding the issue.

One of the aims of this thesis is to test the ‘sleep – mood’ relationship using a range of research designs. Based upon the directionality found by Lovato and Gradisar’s meta-analysis (2014), and further corroborated by other studies (Goldstone et al., 2020; Reddy et al., 2017), it is predicted that there is a greater likelihood of sleep influencing mood. The study in **Chapter 2** will use a cross-sectional design to establish the presence and strength of the sleep-mood relationship, this will be followed by a prospective study which will use ecological momentary assessment (EMA) measures over a period of one week to analyse the sleep-mood relationship on a daily scale (**Chapter 3**). The final design is experimental, and the directionality of the sleep-mood relationship will be tested in a sleep laboratory, also over the course of one week (**Chapter 4**). This thesis will also consider how physical activity is associated with the relationship between sleep and mood in adolescents. As will be discussed next, physical activity has been shown to be associated both with mood and with sleep.

1.4 Physical Activity and Mood

Mood is impacted not only by sleep, but also by physical activity, and the interrelationship between physical activity and depressed mood has been demonstrated across the lifespan. From children to the elderly, participation in physical activity displays a dose-response relationship with mood. Evidence from a meta-analysis in children (Ahn & Fedewa, 2011), and a longitudinal cohort study of 6,500 US adults aged 20-88 years (Galper et al., 2006) illustrate that greater levels of fitness/physical activity are related to lower depression scores. Although less research has been conducted in adolescent samples, this same relationship has been demonstrated. Multiple meta-analyses of adolescent studies have indicated that physical activity has a small-to-medium effect on mood in this population, with higher levels of participation in physical activity being related to lower levels of depressive mood (Biddle & Asare, 2011; Brown et al., 2013; Carter et al., 2016; Das et al., 2016; Larun et al., 2006). A notable contributor to the range of effect sizes found between the meta-analyses are the many differences in physical activity interventions between the studies analysed (Biddle & Asare, 2011). There are many components to the design of a physical activity intervention, including:

(i) intensity of physical activity (e.g., light vs vigorous),
(ii) duration of physical activity session (e.g., 15 minutes versus 1 hour),
(iii) frequency of physical activity (e.g., daily vs weekly),
(iv) type of physical activity (e.g., aerobic vs anaerobic),
(v) the activity itself (e.g., cycling vs weightlifting vs football), and
(vi) variation in the length of interventions (e.g., 1 day vs 3 months).

The high variability of physical activity interventions between studies (particularly when restricted to adolescent cohorts) can make it challenging to directly compare results, however the results of the meta-analyses support the general premise that adolescents who participate in more physical activity have a better mood profile than adolescents who participate in less physical activity.

One of the most important and fundamental components of a physical activity intervention is the intensity (listed above as point (i)). The intensity of physical activity is categorised as sedentary, light, moderate, and vigorous, and there are multiple methods through which this is measured (Innerd, 2020a). This thesis includes physical activity measurement through both self-report questions and accelerometry. Accelerometry provides an objective and ecologically-valid intensity measure (Eslinger et al., 2011; LaMunion et al., 2020) - whereas self-report questions offer a subjective comparison point and enable larger sample sizes due to the lower financial cost and labour required (Innerd, 2020b). Measurement of physical activity intensity using accelerometry involves wearing a monitoring device, similar to a smart watch (e.g., FitBit), which continuously measures movement. The data from the device are analysed by software which applies validated cut-off points for the different intensities (vigorous, moderate, light, sedentary) of physical activity, thus producing output of the amount of time a participant spent in each intensity of physical activity during the day (Innerd, 2020c; Migueles et al., 2019).

1.5 Physical Activity and Sleep

The interrelationships between physical activity, sleep, and mood are complex. Variations in adolescents’ physical activity and sleep can both impact mood. It is therefore notable that physical activity and sleep are also related to each other. Similar to the previous discussion of the connection between physical activity and mood, there are difficulties when comparing research studies of the impact of physical activity on sleep, as physical activity interventions vary widely between research designs. Physical activity interventions vary in length and frequency, with variation in the type of activity, duration and intensity of the exercise session (see previous Section 1.4 Physical Activity and Mood for examples). Due to this high variability, it is difficult to discern a precise picture of the extent to which physical activity affects different elements of sleep - although commonalities between the results of different studies do indicate that physical activity does indeed impact sleep.

A meta-analysis of adult studies by Kredlow and colleagues (2015) looked at the impact of physical activity on sleep variables in both between-subject and within-subject studies (comparing a control group to a physical activity group, or comparing physical activity days to control days). Participating in a physical activity intervention, regardless of overall duration (range: 30 minutes to 1 year), resulted in longer sleep duration, shorter sleep onset latency (SOL), and increased sleep efficiency[1]. Interventions lasting less than a week also afforded the benefits of less time awake during the night. Further to this, exercise bouts of a longer duration moderated the effect of physical activity on SOL, resulting in a stronger effect where more physical activity shortened SOL. For interventions lasting less than a week, longer bouts of physical activity had stronger effects leading to longer sleep duration.

Similar results have been found in adolescents, where those who participate in more physical activity have better sleep than those who participate in less physical activity. A number of studies with adolescent samples have found that adolescents who engage in more hours of physical activity per week have a shorter SOL, experience longer total sleep time, and have less time awake during the night than adolescents who engage in less hours of physical activity (Baldursdottir et al., 2017; Brand et al., 2010a, 2010b; Harris et al., 2017; Kalak et al., 2012; Lang et al., 2013; Lang et al., 2016; Patte et al., 2018).

1.6 Complex Interrelationships

Clearly physical activity, sleep, and mood are interconnected with each variable exhibiting a direct relationship with the others, however it is possible that there could also be a more complex relationship pattern involved. The Lovato and Gradisar (2014) meta-analysis demonstrated that more often poor sleep proceeds low mood. As physical activity is associated with both sleep and mood, and sleep has been shown to often precede mood, it is possible that the mechanism by which physical activity is associated with higher or lower mood is *via* sleep. For instance, participating in more physical activity may result in improved sleep parameters, and this improved sleep results in better mood - or participating in less physical activity results in worse sleep, which in turn results in lower mood. The possibility of sleep acting as a mediating mechanism has been suggested previously. In a longitudinal study of physical activity and mood in adolescents by Langguth and colleagues (2016), it was found that participating in moderate-to-vigorous physical activity (measured objectively with accelerometers) for an hour longer than the individual's average length of physical activity participation, resulted in an improved mood score the next day (50% lower depressed mood). The

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[1] Sleep efficiency refers to the percentage of time a person is asleep versus awake during the time in which they were trying to sleep. E.g., a person who tries to fall asleep at 10 p.m. and wakes up in the morning at 8 a.m. (10 hours trying to sleep) and who has slept for 8 hours, has a sleep efficiency of 80%. Higher sleep efficiency is generally associated with better outcomes (Schutte-Rodin et al., 2008).

authors discussed that there seemed to be a mediating mechanism, and although they did not measure sleep they posited that sleep may have mediated the relationship between physical activity and mood. At this stage, no research has tested this mediational model. If indeed sleep is a mediator in the physical activity-mood connection there are multiple aspects of sleep through which this model might be evident. This thesis will address how the relationship between physical activity and mood in adolescents may be mediated by sleep onset latency (**Chapter 2**), total sleep time (**Chapter 2, Chapter 3**), and chronotype (**Chapter 2, Chapter 3, Chapter 4**).

1.7 Evening Physical Activity and Sleep Onset Latency

Further examination of the effect of physical activity on sleep onset latency (SOL) has identified the potential impact of time of day. Some adult studies have noted that physical activity in the evening or close to sleep is associated with increased SOL (Tworoger et al., 2003; Youngstedt et al., 1997). In a meta-analysis by Youngstedt and colleagues (1997), an acute burst of physical activity did not have a significant effect on SOL unless the time of day of physical activity participation was taken into account. It was found that physical activity 4-8 hours prior to bedtime decreased SOL compared to controls, whereas physical activity < 4 hours prior to bedtime *increased* SOL compared to controls. Similarly, another study found that older adults who spent longer per week participating in morning exercise had less difficulty falling asleep than those who participated in less morning exercise (Tworoger et al., 2003). However, those with a longer duration of *evening exercise* had more difficulty falling asleep than those who participated in less evening exercise (Tworoger et al.).

Furthermore, participation in physical activity prior to bedtime has been shown to delay the circadian rhythm. The vast majority of research into the impact of physical activity on the circadian rhythm has been conducted in adult participants, however amongst adults, the findings are robust that physical exercise conducted in a single bout or a daily routine can phase delay the circadian rhythm (Atkinson et al., 2007; Yamanaka et al., 2006). Due to the variability of physical activity interventions there is some uncertainty regarding the “dose” of physical activity required to delay or advance the circadian rhythm at different times of day (Mistlberger & Skene, 2005; Richardson et al., 2017; Youngstedt et al., 2019). However a comprehensive experiment by Youngstedt, Elliot, and Kripke (2019) has identified a phase response curve of the circadian rhythm to physical activity and it is notable that physical activity creates large phase delays when undertaken between 7-10 p.m. Research into the impact of evening physical activity on sleep has been conducted in adults and young adults, but not in adolescents (Brand et al., 2014; Mistlberger & Skene, 2005; Richardson et al., 2017; Stutz et al., 2019; Weinert & Waterhouse, 2007; Yamanaka et al., 2006). Considering the natural delay in circadian rhythm experienced during adolescence which occurs even independent of other contributing factors (Roenneberg et al., 2004), it is important to consider how evening physical activity may further affect this vulnerable population (Richardson et al., 2017).

During physical activity, small but important changes occur within the body's sympathetic nervous system and core body temperature which result in a physiological-arousing effect (Silverman & Deuster, 2014; Wenger, 1995). This physiological arousal is purported to negatively impact sleep, and initial sleep hygiene recommendations discouraged participating in physical activity in the evening to avoid a negative impact on sleep (1990), a recommendation which often persists today (Krishnan & Patel, 2022; Shriane et al., 2020). There is however contention over this issue, because although the timing of exercise is one of the most consistent moderators of the impact of physical activity on sleep (Driver & Taylor, 2000), the results of the impact of evening physical activity on sleep are mixed.

Few studies have specifically evaluated the impact of evening physical activity on sleep parameters. The majority of studies in this area have considered whether physical activity is comparable to bright light in its effect on sleep, and to this end, study designs often result in unrealistically timed physical activity manipulations (Barger et al., 2004; Buxton et al., 2003; Eastman et al., 1995; Miyazaki et al., 2001; van Reeth et al., 1994). Within the small number of research studies which have considered the impact of late-night physical activity on sleep, some have found support for a detrimental effect. For instance, Bonnet and Arand conducted multiple studies (1998, 2000, 2005) in groups of 12-13 participants to compare the impact of a 5-minute walk versus 10-15 minute bedrest on participants' sleep onset latency (SOL). Each study was conducted in a controlled sleep laboratory environment using objective measures of sleep latency (i.e., EEG from polysomnography - described in more detail later in Section 1.10 The Role of Total Sleep Time). In all three studies, a significant increase in SOL was found following the 5-minute walk, and although the increase itself was only 5-6 minutes, it was notable that this occurred following a short duration of light intensity physical activity. Possibly another way of interpreting this finding, is that for every minute of physical activity, it took 1 minute longer to fall asleep. Furthermore, Bonnet and Arand also noted that following the 5-minute walk condition participant's heart rates were significantly higher for at least 90 minutes following the walk.

Conversely, there has also been research to indicate that evening physical activity can either be beneficial or has no effect on sleep (Brand et al., 2014; O'Connor et al., 1998; Stutz et al., 2019). Stutz and colleagues (2019) conducted a systematic review of the physiological arousing effect of physical activity on sleep in adults. They found that evening exercise (ceasing anywhere from 10 minutes to 4 hours before bedtime) had a small beneficial effect on sleep, and no impact on sleep onset latency. They did find however that body temperature and exercise intensity moderated the physical activity to sleep relationship - with higher temperature and greater intensity resulting in lower sleep efficiency and more time awake after sleep onset. The authors posited that although the main analysis did not show a relationship between evening physical activity and SOL, when studies were considered categorically as whether physical activity concluded more or less than 1 hour before sleep, the pattern of results indicated it is plausible that intense physical activity ceasing less than 1 hour before bedtime may be detrimental to sleep.

Conversely, in two further studies focused on young adult samples it was found that evening physical activity had a beneficial or non-existent effect on sleep onset latency. Brand and colleagues (2014) analysed 52 young adults who ceased exercise only 90 minutes prior to bed and found correlations between participants' reports of higher physical exertion during their regular exercise (60-90 minutes, 2-3 nights a week) and higher subjective sleep quality, higher objective sleep efficiency, and reduced wake after sleep onset (WASO). Interestingly, higher physical exertion was associated with a reduction in SOL. Miller and colleagues (2020) used a crossover design to test the effect of 30 minutes of evening physical activity in 12 young adult males and found no significant effect of physical activity condition (control, resistance, or aerobic) on SOL, TST, WASO, or sleep efficiency. Although core temperature rose during both physical activity interventions it fell to the same level as the control condition during the 90 minutes before sleep.

Whilst it makes conceptual sense that evening physical activity would increase heart rate, elevate core body temperature (via heat production), and that this physiological alertness would translate to a longer time taken to fall asleep, the research in this area is not entirely consistent. Given the pervasive nature of the sleep hygiene recommendation to avoid evening physical activity, early studies by Bonnet and Arand, as well as Youngstedt et al.'s meta-analysis finding an effect of evening exercise on SOL, this thesis will consider the impact of evening physical activity on adolescents' sleep in **Chapters 2**, **3**, and **4**. However, there is emerging evidence that whilst physical activity may raise physiological arousal to affect sleep and mood, there may also be a meaningful contribution from a cognitive component.

1.8 The Role of Repetitive Negative Thinking

Repetitive negative thinking refers to the experience of repeatedly, and seemingly uncontrollably, having thoughts about negative content (Ehring & Watkins, 2008). Although the specific content of the thoughts may vary (e.g., worries about future problems or rumination on past events), the negative aspect of the thoughts in addition to the recurring and uncontrollable nature of the thoughts are persistent features (Ehring & Watkins, 2008). If indeed evening physical activity prolongs sleep onset latency it is possible that this extra time before sleep onset provides more opportunity for adolescents to experience repetitive negative thinking (RNT). Adolescents who spend a longer amount of time trying to fall asleep are subject to a longer amount of time lying in bed with minimal-to-no-distractions (i.e., lack of visual and auditory stimulation). This lack of distraction afforded by a dark and quiet bedroom provides these adolescents with much more opportunity to begin to worry and engage in RNT. Evidence has been found for an association of RNT with bedtime and SOL in adolescents and young adults (Nota & Coles, 2015; Stewart et al., 2020; Takano et al., 2014). Both Stewart et al. (2020) and Takano et al. (2014) found that a longer SOL was associated with more repetitive thoughts. In a sample of 1,021 adolescents (aged 11-17 years), Stewart and colleagues found that RNT was associated with longer SOL and a later bedtime. Further to this, Takano and colleagues assessed RNT throughout the day in a sample of 43 undergraduate students. It was found that longer SOL was significantly associated with evening repetitive thoughts, but not repetitive thoughts in the morning or afternoon - thus indicating a link between evening RNT and SOL. This preliminary evidence indicates a link between RNT and SOL in this population, and further research indicates that SOL may be linked to mood with RNT as the linking mechanism.

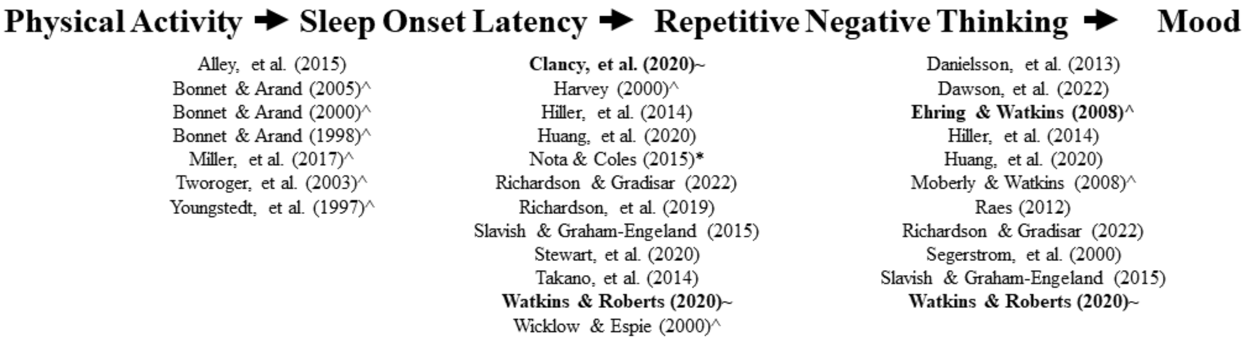
Research across multiple life-stages has also identified a relationship between RNT and mood (Watkins & Roberts, 2020). A study of 81 undergraduate students found that repetitive negative thinking predicted depression symptoms 3 years later (Raes, 2012). In another study of 188 adults, it was found that ruminative self-focus - a subtype of RNT - was highest in the morning and evening, and was strongly associated with negative affect (Moberly & Watkins, 2008). Indeed, there is evidence to indicate the presence of a bidirectional relationship between RNT and mood. Moberly and Watkins (2008) measured ruminative self-focus and affect 8 times a day for 7 days and found that increased levels of a measure at one time point predicted increased levels of the other measure at the following time point (i.e., more ruminative self-focus predicted more negative affect, and vice versa). A bidirectional relationship has also been identified in a study of 408 early adolescents (10-14 years old) (Krause et al., 2017). In girls, rumination at baseline predicted depression symptoms 6 months later, and equally depression symptoms predicted rumination 6 months later. There is an identifiable link between RNT and mood, where the presence of RNT predicts negative affect in the short term and depression symptoms in the long term.

Despite the links between sleep, RNT, and mood, minimal research has been conducted to establish the interconnections between all three variables in the adolescent/young adult population. In one study of 165 undergraduates, Slavish and colleagues (2015) considered a model where rumination mediated the relationship between depressed mood and sleep quality. Using measurements from baseline and 2-month follow-up, depressed mood was associated with higher levels of rumination which was in turn associated with poorer sleep quality. Although not causal, these findings provide evidence for an interrelationship between sleep, mood, and RNT, where RNT may explain the path between sleep and mood. In another study of 1,713 adolescents (16-18 years old), Danielsson and colleagues (2013) tested the relationships between sleep disturbance, depressive symptoms, and catastrophic worry at three time points over 3 years. It was found that greater sleep disturbance predicted more depressive symptoms at the following time point (1 year apart), and that this relationship was partially mediated by the presence of more catastrophic worry. These studies present further support to indicate that SOL may be linked to mood by repetitive negative thinking. It is also important to consider, that as individuals may have higher or lower levels of RNT, RNT may moderate the relationship between SOL and mood. It is important that more research into the links between SOL, RNT, and mood is conducted in adolescents, as this population is distinct from other cohorts in both the factors contributing to and influencing their sleep (e.g., changes in circadian rhythm, school start times) and the unique challenges of their life stage that may race through their mind at night (e.g., dramatic cognitive, emotional, and social changes). Further research in this area will not only corroborate the initial connections found between sleep, RNT, and mood, but also provide insights on how to intervene early before this pattern continues into adulthood.

This leads to this thesis' first model (Figure 1.1), and introduces the first research questions: does evening physical activity affect mood via a lengthened sleep onset latency? And if so, is the link between sleep onset latency and mood moderated by repetitive negative thinking?

Figure 1.1

Evidence for the Predicted Association Between Physical Activity, Sleep Onset Latency, Repetitive Negative Thinking, and Mood for the Present Thesis.



Physical Activity ➔ Sleep Onset Latency ➔ Repetitive Negative Thinking ➔ Mood

Alley, et al. (2015)
Bonnet & Arand (2005)^
Bonnet & Arand (2000)^
Bonnet & Arand (1998)^
Miller, et al. (2017)^
Tworoger, et al. (2003)^
Youngstedt, et al. (1997)^

Clancy, et al. (2020)~
Harvey (2000)^
Hiller, et al. (2014)
Huang, et al. (2020)
Nota & Coles (2015)*
Richardson & Gradisar (2022)
Richardson, et al. (2019)
Slavish & Graham-Engeland (2015)
Stewart, et al. (2020)
Takano, et al. (2014)
Watkins & Roberts (2020)~
Wicklow & Espie (2000)^

Danielsson, et al. (2013)
Dawson, et al. (2022)
Ehring & Watkins (2008)^
Hiller, et al. (2014)
Huang, et al. (2020)
Moberly & Watkins (2008)^
Raes (2012)
Richardson & Gradisar (2022)
Segerstrom, et al. (2000)
Slavish & Graham-Engeland (2015)
Watkins & Roberts (2020)~

Note. All studies in this figure were conducted with adolescent/young adult cohorts unless otherwise indicated.
Bold = review or meta-analysis. ^ = adult cohort. ~ = all ages. * = relationship between bedtime and repetitive thinking.

1.9 The Role of an Adolescent's Chronotype

Upon considering the first research question - that evening exercise may prolong the time taken to fall asleep – it is feasible that a late sleep onset time may mean one needs to also wake late to obtain their full complement of sleep. Thus, evening exercise may be related to a delay in the timing of sleep. Where 'circadian rhythm' refers to the intrinsic sleep/wake cycle, chronotype refers to the actual timing of sleep (Roenneberg et al., 2003). Measurement of chronotype is much less costly and labour intensive than the arduous process required for the measurement of the circadian rhythm

(Bauducco et al., 2020) and their similarity can allow for chronotype to be used as a substitute measurement in some instances (Roenneberg, 2012).

Chronotype is measured by calculating the ‘midpoint’ of sleep on ‘free days’ (Roenneberg et al., 2003). A free day refers to a day when the individual has no commitments the morning/day after the night of sleep. This ensures that the measure more accurately reflects the individual’s intrinsic sleep timing without being confounded by other social or work commitments. The midpoint of sleep is the clock time in the middle of the sleep period - between sleep onset and waking up. For example, if an individual fell asleep at 10 p.m. and woke up at 6 a.m., their sleep midpoint would be 2 a.m. as this is the time in the middle of their sleep period. Chronotype is deemed early, intermediate/neither, or late, depending on when an individual would normally fall asleep and wake up (e.g., falling asleep close to midnight and waking late in the morning is a late chronotype). As a result of the delay in adolescent circadian rhythms, many adolescents are categorised as having a late chronotype, due to their falling asleep late and waking up late (Roenneberg et al., 2004).

Substantial research has been conducted in adult samples to demonstrate the ability of physical activity to both advance and delay the timing of the circadian rhythm (Mistlberger & Skene, 2005; Richardson et al., 2017; Yamanaka et al., 2006; Youngstedt et al., 2019). However there has been relatively less research conducted into the relationship between evening physical activity and timing of chronotype. One study into this relationship by Glavin and colleagues (2020) found that evening exercisers had a later bedtime than morning exercisers. Another study of the association between the timing of physical activity and the timing of sleep found that, although evening physical activity (after 7 p.m.) was not significantly associated with sleep measures, morning physical activity (before midday) was associated with an earlier bedtime, risetime, and chronotype (as measured by activity levels) (Quante et al., 2019). These studies provide some evidence for the potential impact of physical activity on chronotype, and given the ability of physical activity to alter the timing of the circadian rhythm (Atkinson et al., 2007; Barger et al., 2004; Miyazaki et al., 2001), and the previously discussed physiological arousal which results from physical activity (Bonnet & Arand, 2005; Tworoger et al., 2003), it is possible that physical activity conducted in the evening could impact chronotype by pushing sleep timing later.

There is also limited research on the relationship between chronotype and mood in adolescent populations, however some cross-sectional studies have identified an association between late/evening chronotypes (measured via sleep midpoint) and lower mood. For example, in a large-scale study of almost 30,000 adolescents Gariépy and colleagues (2019) found that a later chronotype was associated with more emotional problems (e.g., how often felt low/depressed in last 6 months, how often felt helpless). Similarly, in a specific assessment of depression symptoms using the Beck Depression Inventory in a sample of 351 adolescents, de Souza and Hidalgo (2014) also found that later chronotype was associated with higher levels of depression. Longitudinal studies also substantiate these cross-sectional relationships between late chronotype and lower mood. In a study which followed 3,843 adolescents over 5 years (McGlinchey & Harvey, 2015), late bedtime at age 16 years increased the odds at age 21 of emotional distress (e.g., feeling depressed, bothered by things that normally wouldn't bother you, not being able to shake the blues for the past week). Likewise, another longitudinal study of 255 adolescents also found that eveningness[2] predicted an increase in depressive symptoms 1 year later (Haraden et al., 2017). It is evident that there is a relationship between late chronotype and lower mood in adolescents, and although to date there is minimal causal research in adolescent populations, there is evidence to suggest that a late chronotype can lead to lower mood.

Substantial research has established the relationship between physical activity timing and circadian rhythm timing in adults, and similarly in the last decade numerous studies have investigated the relationship between chronotype and mood in adolescents. Much less research, however, has addressed the relationships between physical activity timing and chronotype, and circadian rhythm and mood. Figure 1.2 and Figure 1.3 demonstrate evidence for the links between physical activity, sleep, and mood, when considering chronotype and the circadian rhythm. Although less research has considered the relationship between evening physical activity and late chronotype, there is ample evidence of the association between late chronotype and low mood in adolescents (Figure 1.2). Although circadian rhythm measurement is not the same as chronotype measurement, the evidence for the relationship between late physical activity and late circadian rhythm (Figure 1.3) when taken with the evidence for the relationship between late chronotype and lower mood (Figure 1.2), suggests that it is possible that chronotype acts as a mediator between physical activity and mood. Where late physical activity results in late chronotype which in turn results in low mood (see Figure 1.2). Thus, this thesis' second model shows the framework for the next research question: does evening physical activity affect mood via later sleep timing?

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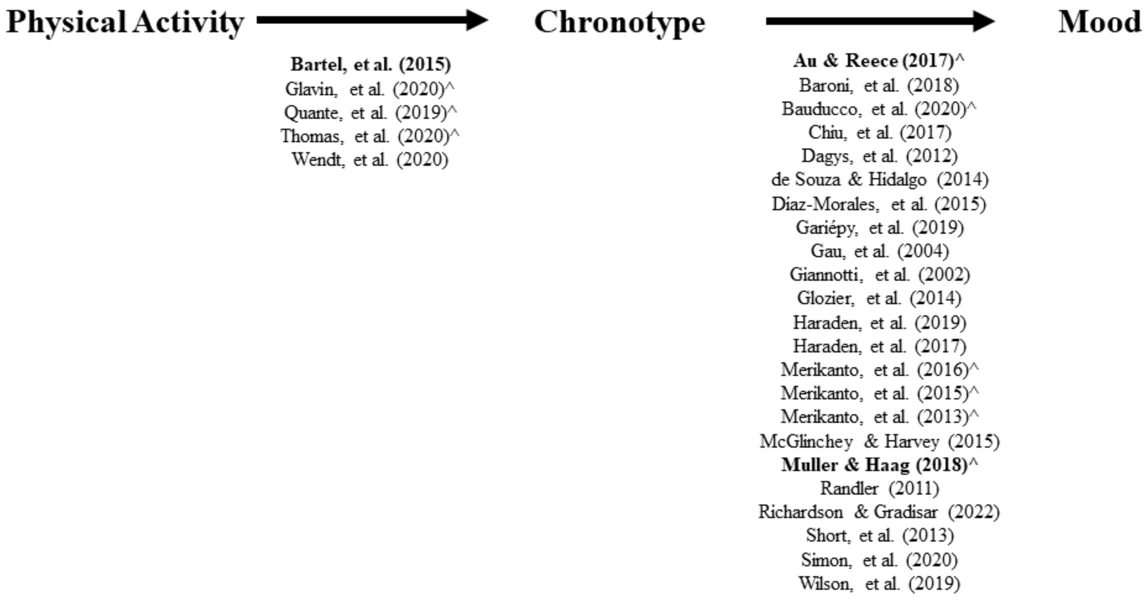
[2] "eveningness" refers to the preference for performing activities (e.g., work and study) during the evening, as opposed to morning (Bauducco et al., 2020; Horne & Östberg, 1976).

Figure 1.2

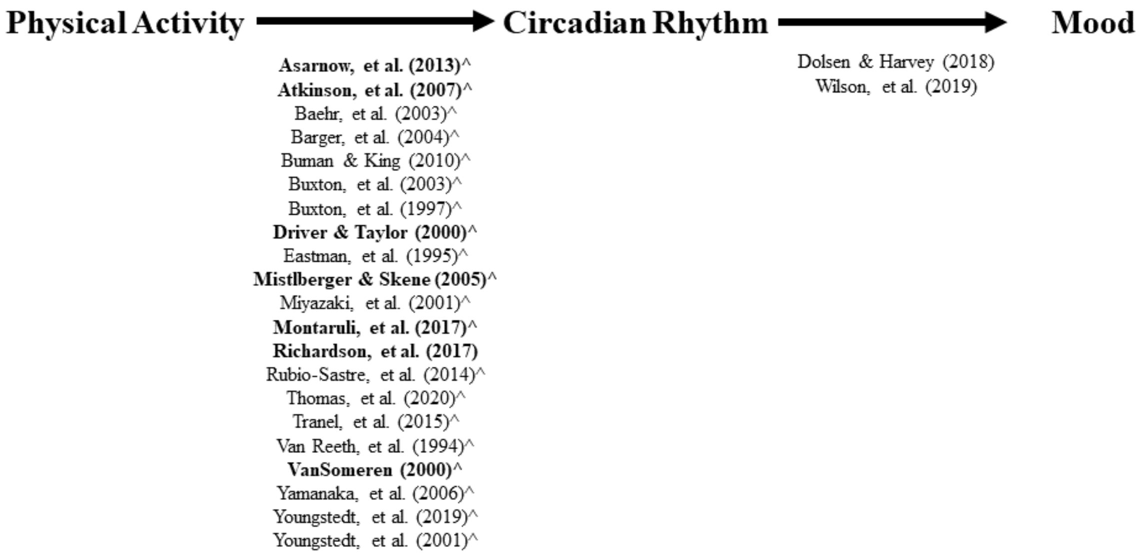
Evidence for the Predicted Association Between Physical Activity, Chronotype, and Mood for the Present Thesis.



Note. All studies in this figure were conducted with adolescent/young adult cohorts unless otherwise indicated.
Bold = review or meta-analysis. ^ = adult cohort.

Figure 1.3

Evidence for the Predicted Association Between Physical Activity, Circadian Rhythm, and Mood for the Present Thesis.



Note. All studies in this figure were conducted with adolescent cohorts unless otherwise indicated.
Bold = review or meta-analysis. ^ = adult cohort.

1.10 The Role of Total Sleep Time

A recent systematic review and meta-analysis have shown the consistent evidence that more participation in physical activity is associated with a longer sleep duration in adult samples (Dolezal et al., 2017; Kredlow et al., 2015). Although comparatively less research has been conducted within adolescent populations, the available research indicates that more participation in physical activity is also associated with a longer sleep duration in young people. Many large-scale studies have found evidence for this association using subjective sleep measures. Such self-report measures include sleep diaries, where the times of sleep onset and offset are recorded by the participant each night, or validated questionnaires to measure specific facets of sleep, or direct questions such as "How many hours did you sleep last night?" (Ji & Liu, 2016; Spruyt & Gozal, 2011). These large-scale studies (with sample sizes ranging from 15,000 to 177,000) have repeatedly found that adolescents with higher levels of physical activity are more likely to report ≥ 8 hours sleep than those with lower levels of physical activity (Foti et al., 2011; Kim et al., 2016; Patte et al., 2018; Tambalis et al., 2019).

The relationship between physical activity and sleep duration can also be seen in studies with objective measures in smaller cohorts. Objective measures of sleep include polysomnography and actigraphy (Sadeh, 2011). Polysomnography (PSG) measures brain, eye, and muscle activity (electroencephalography, electrooculography, and electromyography, respectively) allowing for exact measurement of sleep onset/offset, waking time during sleep, and sleep stages (Berry et al., 2015). PSG provides a more detailed picture of sleep, however it is expensive and labour intensive to collect and interpret the data (Hirshkowitz, 2016). As mentioned previously, actigraphy measures activity patterns via an accelerometer, commonly worn on the wrist like a watch (Ancoli-Israel et al., 2003). Objective evidence, using both PSG and actigraphy, of the relationship between physical activity and sleep duration can be seen in a study of 40 adolescents by Mendelson and colleagues (2016). At baseline healthy weight adolescents had a longer total sleep time (TST) than overweight adolescents, however after the overweight adolescents participated in a 12-week physical activity intervention they had a longer TST (~ 1 hour longer) than the healthy weight adolescents (who did not participate). Similarly, a temporal study by Master et al. (2019) found that in a cohort of 417 15-year-olds, adolescents had a longer TST on nights after they had participated in more moderate-to-vigorous physical activity. Indeed, a 1-hour increase in physical activity was associated with a 10-minute increase in TST. Furthermore, the same relationship was also demonstrated from the perspective of sedentary activity in the Master et al.'s study, wherein adolescents with more sedentary time (1 hour) had less TST (11 minutes) than adolescents with less sedentary time. Within the available adolescent research, evidence for the association between physical activity and total sleep time can be seen across studies with different sized cohorts, different study designs, and objective and subjective measures.

As previously discussed, sleep difficulties and poor sleep are closely associated with lower mood in adolescents (Lovato & Gradisar, 2014; Shochat et al., 2014). Further to this, there is also evidence for a relationship between TST and mood in adolescents (Fuligni & Hardway, 2006; Ojio et al., 2016; Short et al., 2020). Indeed, in a recent meta-analysis of 73 adolescent studies, Short and colleagues (2020) found that adolescents with shorter TST had a higher likelihood of reduced positive affect, increased depression, and increased negative affect. This relationship between shorter sleep duration and lower mood is also seen longitudinally (Orchard et al., 2020; Roberts & Duong, 2014). In a birth cohort study Orchard and colleagues (2020) found cross-sectional and longitudinal associations between reduced TST and depression in a subsample of 5,033 adolescents. At age 15, the adolescents with depression reported falling asleep 35 minutes later than those without depression on both weekdays and weekends. Those with depression also reported having significantly less TST on weekdays (42 minutes) and weekends (31 minutes) than adolescents without depression. Most notably, shorter TST at age 15 was a significant predictor of depression symptoms at all follow-ups (ages 17, 21, and 24). Thus, in addition to the evidence for an association between physical activity and sleep duration, there is also evidence for the association between sleep duration and mood, with longitudinal research indicating that shorter sleep results in lower mood.

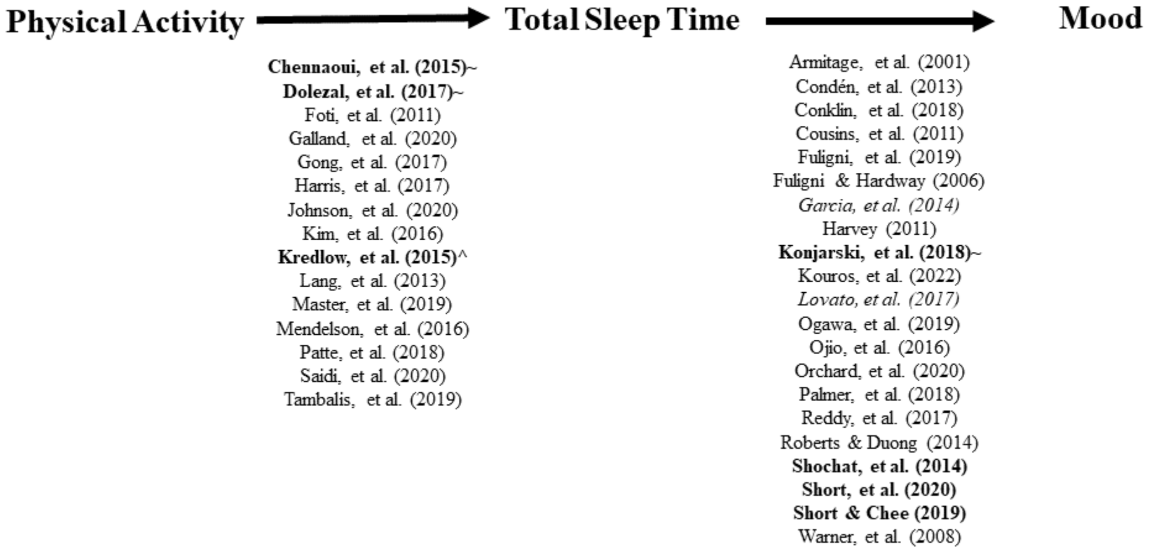
However, the relationship between TST and mood is complex. Previous research has noted a variability in results due to individual differences (Fuligni et al., 2019). Indeed, in one study (Baum et al., 2014) some adolescents reported reduced levels of negative mood when they obtained a longer sleep duration, meanwhile other adolescents reported reduced levels of negative mood after a *shorter* sleep duration. Although further details of individual differences in the links between sleep duration and mood are still being determined, it is nonetheless evident that sleep duration and mood are related within this population.

Furthermore, it has also been shown that general physical activity participation and mood are related. Evidence from systematic reviews and meta-analyses using adolescents has shown that physical activity participation and interventions can improve low mood and reduce depression symptoms in this population (Carter et al., 2016; Das et al., 2016). Research since has further confirmed these associations, with decreases in physical activity over a 2-year period significantly related to an increase in symptoms of depression (Raudsepp & Vink, 2019). These findings illustrate that an adolescent's physical activity impacts mood in two ways. First, participating in physical activity can improve mood. Second, non-participation in physical activity can worsen mood. More research into the relationship between adolescents' physical activity and mood is needed, as the current research has been identified as both limited in number, and sometimes, quality (Biddle & Asare, 2011; Das et al., 2016).

This thesis aims to add to the currently narrow pool of research into the links between physical activity, total sleep time, and mood in adolescents. It is possible, given the existing relationships between these three factors, that sleep duration is one of the mediating mechanisms through which physical activity is related to mood. Given the impact of physical activity on TST (e.g., more physical activity leads to longer TST) and the impact of TST on mood (e.g., more TST leads to better mood), this thesis' third and final model and research question is: does physical activity affect mood via total sleep time? (see Figure 1.4).

Figure 1.4

Evidence for the Predicted Association Between Physical Activity, Total Sleep Time, and Mood for the Present Thesis.



Note. All studies in this figure were conducted with adolescent cohorts unless otherwise indicated. **Bold** = review or meta-analysis. ^ = adult cohort. * = all ages across the lifespan. *Italics* = relationship in opposite of hypothesised direction (i.e., mood impacts total sleep time).

1.11 Aims and Outline of Thesis

Although it is clear that physical activity, sleep, and mood are closely interrelated, the mechanisms through which all three are connected are less well established, and research into these connections is lacking in adolescent samples. It is important that more research is conducted in adolescent cohorts as adolescence marks a unique and sensitive period of a person's life (Towbin et al., 2015). As discussed in Sections 1.1 and 1.2, adolescents undergo many physiological and social changes during this time, and the interaction of these changes makes adolescent sleep distinct from the sleep of children and adults (Crowley et al., 2018). Adolescence also marks a crucial stage of life where events can have far reaching consequences. The development of sleep and/or mood difficulties can impact many areas of an adolescent's future, including academic achievement (Owens & Weiss, 2017; Wickersham et al., 2021), health (Shochat et al., 2014), mental health (Bertha & Balázs, 2013), risk taking behaviours such as substance use (Owens & Weiss, 2017), and long term psychosocial outcomes (Bertha & Balázs, 2013). Conducting research in adolescents allows for the development of appropriate interventions and preventions to mitigate the long-term impact of problems during this life stage.

Current research into the connections between physical activity, sleep, and mood in adolescents shows that more or less physical activity can improve and worsen both sleep and mood. Yet, sleep has a similar relationship with mood, where better or worse sleep can also improve or lower mood. Thus, one possible explanation for the close relationships between physical activity, sleep, and mood is that *sleep acts as a mediator* between physical activity and mood. Within this thesis, three mechanisms of interest are tested in order to understand how sleep might mediate the link between physical activity and mood. The aspects of sleep include:

i. sleep onset latency,
ii. chronotype,
iii. and total sleep time;

all of which have been shown to be impacted by physical activity, and in turn, have their own impact on mood. If it is determined that these aspects of sleep are mechanisms through which physical activity impacts mood, this will inform the use of physical activity and sleep interventions for adolescents with sleep and/or mood difficulties. Indeed, the assessment of whether evening physical activity is detrimental to sleep will inform recommendations for sleep and mood difficulties and the timing of adolescent/school physical activity and sports practice.

Understanding the mediational role of sleep on the relationship between physical activity and mood can be accomplished via different study designs, each of which presents certain benefits. In **Chapter 2** the mediational models are considered in a population-based cross-sectional study conducted in Helsinki, Finland, where every adolescent in the city aged 16-17 years was invited to participate (valid responses N = 1,367 adolescents). This study was able to assess the presence of the associations between physical activity, sleep and mood in adolescents within a large sample. Although this study was unable to determine causality due to the cross-sectional study design, it provided a basis for continuing investigation with more rigorous study methods.

This is followed by a temporal assessment of the possible mechanisms by which sleep mediates the relationship between physical activity and mood using in an ecological momentary assessment (EMA) study in **Chapter 3**. This EMA study of 19 female adolescents (aged 17-20 years) allowed assessment of the relationships between physical activity, sleep, and mood on a temporal scale, and consideration of the associations on a much smaller daily basis.

A final assessment of the mediational models takes place in **Chapter 4** with an experiment. 18 adolescents (aged 15-18 years) spent 1 week in a sleep laboratory to assess the effect of physical activity (45 minutes treadmill walking) vs sedentary activity on sleep and mood. This experiment allowed for direct analysis of the mediation of physical activity and mood via sleep, while controlling for other notable variables (e.g., light). It also offered an opportunity consider this relationship over time and infer causality.

Discussion and synthesis of the research findings is presented in **Chapter 5**. Within this section, the role of sleep as a mechanism between physical activity and mood is discussed in addition to how this information can be used clinically to improve adolescents’ lives.

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CHAPTER 2 -

SLEEP, MEDIATES THE RELATIONSHIP BETWEEN PHYSICAL ACTIVITY AND MOOD IN FINNISH ADOLESCENT GIRLS: A CROSS-SECTIONAL POPULATION STUDY

2.1 Abstract

Objectives: To identify initial evidence for the mediating effect of sleep (via sleep onset latency, total sleep time, and chronotype) on the impact of physical activity on depressed mood.

Design: A population based cross-sectional study conducted in Helsinki, Finland.

Participants: 1,367 adolescents (aged 15-17 years, 33% males).

Measurements: A self-report 30-minute online survey on sleep, health, and behaviour. Measures included Beck Depression Inventory-II, items from the Adolescent Sleep Hygiene Scale and School Sleep Habits Survey.

Results: In adolescent girls the mediation models were significant (all p's <.04): more physical activity overall and during free time were associated with longer total sleep time, which was associated with better mood. Further, although we expected that more evening physical activity would be detrimental to sleep, more physical activity after 6 p.m. was associated with shorter sleep onset latency and earlier chronotype, which were both associated with better mood. These mediation models were not significant for adolescent boys.

Conclusions: Our results provide initial support for the relationship between physical activity and mood occurring via sleep, and provide support for the development of physical activity interventions to improve adolescent sleep and mood.

2.2 Introduction

Worldwide it is estimated that the prevalence of depression in adolescents is 2.6% (Polanczyk et al., 2015). Depression has a substantial impact on many aspects of adolescent life, including academic achievement, social relationships, and quality of life (Bertha & Balázs, 2013; Wesselhoeft et al., 2013). Yet, adolescents are *les*s likely to have depression and low mood if they regularly participate in physical activity (Brown et al., 2013; Kalak et al., 2012). Indeed, physical activity has also been shown to be a beneficial treatment for adolescent depression (Brown et al., 2013; Carter et al., 2016).

Adolescent depression is not only altered by physical activity, many studies have also demonstrated a strong connection between sleep and mood in young people. Depression is associated with poorer sleep, typified by longer sleep onset latency (SOL), longer wake time after sleep onset (WASO), a greater number of awakenings during sleep, lower sleep efficiency, and lighter sleep (Kouros & El-Sheikh, 2015; Lovato & Gradisar, 2014). A meta-analysis by Lovato and Gradisar (2014) found that research supports the existence of sleep difficulties prior to depressed mood. Despite popular beliefs, they found less evidence suggesting that depression occurs prior to poor sleep.

Previous research has demonstrated that both sleep and physical activity have a meaningful role in determining mood. It is therefore of note that a relationship also exists between physical activity and sleep. Studies have found that adolescents who engage in more hours of physical activity per week have a shorter SOL, experience longer total sleep time (TST), obtain more deep sleep, and have less WASO than adolescents who engage in less hours of physical activity (Brand et al., 2010a, 2010b; Patte et al., 2018).

Physical activity, sleep, and mood may be complexly interrelated. For example, it is plausible that physical activity does not directly affect mood, but indirectly affects mood through its effect on sleep. Our objective is to look for evidence indicating that the effect of physical activity on depressed mood could be mediated by sleep via three mechanisms (Figure 2.1).

2.2.1 Longer Total Sleep Time (TST)

Some studies of the relationship between physical activity and sleep in adolescents suggest that more physical activity results in a longer TST (Kim et al., 2016; Patte et al., 2018). In addition, shorter TST in adolescents has been associated with lower mood, and poorer emotional regulation (McKnight-Eily et al., 2011; Shochat et al., 2014). We propose that less physical activity during the day will be associated with shorter TST and lower mood in the adolescents, and that the effect of physical activity on mood will be mediated by TST.

2.2.2 Longer Sleep Onset Latency (SOL)

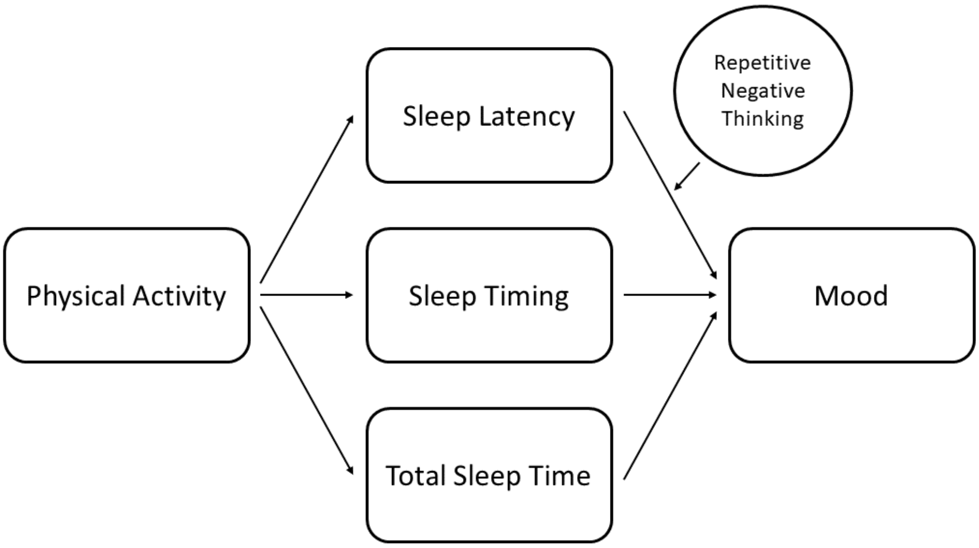
Engagement in physical activity instigates changes to the sympathetic nervous system and core temperature which ultimately result in physiological arousal in the body (Silverman & Deuster, 2014; Wenger, 1995). Evidence suggests that if physiological arousal occurs too close to the sleep attempt that this may cause difficulty falling asleep, and for this reason sleep hygiene recommendations suggest not participating in physical activity close to bedtime (Bonnet & Arand, 2005; Tworoger et al., 2003). The increase in physiological arousal caused by physical activity could result in longer SOLs, thus providing adolescents with time to ruminate about their day, and in turn resulting in overall lower mood (Danielsson et al., 2013; Krause et al., 2017; Lovato & Gradisar, 2014). We propose that more physical activity in the evening will be related to longer SOL and lower mood for the adolescents, and that the effect of physical activity on mood will be mediated by SOL. Additionally, we propose that the mediating effect of SOL between evening physical activity and mood will be moderated by repetitive negative thinking which takes place during the time that the adolescents are trying to fall asleep.

2.2.3 Later Chronotype

Physical activity has been shown to impact the circadian rhythm, and exercising later in the day can have a phase delaying effect resulting in later sleep timing (Miyazaki et al., 2001; Richardson et al., 2017). In turn, later sleep timing in adolescents has also been connected with lower mood (Au & Reece, 2017; Glozier et al., 2014; Müller & Haag, 2018). We finally propose that more physical activity in the evening will be related to later chronotype and lower mood in the adolescents, and that the effect of physical activity on mood will be mediated by chronotype.

Figure 2.1

Proposed Mediating Relationships of Sleep Variables Between Physical Activity and Mood



2.3 Method

2.3.1 Participants

In September 2016 the Finnish Population Register Centre was used to identify 7,539 adolescents (50% registered as male sex) born between 1/1/1999 and 31/12/2000, with a home address in Helsinki, Finland. Adolescents were invited to participate in a 30-min online survey targeting mainly sleep, health and behaviour. The survey was completed in Finnish, the native language of the participants. Valid responses were received from 1,367 participants (18% of the initial cohort). Each adolescent's sex was taken from their information at the Finnish Population Register Centre, 33% were registered as male. The mean age of the valid respondents was 16.84 years (*SD* = 0.58). All respondents signed an electronic consent form. Ethical permission was obtained from The Hospital District of Helsinki and Uusimaa Ethics Committee for gynaecology and obstetrics, paediatrics and psychiatry (Decision number: 50/13/03/03/2016). The SleepHelsinki! study was registered on ClinicalTrials.gov (Identifier: NCT02964598).

2.3.2 Measures

2.3.2.1 Depressive Symptoms

The Beck Depression Inventory-II (BDI-II) summary score was composed of 20 items scored from 0 (low score) to 3 (high score) (Beck et al., 1996). The question about sleep problems was excluded from analyses so as to not incorrectly inflate correlations between sleep and the BDI-II.

2.3.2.2 Repetitive Negative Thinking (RNT)

The RNT variable was the mean of three items from the Adolescent Sleep Hygiene Scale (ASHS) (LeBourgeois et al., 2005). "*I go to bed and think about things I need to do", "I go to bed and replay the day's events over and over in my mind",* and *"I go to bed and worry about things happening at home or at school"*. Response categories were from 0 = Never, to 5 = Always.

2.3.2.3 Sleep

Sleep variables were collected via questions derived from the School Sleep Habits Survey (Wolfson et al., 2003). Collection of sleep data via online questionnaire is correlated with objective measures of sleep in child and adolescent samples (Matricciani, 2013), and was the most resource effective way to collect this data in a large sample size. Total sleep time during the week and on weekends was computed by subtracting sleep onset latency time from time spent in bed. Time spent in bed was counted as the time from 'lights off' to waking time. Weekdays data were chosen as these are susceptible to restricted sleep (Shochat et al., 2014). Chronotype was derived from sleep midpoint on weekends, which was defined as the clock-time in the middle of the sleep period (Roenneberg et al., 2004). The variable was computed by dividing the total sleep time variable by two and subtracting it from the waking time.

2.3.2.4 Physical Activity

The ‘exercise in free time’ variable was composed of two items: “*How often do you exercise or play sports in your free time?”* (from 0 = None, to 6 = Every day), and “*What is the average duration of one exercise occasion?”* (from 0 = I do not exercise, to 4 = Two hours or longer). The ‘exercise in free time’ variable was computed by multiplying the reported exercise frequency with the average duration variable, resulting in an estimation of the average time spent (in hours) exercising in free time over the period of a month.

The ‘physical activity after 6 p.m.’ variable was item 5 from the ASHS, “*After 6:00 in the evening I do some kind of physical activity*” (0 = Never, 5 = Always).

A physical activity composite score was comprised of three components: the physical activity after 6 p.m. variable, the exercise in free time variable, and ASHS item 10 “*During the 1 hour before bedtime I am very active*” (0 = Never, 5 = Always). These were rescaled by ranking the participants based on their physical activity into 6 equal categories (values from 0 to 5).

2.4 Results

2.4.1 Descriptive Statistics

Analysis of the descriptive statistics using independent *t*-tests and chi-squares for key variables showed largely normative results (Table 2.1). There were similar levels of physical activity between boys and girls. The mean BDI-II scores for both girls and boys were in the minimal range (less than 13), although it should be noted that the boys had a significantly lower mean BDI-II score (less low mood) than girls.

Table 2.1

Descriptive Statistics for the Key Variables by Sex

	N	Range	Female *M (SD)*	Male *M (SD)*	All *M (SD)*	t /χ2
Age	1367	15.75–17.88	16.84 (0.59)	16.86 (0.57)	16.84 (0.58)	-0.70
Current education*						17.55 **
Comprehensive school	58		33 (3.6)	25 (5.5)		
Vocational school	169		92 (10.1)	77 (16.9)		
High school	1115		770 (84.9)	345 (75.7)		
Other	21		12 (1.3)	9 (2.0)		
Bedtime (hh:mm)						
Weekday	1367	0:00–23:50	22:23 (1:00)	22:45 (1:00)	22:30 (1:01)	-6.59 ***
Weekend	1367	0:00–23:59	23:34 (1:20)	0:27 (1:32)	23:52 (1:28)	-10.85 ***
Total Sleep Time (hours)						
Weekday	1367	2:10–13:50	7:13 (1:11)	7:23 (1:09)	7:11 (1:11)	-2.40 *
Weekend	1367	3:30–14:30	9:16 (1:13)	9:14 (1:19)	9:15 (1:15)	0.33
Midpoint of sleep (hh:mm)						
Weekday	1367	1:30–9:30	3:09 (0:43)	3:26 (0:50)	3:15 (0:46)	-6.76 ***
Weekend	1367	2:02–11:30	5:30 (1:16)	5:59 (1:28)	5:40 (1:21)	-6.06 ***
Sleep Onset Latency (hours)						
Weekday	1367	0–3:20	0:20 (0:18)	0:17 (0:17)	0:19 (0:17)	2.46 *
Weekend	1367	0–3:00	0:15 (0:14)	0:13 (0:14)	0:15 (0:14)	2.40 *
Physical Activity						

In free time (h/month)	1355	0:00–56:00	16:40 (16:19)	16:26 (16:37)	16:35 (16:25)	0.25
† Composite score	1367	0–5	2.17 (1.08)	2.16 (1.13)	2.17 (1.09)	0.27
† After 6 p.m.	1367	0–5	2.27 (1.37)	2.17 (1.39)	2.23 (1.38)	1.26
Mood						
Depressive symptoms (BDI-II)	1367	0–53	11.57 (10.06)	6.22 (6.88)	9.78 (9.46)	11.5 ***

Note. SD = standard deviation; BDI-II = Beck Depression Inventory. BDI-II score: 0-13 minimal range, 14-19 mild, 20-28 moderate, 29-63 severe.

*Finnish secondary education is 3-4 years and refers to education after the compulsory comprehensive school. Comprehensive school = up to 9th grade; Vocational School = secondary school; High School = secondary school.

† Six point scale (0 = Never, 5 = Always).

***p <.001, **p <.01, *p<.05

2.4.2 Correlations

Total Sleep Time: The physical activity composite score had significant small correlations with TST, *r = 0.08, p <.01,* and BDI-II score, *r = -0.12, p <.001,* in the expected directions. Similarly, ‘exercise in free time’ also had significant small correlations, positive and negative respectively, with weekday TST, *r = 0.09, p <.01,* and BDI-II score, *r = -0.11, p <.001.* As anticipated, more physical activity in free time and overall were related to a longer TST and better mood. There was a small-to-medium negative correlation between weekday total sleep time and BDI-II score, *r = -0.25, p <.001,* longer TST was related to better mood.

Sleep Onset Latency: Interestingly, physical activity after 6 p.m. had significant small negative correlations with weekday SOL, *r = -0.06, p <.05,* and BDI-II score, *r = -0.11, p <.05.* That is, more physical activity after 6 p.m. was related to shorter SOL and better mood. Weekday SOL had a significant small-to-medium positive correlation in the hypothesised direction with BDI-II score, *r = 0.24, p <.001,* where longer SOL was related to worse mood.

Chronotype: There were significant small negative correlations between participation in physical activity after 6 p.m. and the mid-point of sleep on weekends (used to indicate chronotype), *r = -0.12, p <.001,* and BDI-II score, *r = -0.11, p <.001,* with more late physical activity related to earlier chronotype and better mood. There was also a significant small positive correlation between chronotype and mood, *r = 0.19, p <.001,* with later chronotype related to worse mood.

2.4.3 Meditation Models

2.4.3.1 Total Sample

The hypothesised mediation models were tested using Model 4 of Hayes’ PROCESS bootstrapping method (Preacher & Hayes, 2008). In the analyses for the total sample, sex, age, and education were included as covariates. Results are presented in Table 2.2. All direct effects tested within the mediation models were significant, as were the indirect effects for each proposed mediation. However, physical activity after 6 p.m. was found to have the opposite effect on SOL and chronotype than that which was hypothesised - it was associated with shorter weekday SOL and earlier weekend midpoint of sleep (chronotype). All other associations occurred in the anticipated direction. More physical activity in free time and more physical activity in the composite score were associated with longer weekday TST, better mood was associated with shorter weekday SOL, longer weekday TST, and earlier chronotype, and more physical activity (after 6 p.m., in free time, and composite score) was associated with better mood. Overall, increased physical activity was associated with higher mood with the association partially mediated by SOL, TST, and chronotype.

Table 2.2

Total Sample Results of Bootstrapping Analysis on Direct Effect of Physical Activity on Mood and Indirect Effect of Physical Activity on Mood Through Sleep Variables

	B	SE_B	*p*	Bootstrap 95% CI
Hypothesis 1				
Exercise in free time – Weekday TST	0.006	.002	.001	-
Weekday TST – BDI-II score	-0.21	.02	<.001	-
Exercise in free time – BDI-II score	-0.007	.002	<.001	-
Indirect effect	-0.001	.0004	.001	[-0.002, -0.005]
PA composite score – Weekday TST	0.09	.03	.003	-
Weekday TST – BDI-II score	-0.21	.02	<.001	-
PA composite score – BDI-II score	-0.09	.02	<.001	-
Indirect effect	-0.02	.007	.005	[-0.033, -0.007]
Hypothesis 2				
PA after 6 p.m. – Weekday SOL	-0.78	.35	.03	-
Weekday SOL – BDI-II score	0.01	.001	<.001	-
PA after 6 p.m. – BDI-II score	-0.07	.02	<.001	-
Indirect effect	-0.009	.004	.04	[-0.018, -0.0006]
Hypothesis 3				
PA after 6 p.m. – Weekend sleep midpoint	-0.09	.03	<.001	-
Weekend sleep midpoint – BDI-II score	0.17	.02	<.001	-
PA after 6 p.m. – BDI-II score	-0.06	.02	<.001	-
Indirect effect	-0.015	.005	.002	[-0.027, -0.007]

Note. PA = Physical activity; SOL = Sleep onset latency; TST = Total sleep time; BDI-II = Beck Depression Inventory.

2.4.3.2 Sex effects

The average mood scores were different between the sexes, the boys mood score was much lower, indicating less low mood than the girls, which concurs with a number of previous studies (Salk et al., 2017; Shore et al., 2018). With such differences it is important to identify for ‘who’ these models apply, thus the data were stratified by sex and the mediation model analysis repeated using age and education as covariates. No evidence was found for the mediations in the boys’ data (Table 2.3).

Table 2.3

Boys Sample Results of Bootstrapping Analysis on Direct Effect of Physical Activity on Mood and Indirect Effect of Physical Activity on Mood Through Sleep Variables

	B	SE_B	*p*	Bootstrap 95% CI
Hypothesis 1				
Exercise in free time – Weekday TST	0.003	.003	.42	-
Weekday TST – BDI-II score	-0.15	.04	<.001	-
Exercise in free time – BDI-II score	-0.01	.003	<.001	-
Indirect effect	-0.0004	.0005	.43	[-0.002, 0.0004]
PA composite score – Weekday TST	0.04	.05	.40	-
Weekday TST – BDI-II score	-0.16	.04	<.001	-
PA composite score – BDI-II score	-0.09	.04	.02	-
Indirect effect	-0.006	.008	.40	[-0.023, 0.007]
Hypothesis 2				
PA after 6 p.m. – Weekday SOL	-0.24	.59	.69	-
Weekday SOL – BDI-II score	0.01	.003	<.001	-
PA after 6 p.m. – BDI-II score	-0.05	.03	.10	-
Indirect effect	-0.003	.006	.67	[-0.015, 0.008]
Hypothesis 3				
PA after 6 p.m. – Weekend sleep midpoint	-0.08	.05	.12	-
Weekend sleep midpoint – BDI-II score	0.12	.03	<.001	-
PA after 6 p.m. – BDI-II score	-0.05	.03	.15	-
Indirect effect	-0.009	.006	.15	[-0.024, 0.0008]

Note. PA = Physical activity; SOL = Sleep onset latency; TST = Total sleep time; BDI-II = Beck Depression Inventory.

Analysis of the mediation models for the girls' data, using age and education as covariates, found statistically significant results (Table 2.4; Figure 2.2 for diagrammatic representation of the path estimates for the four models). Significant direct and indirect effects were found for all elements of the proposed mediation models in girls. Again, physical activity after 6 p.m. had a negative association with weekday SOL and weekend midpoint of sleep (chronotype), more physical activity after 6 p.m. was associated with shorter SOL and earlier chronotype. However, all other relationships were as hypothesised. More physical activity in free time and a greater physical activity composite score were associated with longer TST. Better mood was associated with shorter SOL, longer TST, later chronotype and more physical activity (after 6 p.m., in free time, and composite score).

Table 2.4

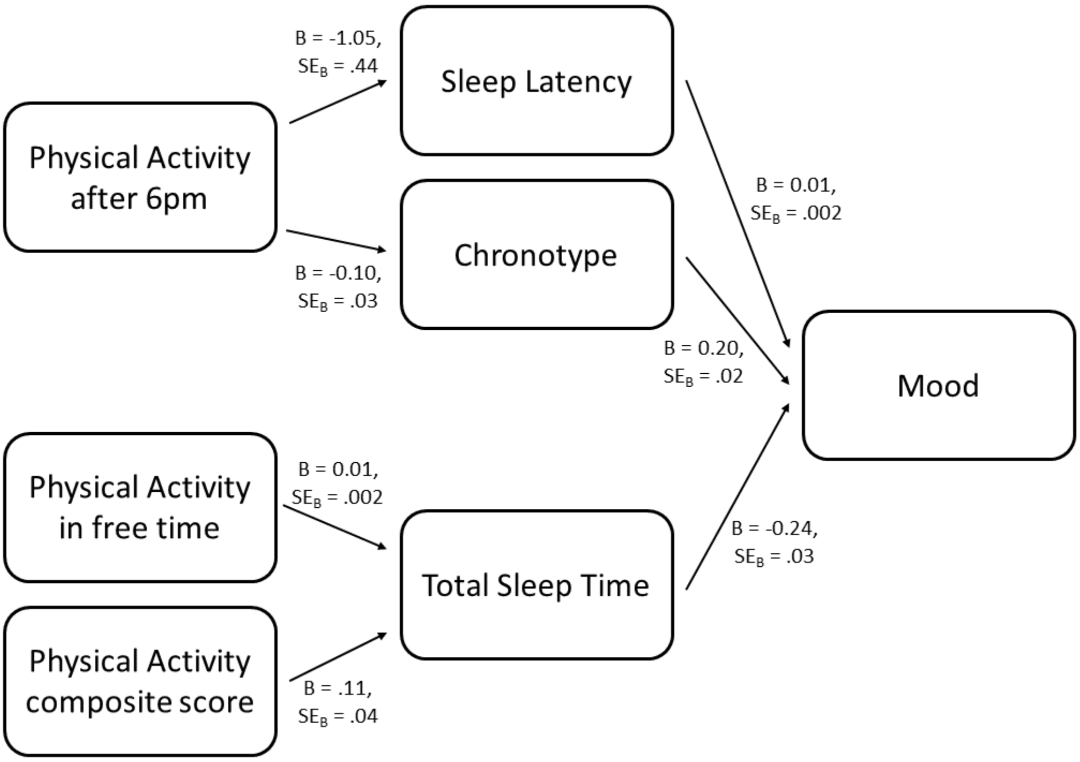
Girls Sample Results of Bootstrapping Analysis on Direct Effect of Physical Activity on Mood and Indirect Effect of Physical Activity on Mood Through Sleep Variables

	B	SE_B	*p*	Bootstrap 95% CI
Hypothesis 1				
Exercise in free time – Weekday TST	0.008	.002	<.001	-
Weekday TST – BDI-II score	-0.24	.03	<.001	-
Exercise in free time – BDI-II score	-0.004	.002	.02	-
Indirect effect	-0.002	.0006	.002	[-0.003, -0.0008]
PA composite score – Weekday TST	0.11	.04	.002	-
Weekday TST – BDI-II score	-0.24	.03	<.001	-
PA composite score – BDI-II score	-0.09	.03	.002	-
Indirect effect	-0.027	.01	.007	[-0.048, -0.009]
Hypothesis 2				
PA after 6 p.m. – Weekday SOL	-1.05	.44	.02	-
Weekday SOL – BDI-II score	0.01	.002	<.001	-
PA after 6 p.m. – BDI-II score	-0.07	.02	.001	-
Indirect effect	-0.013	.006	.04	[-0.026, -0.002]
Hypothesis 3				
PA after 6 p.m. – Weekend sleep midpoint	-0.10	.03	.001	-
Weekend sleep midpoint – BDI-II score	0.20	.02	<.001	-
PA after 6 p.m. – BDI-II score	-0.07	.02	.003	-
Indirect effect	-0.02	.007	.007	[-0.037, -0.007]

Note. PA = Physical Activity; SOL = Sleep Onset Latency; TST = Total Sleep Time; BDI-II = Beck Depression Inventory.

Figure 2.2

Combined Diagram of the Four Models Tested Showing the Mediating Relationships Between Physical Activity Variables, Sleep Variables, and Mood for Girls



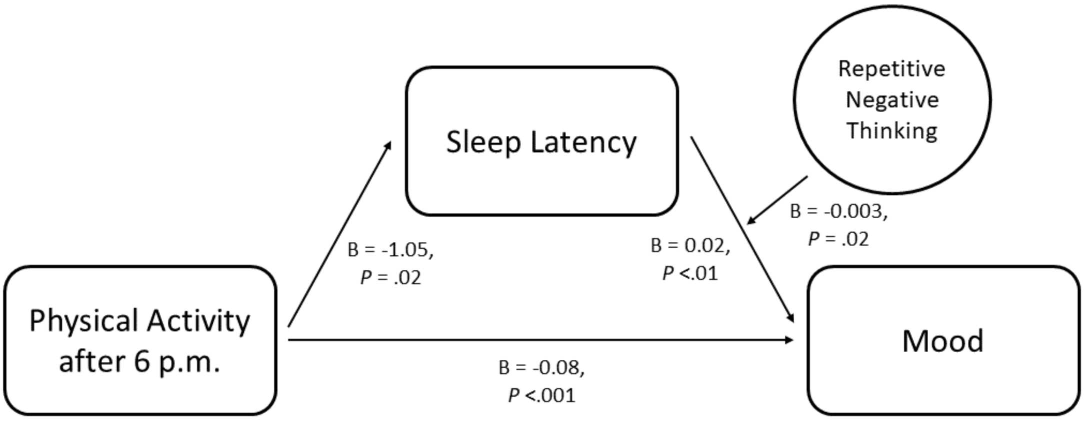
2.4.4 Moderated Mediation

Further analyses were conducted to test our proposal of whether repetitive negative thinking (RNT) moderated the relationship between weekday SOL and mood within the mediation model for physical activity after 6 p.m., weekday SOL, and mood. The moderated mediation was tested for by Hayes PROCESS Model 14 (Preacher & Hayes, 2008). As the mediated relationship was not significant for boys, girls' data were used to test for moderated mediation.

Education level and age were controlled for in the moderated mediation analyses. As expected, there was a moderated mediation (illustrated in Figure 2.3), with RNT significantly moderating the relationship between weekday SOL and mood. As expected, there was a significant effect of physical activity after 6 p.m. on mood. Further analysis determined the conditional indirect effect of physical activity after 6 p.m. on mood through weekday SOL at three levels of RNT (mean value, and one standard deviation above and below the mean). It showed that the effect sizes at higher levels of RNT were smaller than those at lower levels, indicating that at higher levels of repetitive negative thinking weekday SOL had a weaker relationship with mood than at lower levels of repetitive negative thinking.

Figure 2.3

Moderated-Mediation Model for the Association Between Physical Activity and Mood via an Interaction Between Sleep Onset Latency and Repetitive Negative Thinking



2.5 Discussion

Using a large sample of adolescents, the present study tested whether the relationship between physical activity and mood was mediated via various aspects of sleep. Whilst the majority of predictions were supported for adolescent girls, physical activity in the evening (i.e., after 6 p.m.) was not linked with worse sleep, but instead was related to shorter SOL and earlier chronotype. We discuss the implications of each of the proposed mechanisms below.

2.5.1 Does Total Sleep Time Mediate the Impact of Physical Activity on Mood?

Evidence was found for the hypothesised mediation within the total sample and for girls. Total sleep time was found to partially mediate the relationship between daytime physical activity and mood, with more physical activity in free time, and a higher physical activity composite score, both being associated with longer total sleep time and higher mood. The associations found matched those demonstrated in previous adolescent research. More physical activity was associated with longer total sleep time as seen in Kim et al. (2016) and Patte et al. (2018), longer sleep duration was associated with better mood (e.g., Shochat et al., 2014), and more physical activity was also associated with better mood (e.g., Carter et al., 2016). The results of our study build upon these individually established relationships, to bring them together and indicate a more precise pattern of relationships where the potential impact of physical activity on mood may occur partially via sleep. Although the design of our study cannot ascertain causality, our results suggest improved sleep duration may be a mechanism linking physical activity and mood.

2.5.2 Does Sleep Onset Latency Mediate the Impact of Physical Activity on Mood?

The second prediction, that sleep onset latency would mediate the relationship between evening physical activity and mood, was found to be true for both the total sample and the sub-sample of girls. However, more evening physical activity was related to shorter sleep onset latency thereby benefiting sleep, not hindering it, as hypothesised. Nevertheless, longer sleep onset latency was associated with lower mood (Danielsson et al., 2013; Lovato & Gradisar, 2014), and more participation in physical activity was associated with better mood (Maraki et al., 2005), thus supporting our other predictions.

Although we expected that more evening physical activity would be detrimental to sleep latency, the association between higher levels of ‘general’ physical activity and shorter sleep onset latency is in accordance with much of the research available on this topic (e.g., Kalak et al., 2012 ; Brand et al., 2010b). It is important to note that we anticipated that the physical activity would be linked with shorter SOL due to its timing. Sleep hygiene recommendations and focused research in adult and adolescent samples have indicated that when physical activity is undertaken in the evening, too close to the sleep attempt, this may increase physiologic arousal and the time taken to fall asleep (e.g., Bonnet & Arand, 2005; Tworoger et al., 2003). For example, Tworoger et al. (2003) found that adult women who participated in more moderate intensity exercise from 6:15 p.m.-7:15 p.m. had more difficulty falling asleep than those who participated in less moderate intensity exercise at this time. Similarly, research by Bonnet and Arand (2005) has indicated that 5 min of low-intensity exercise (walking) can result in an increased sleep onset latency for at least 95 min after the cessation of activity. The discrepancy in our findings may be attributed to our self-report measure, in that the ‘physical activity after 6 p.m.’ from the Adolescent Sleep Hygiene Scale did not specify the intensity of the activity. Also worth noting is that as the average weekday bedtime of the girls’ was 10:23 p.m., it is possible that physical activity ~4 hours before bedtime is not near enough to see a negative impact. Notably, much of the research into the impact of evening physical activity on sleep onset latency has been conducted in adult samples (Bonnet & Arand, 2005; Tworoger et al., 2003). Thus, it is possible that the positive association between evening physical activity and sleep onset latency seen in the present sample of adolescents may be due to differences in intensity and timing, or between adults and adolescents.

2.5.3 Does Chronotype Mediate the Impact of Physical Activity on Mood?

Evidence was found in the total sample and sub-sample of girls to support the prediction that chronotype would mediate the relationship between evening physical activity and mood. Interestingly, more evening physical activity was again linked with better sleep, with more participation in evening physical activity associated with earlier chronotype. The other relationships were consistent with research in this area, earlier chronotype and more evening physical activity were associated with better mood (Au & Reece, 2017; Glozier et al., 2014; Maraki et al., 2005; Müller & Haag, 2018), providing added support for these relationships.

Prior research into the relationship between chronotype and physical activity has shown an association between earlier chronotype and more participation in physical activity in adolescents (Kauderer & Randler, 2013; Urbán et al., 2011), however this research is typically performed without division relating to the time of day. Our research supports the basic relationship between chronotype and physical activity. Adolescents who reported that they more often participated in physical activity in the evening had an earlier chronotype than those who reported participating in evening physical activity less often. Yet, research into the impact of specially timed physical activity has indicated that evening physical activity can delay circadian timing (Miyazaki et al., 2001; Richardson et al., 2017), and it was expected that this would be replicated in our findings. Again, it is possible that the use of an item pertaining to physical activity participation after 6 p.m. was a less precise measure of ‘evening’ physical activity in our adolescent sample with an average bedtime nearing 10:30 p.m. Indeed, as we cannot specify when during this time period adolescents were physically active, it is possible that the physical activity occurred too early in the evening to delay adolescents’ chronotype.

2.5.4 The Impact of Repetitive Negative Thinking

For girls, repetitive negative thinking (RNT) was found to moderate the relationship between sleep onset latency and mood. As RNT increased, the relationship between sleep onset latency and mood decreased. That is, girls with lower levels of RNT had a stronger relationship between sleep onset latency and mood than girls with higher levels. Interestingly this is yet again the opposite of what we would have expected. Longer sleep onset latency has been associated with more negative thoughts during this time before sleep (Harvey, 2000; Hiller et al., 2014), and higher levels of RNT are related to lower mood (Danielsson et al., 2013; Krause et al., 2017). RNT occurs throughout the day, ranging from the early morning to late evening (Moberly & Watkins, 2008). One possibility for the connection found between longer SOL and less RNT is that girls with long SOLs do usually ruminate throughout the day but distract themselves from ruminating by using technology. Thus, most of the time during their perceived sleep onset process, they are using technology (e.g., watching TV) and only experience smaller moments of RNT. We acknowledge this is a speculative explanation for the negative relationship between SOL and RNT, so further research is needed to observe whether this negative relationship persists.

2.6 Limitations and Implications

Although it would be ideal to have included objective measures alongside the self-report measures in the present study, this was not logistically feasible. Furthermore, measures like wrist actigraphy are more valid for sleep onset and offset (and thus, sleep mid-point/chronotype), but less valid for total sleep time and sleep latency (Short et al., 2012). Nevertheless, the models proposed and tested in the present study could be confirmed via alternative research designs with smaller sample sizes and both subjective and objective measures of sleep (and physical activity). For example, it is possible that a physical activity ‘intervention’ could be a feasible option in this young population to target poor sleep and low mood. Alternatively, longitudinal designs and the use of ecological momentary assessment could test these models, and simultaneously confirm the direction of effect between the inter-connected factors. It is difficult to determine if the sex differences found in this study are due to a restriction in the statistical range of the boys’ mood scores or an actual difference in the relationships tested in this study between boys and girls. Certainly there is some evidence of a closer relationship between sleep and mood difficulties in adolescent girls than boys (Conklin et al., 2018; van Zundert et al., 2015). If these sex differences are not due to statistical or methodological factors, investigation of this difference in future research could help ascertain to what degree it plays a role in the relationships between physical activity, sleep, and mood between male and female samples. The association between evening physical activity and shorter sleep onset latency and earlier chronotype suggests that participation in physical activity earlier in the evening (i.e., closer to 6 p.m. and further away from bedtime) may be beneficial for adolescents. It also further indicates the value of using physical activity interventions for adolescents with sleep difficulties and low mood.

2.7 Conclusions

The individual relationships between participation in physical activity, sleep, and mood and the bi-directional nature of these relationships have been well established. Yet the more complex interplay of how sleep mediates the relationship between physical activity and mood has not, to the authors’ knowledge, been previously demonstrated. A number of the proposed relationships were not significant for adolescent boys, revealing some unexpected sex differences, however for the adolescent girls’ sleep was found to partially mediate the relationship between physical activity and mood. Participation in more physical activity was associated with longer sleep onset latency, longer total sleep time, and earlier chronotype, which were in turn associated with better mood. Interestingly, physical activity was associated with better sleep regardless of the time of day the girls were physically active. Longitudinal research is needed to confirm the posited direction of the mediations. However, our results indicate that physical activity interventions show promise for improving adolescent sleep and mood.

2.7.1 Acknowledgements

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CHAPTER 3 -

MOVE, SLEEP, MOOD, REPEAT: A TEMPORAL ASSESSMENT OF PHYSICAL ACTIVITY, SLEEP, AND MOOD CONNECTIONS IN ADOLESCENT GIRLS

3.1 Abstract

Sleep and mood problems can have a strong detrimental effect on adolescents (Clayborne et al., 2019; Galván, 2020; Gradisar et al., 2022). Complex interrelationships have been identified between physical activity, sleep, and mood, and a greater understanding of these connections can help inform new treatment options for sleep and mood difficulties using physical activity. The aim of this study was to determine if sleep (total sleep time and chronotype) mediated the relationship between physical activity and mood from day-to-day. Nineteen female adolescents (aged 17-20 years) participated in a weeklong study. Physical activity and sleep were measured using accelerometry (GENEActiv wrist accelerometer), and mood was measured by ecological momentary assessment five times each day. Results from mixed-model analysis showed mediation on a daily scale. On Wednesday, Friday, and Sunday, less total sleep time (TST) mediated the relationship between more moderate-to-vigorous physical activity (MVPA) during the day and mood, although the direction of the mood change differed depending on the day. That is, more MVPA → less TST → better/worse mood. Chronotype also mediated the relationship between evening MVPA and mood: more evening MVPA → earlier sleep midpoint → more positive affect. This relationship between more evening physical activity and earlier chronotype builds upon the gathering evidence, since the initial publication of sleep hygiene guidelines, that evening physical activity is beneficial to sleep. The association between more physical activity and shorter total sleep time was not anticipated and suggests a possible misattribution of sleep and wake by the actigraphy measure (Mead et al., 2019; Vitale et al., 2017; Youngstedt, 2005), however further investigation is required into the process involved with this. The results of this study illustrate the complexity of the interrelationships between physical activity, sleep and mood in adolescents. The relationships found in this sample were not always in the expected directions and patterns. Greater understanding of these relationships is required in order to develop interventions for poor sleep and low mood in this population.

3.2 Introduction

To date, extensive research has established connections between physical activity, sleep, and mood. Physical activity is related to both sleep and mood (Lopresti et al., 2013; Stutz et al., 2019), and sleep and mood are related to each other (Asarnow et al., 2013). Amongst this rich knowledge base there is evidence to show the possibility that sleep could act as a mediating mechanism between physical activity and mood; where physical activity influences sleep, which in turn influences mood. Although most of the research in this area has been conducted in adults, some has considered the relationships in adolescent populations (Gianfredi et al., 2020; Kredlow et al., 2015; Richardson et al., 2017). Adolescence is a unique time of life socially, and physiologically (Towbin et al., 2015). Adolescents are also uniquely prone to experiencing a later chronotype (sleep timing) than other developmental periods (Roenneberg et al., 2004), and as such, it is important to study adolescent populations at this unique time of life.

Although the links between the three aspects of physical activity, sleep, and mood have been minimally researched in adolescent populations, much more research has been conducted into the connection between physical activity and sleep in this age group. Participation in physical activity has been shown to impact multiple aspects of sleep, including sleep duration and timing, and this has been demonstrated in large scale studies of adolescents (Patte et al., 2018) and systematic and theoretical reviews across the lifespan (Dolezal et al., 2017; Montaruli et al., 2017). In adolescents, more physical activity during the day (both intensity and duration) has been shown to be connected to *longer sleep duration* (Harris et al., 2017; Master et al., 2019), and less depression symptoms (meta-analysis by Rodrigues-Ayllon et al. 2019). In turn, a more recent meta-analysis has shown that *longer sleep duration* in adolescents also relates to better mood (more positive affect and less negative affect) (Short et al., 2020). Indeed, a review of day-to-day associations between subjective sleep quality and mood showed that in a majority of studies better sleep is associated with more positive affect and less negative affect (Konjarski et al., 2018). These connections between physical activity, sleep duration, and mood provide the building blocks for a potential mediation of the relationship between physical activity and mood by sleep duration (i.e., total sleep time [TST]), where more physical activity results in longer total sleep time, which in turn results in better mood.

In addition, the necessary links exist between physical activity, circadian timing, and mood to suggest a potential mediation by sleep timing in the relationship between evening physical activity and mood. For instance, there is evidence that late chronotypes and late circadian rhythms are associated with less positive affect, more negative affect and more depression symptoms. This is seen in both adult (Au & Reece, 2017), and adolescent research (Gariépy et al., 2019; Haraden et al., 2017). Theoretical reviews propose that late-timed evening physical activity in adolescents could result in later chronotype (Montaruli et al., 2017; Richardson et al., 2017). Thus, it is possible that conducting more physical activity in the evening may result in later sleep timing, which in turn results in worse mood. As such it is important for research to analyse the potential impact of the timing of physical activity on sleep and mood outcomes.

In **Chapter 2** a cross-sectional design was used in a sample of 1,367 Finnish adolescents to test the basic framework required for sleep to mediate the impact of physical activity on depression symptoms through sleep duration, sleep timing, and sleep onset latency. The results showed correlations between physical activity, sleep, and mood that supported the mediation framework. More physical activity was associated with longer TST and both were associated with less depression symptoms. Evening physical activity was also associated with sleep onset latency (SOL) and chronotype - and all three were again associated with depression symptoms, although not in the expected direction. It was found that more evening physical activity was associated with a shorter SOL, earlier chronotype and less depression symptoms. Thus, instead of evening physical activity being detrimental to sleep and mood, it was found to be beneficial. Interestingly there were sex differences, in that these correlations were significant for female adolescents but not males. However, there is little research investigating how the interrelationships between physical activity, sleep, and mood work on a day-to-day level in a way to identify temporal associations, and even less research in this area has been conducted in adolescent populations, whose sleep duration is limited by a set school start time.

Of the research which has been conducted, four adolescent studies have considered notable aspects of the day-to-day relationships between physical activity, sleep, and mood, including how sleep may mediate the relationship between physical activity and mood. Each of these studies has its benefits and the following review shows how the present study will advance upon them.

The relationship between a single pulse of physical activity and subsequent sleep in adolescents has been considered in a cross-over experimental study by Saidi and colleagues (2020). In a cohort of 16 female adolescents (aged 12-18) with evening chronotypes, it was found that after a 40-minute morning cycling session the adolescents slept that night for one hour longer than when they participated in the control condition with no physical activity. Saidi et al.'s study is noteworthy due to the use of objective measures of sleep (actigraphy) and physical activity (via experimental protocol) which strengthens the finding of the 'physical activity – sleep' relationship. Building upon the finding that a single pulse of physical activity has a beneficial effect on sleep duration that night, the current study will consider how the physical activity partaken in one day can impact sleep that night - and thus mood the next day.

The daily associations between physical activity and sleep in adolescents have been considered by Master et al. (2019). Master and colleagues looked separately at each day of a weeklong protocol to tease out daily relationships between physical activity and sleep in a sample of 417 adolescents (aged 15 years). They found that if an adolescent participated in more moderate-vigorous physical activity (MVPA) on a certain day (compared to their daily average MVPA as calculated over the week), that for each extra hour of MVPA that day, the adolescent had 18 minutes earlier sleep onset time and 10 minutes longer TST. Correspondingly, on a day when an adolescent had more sedentary behaviour than their daily average over the week, for each extra hour of sedentary behaviour they had 11 mins shorter TST, and delayed sleep onset time and wake up time (18 mins and 11 mins, respectively). Furthermore, in a subgroup of 293 adolescents, analysis of the timing of the densest MVPA cluster[3] on each day identified that when a participant's densest MVPA cluster occurred earlier than it would on average, then their sleep onset time was significantly earlier. All of these results indicate that on a daily scale, more physical activity is related to a longer sleep duration and earlier sleep timing that night, and that earlier physical activity during the day is related to earlier sleep timing that night as well. The current study is also interested in the daily relationships between physical activity and sleep, however as mood is closely connected with both of these constructs the study will consider not just the daily relationships between physical activity and sleep, but the possibility of daily mediation of the 'physical activity – mood' connection through sleep.

Previous research into the links between physical activity, sleep, and mood in adolescents has been conducted by Langvik and colleagues (2019), in a cross-sectional study of 1,485 adolescents (aged 16-21 years). They found that insomnia symptoms, including experiencing a long sleep onset latency, and long periods of wake time during the night, had a strong positive association with depression symptoms in both girls and boys, yet the association was much stronger in girls. Mediational models were run to consider how physical activity, sleep, and mood might be interconnected. To a small degree, physical activity was found to mediate the relationship between insomnia and depression (accounting for 4% of variance), however, stronger evidence was found for the mediating role of insomnia between physical activity and depression. Insomnia symptoms were found to account for 62% of variance in the effect of physical activity on depression.

These findings support the theory that sleep is a mediating mechanism in the relationship between physical activity and mood. However, it should be noted that the physical activity measure in

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[3] Densest MVPA (moderate to vigorous physical activity) cluster was calculated over the 2-hour period in which each adolescent was most active that day. The 2-hour period was measured from the midpoint of the largest number of minutes of MVPA (one hour before and one hour after). The sum of all MVPA in this cluster was calculated and only adolescents with a total of 10 or more minutes of MVPA in their densest MVPA cluster were included in the analysis.

Langvik et al.'s study was subjective and only consisted of two questions pertaining to the frequency of participation in physical activity during and outside of school. Similarly, sleep was measured by the subjective Bergen Insomnia Scale, and thus was considered as the broad construct "insomnia symptoms". The separate components of the insomnia measure were not considered individually, and thus it was not possible to consider the mechanisms involved, such as sleep onset latency. The present study will use objective measures to assess the mediational role of sleep in the relationship between physical activity and mood.

Finally, another cross-sectional study, conducted by Harris and colleagues (2017), looked at the relationships between physical activity, sleep, and mood in a sample of 74 adolescents (aged 15-18). The adolescents were recruited in three groups, each of which had a different level of physical activity. The pattern of results found between physical activity, and sleep (TST and chronotype) was strikingly similar to a dose-response relationship. More physical activity was associated with earlier chronotype (assessed by MEQ, and corroborated by bedtime, sleep onset time, and wake up time), longer TST, and more positive affect. These results follow the basic premise of the proposed mediations – more physical activity participation was beneficial to sleep and mood. However, a number of elements were not considered in this study. Harris et al. did not look at the relationship between sleep and mood themselves, nor the impact of physical activity timing. Common sleep hygiene recommendations would suggest that evening physical activity in particular would be detrimental to sleep (Diagnostic Classification Steering Committee, 1990; Krishnan & Patel, 2022; Shriane et al., 2020). The current study will consider the *amount* of physical activity, and its *timing*. Furthermore, the nature of the current study's research design will allow us the assessment of temporal links where the cross-sectional designs of **Chapter 2** and Harris et al.'s study could not.

The use of ecological momentary assessment in the present study to measure mood multiple times throughout the day will allow the exploration of whether sleep affects mood differently at different times of day. It will also present a more detailed pattern of mood throughout the day which may help indicate which pathways are involved. Looking at how physical activity, sleep, and mood are connected in a mediational way from day-to-day will help to uncover a direction of effect where many previous studies could not. This study will assess how physical activity during the day affects sleep that night and how both of these affect mood the next day. Two basic mediational models are hypothesised for TST and chronotype.

3.2.1 Total Sleep Time

On a day an adolescent does more MVPA (as compared to days when the adolescent does less MVPA), they will have a longer TST, which in turn will lead to better mood the next day.

Thus, the relationship between physical activity and mood will be mediated by total sleep time.

3.2.2 Chronotype

Adolescents who participate in more MVPA in the evening (in the 3 hours prior to sleep, or after 6 p.m.) will have later sleep timing (midsleep point) that night and lower mood the next day compared to adolescents who participate in less evening MVPA.

Thus, the relationship between evening physical activity and mood will be mediated by chronotype.

3.3 Method

3.3.1 Participants

This study used the data from 19 female adolescents (self-reported sex) aged 17-20 years. This data was taken from a larger study of 38 female adolescents and young women (self-reported sex) aged 17-25 years. The larger study focused on the connections between physical activity and body satisfaction/dissatisfaction which contributed to the choice to recruit only females. An age limit of 20 years for the current study was chosen as per Roenneberg et al. (2004), which showed that at this age, females exhibit the maximum lateness of chronotype suggesting this is the first biological marker of the end of adolescence.

The present study was conducted at Flinders University during June to August of 2017. Participants were recruited from undergraduate student volunteers, student employment services, and online via website advertising and social media networks. Valid responses were received from all 38 recruited participants. Participants received a reimbursement of AUD$50 for their time. Ethical permission was obtained from Flinders University Social & Behavioural Research Ethics Committee (Decision Number: 7124).

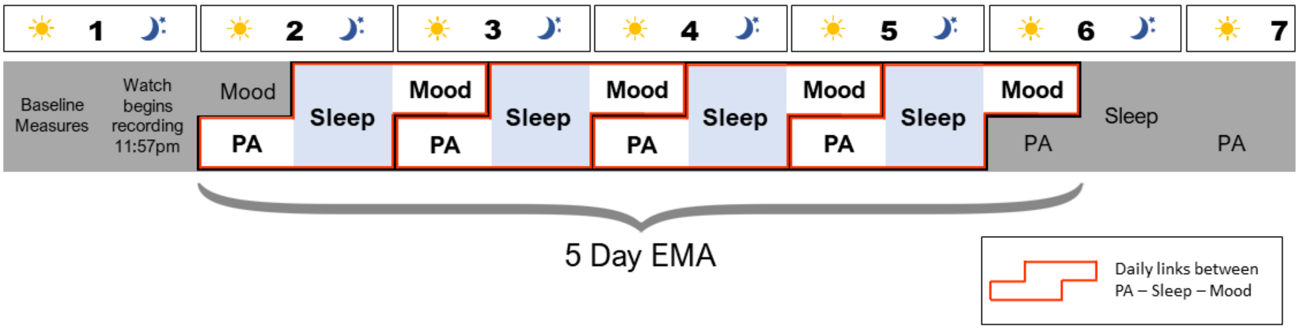
3.3.2 Design

The study was a mixed-model ecological momentary assessment with an observational design. See

Figure 3.1 for a representation of the study procedure. On Day 1 participants completed a baseline questionnaire which included questions targeting demographic information, routine physical activity behaviour, and mood. After completing the baseline questionnaire, participants provided wrist accelerometry data over 6 days and nights to measure physical activity and sleep, this was accompanied by a 6-night sleep diary. During this time participants also undertook a 5-day ecological momentary assessment (EMA) through their smart phone to gather mood data. For 5 days participants received a text message with a link to the online questionnaire five times each day at random intervals between 9 a.m. and 10 p.m. The text messages were a minimum of 1 hour apart and collected information on physical activity behaviour and mood.

Figure 3.1

Study Procedure



Note. PA = Physical activity. EMA = Ecological momentary assessment.

3.3.3 Measures

3.3.3.1 Mood

At baseline, mood state was measured via the 60-item Positive and Negative Affect Schedule – Expanded Form (PANAS-X) (Watson & Clark, 1999) and the DASS-21 (Lovibond & Lovibond, 1995). Participants also completed the Reasons for Exercise Inventory (Silberstein et al., 1988). The three items of relevance to this study in the Reasons for Exercise Inventory were "*to what extent is … the following an important reason that you have for exercising*?"; "*to improve mood", "to cope with sadness, depression",* and *"to cope with stress, anxiety"*.

During the EMA, mood was measured via the 10-item Negative Affect subscale and 10-item Positive Affect subscale of the PANAS-X (Watson & Clark, 1999). As previously mentioned, the EMA was conducted over 5 days with questions answered five times throughout each day, resulting in 25 data points throughout the EMA. The five mood data points for each day were categorised as morning, afternoon, or evening mood. Morning was defined as a data point which was completed between 6 a.m. and midday (12 p.m.), afternoon was defined as 12 p.m. to 6 p.m., and evening 6 p.m. to 1 a.m. For a more detailed discussion of the decision for the cut-off times between morning, afternoon and evening please see **Appendix B**.

3.3.3.2 Physical Activity

Physical activity was measured subjectively by questionnaires, and objectively through accelerometry. For subjective physical activity, adolescents completed a questionnaire at baseline that recorded information such as what physical activities they currently participate in, for how long on each occasion, and how often. At each EMA time-point participants also completed a questionnaire that recorded information such as what physical activity they had participated in since the last time-point and for how many minutes.

Objective physical activity was measured by a triaxial GENEActiv wrist accelerometer (ActivInsights Ltd, Cambridgeshire, UK) worn continuously on the non-dominant wrist for 6 days and nights. Previous research has validated the use of GENEActiv for sleep and activity monitoring in children and adults (Eslinger et al., 2011; Hildebrand et al., 2014; te Lindert & van Someren, 2013). The accelerometer was set to record at a frequency of 75 Hertz, and the data were calculated in R (version 4.0.5) using the accelerometry package GGIR (version 2.3-0) (Migueles et al., 2019; Sabia et al., 2014; van Hees et al., 2013; van Hees et al., 2014). Based upon prior research and standardised recommendations, a valid day was defined as > 10 hours waking wear time, and < 6 hours of non-wear (non-wear was classified as 60 minutes of consecutive activity counts < 25) (Matthews et al., 2012). The majority of participants wore the accelerometer for the entire 6 day/night period, and on no occasion did any participants wear the accelerometer for less than 22 hours in each day.

The intensity of activity was graded as sedentary, light, moderate, or vigorous using cut-points for adolescents established by prior research (i.e., Hildebrand et al., 2017; Hildebrand et al., 2014). The data were measured in milli (10^{-3}) gravity-based acceleration units (mg) which were averaged over 5 second epochs. The cut-points graded the activity as; sedentary (0 to < 46 mg), light (46 to < 93 mg), moderate (93 to < 418 mg) or vigorous (≥ 418 mg) (Hildebrand et al., 2017; Hildebrand et al., 2014). These cut-points have been developed for the GENEActiv accelerometer and defined to match the standardised Metabolic Equivalent of Task (MET) grades for energy expenditure; sedentary (< 1.5 METS), light (1.5-2.9 METS), moderate (3-5.9 METS) or vigorous ≥ 6 METS) (Matthews et al., 2012). Time spent in moderate and vigorous physical activity was calculated in 1 minute bouts[4] (Tarp et al., 2018), where 80% of the bout needed to meet criteria for moderate or vigorous graded physical activity. The full GGIR code used in the accelerometry analysis of this study can be found in **Appendix A**.

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[4] Current health guidelines recommend participation in physical activity regardless of bout length (Physical Activity Guidelines Advisory Committee, 2018; Piercy et al., 2018), as current research shows that physical activity bouts of any length are beneficial to health and reduce all-cause mortality (Jakicic et al., 2019; Millard et al., 2021). Similarly beneficial in research, measuring physical activity using small epochs and small bout lengths provides greater accuracy and a more representative picture of activity in everyday-life than using 10-minute bout lengths (Ayabe et al., 2013; Jakicic et al., 2019; Nettlefold et al., 2016). This is also the case for measuring physical activity in adolescents (Sanders et al., 2014). Due to the greater accuracy of a data set with smaller bout lengths, 1-minute bouts were calculated.

For analysis of the study hypotheses, three variables were created from the objective physical activity data; *daily physical activity* and two definitions of *evening physical activity*. Daily physical activity was the overall physical activity undertaken each day. It was comprised of minutes spent in moderate and vigorous physical activity (MVPA) during the period from wake-up to wake-up. Two variables were created for evening physical activity; one included MVPA minutes which occurred in the 3 hours prior to each adolescent's sleep onset, the other included MVPA minutes which occurred between 6 p.m. and sleep onset. Please see **Appendix B** for a discussion of the decision for a 6 p.m. cut-off time.

3.3.3.3 Sleep

Sleep was also measured subjectively and objectively, by sleep diary and accelerometry respectively. Adolescents completed a 6-night sleep diary during which they recorded their 'go to sleep' time and 'wake up from sleep' time. They also recorded the sleep onset and offset times of any daytime naps.

Objective total sleep time was calculated from the GENEActiv accelerometer using the R version 4.0.5 and R package GGIR version 2.3-0 (Migueles et al., 2019). Data were calculated for each 'day' in the period between wake-up to wake-up (e.g., the time after waking-up on Monday until time waking-up on Tuesday). Sleep was calculated by GGIR's sleep detection algorithm which looked for a sustained period of inactivity which was defined as no change in arm angle > 5 degrees for ≥ 5 minutes (van Hees et al., 2015). The algorithm also determined the sleep window during which the sleep occurred, from the first sleep onset of the night to the last sleep offset in the morning. Total sleep time was the total amount of sleep which occurred during this sleep window. Naps were identified as "sustained inactivity bouts" outside of the sleep window and thus were not included in the nocturnal sleep data. More information on how this algorithm was developed is described in van Hees (2018).

Chronotype was calculated from the GGIR output of the accelerometry data using sleep midpoint on 'freedays' as per Roenneberg et al. (2003). A 'freeday' refers to a day where there is no school or work the next morning (i.e., Friday and Saturday night). This ensures the sleep period is not influenced by other commitments and more accurately reflects the natural timing of sleep. Sleep midpoint is calculated by finding the clock time in the middle of the sleep period (between sleep onset and offset). The sleep midpoints of the two freedays of Friday and Saturday night were then averaged together for each adolescent.

3.3.4 Statistics

Descriptive participant and sleep characteristics all passed Shapiro-Wilk’s test of normality and so differences between weekdays and freedays were analysed using paired samples t-tests.

Mediation: Although PROCESS is widely used in mediation analysis, it was not used in this instance due to the within subjects nature of some study measures. Although the within subjects variables could have been averaged over all days this would have lost the richness and detail of the dataset. As such, mixed-model analysis was used in a three-step procedure to test for mediation. In the first two steps, mixed-model analyses were used to test for the direct effects of: 1) physical activity on sleep, and 2) sleep on mood. In the third step, Sobel’s test was used to test for indirect effects and proof of mediation.

For the analysis of the physical activity → sleep → mood mediation models, there were two measures of physical activity (MVPA and evening MVPA) which were associated with two measures of sleep (TST and sleep midpoint), respectively. Moreover, there were two measures of mood (positive affect and negative affect). Initially analyses were carried out with the daily measures from the weeklong data set aggregated across the week, however subsequent analyses were carried out to see if the relationships varied by day of the week.

3.4 Results

Participants characteristics can be seen in Table 3.1. Participants average age was 19 years and the majority had a BMI in the normal range. The average MVPA level was 22 minutes a day. Participants reported on a scale from 1-7 (1 = *not at all important*, 7 = *extremely important*) that exercising to improve mood was on average more than moderately important (M = 5.5, SD = 1.3).

Sleep characteristics of the sample can be seen in Table 3.2. Using paired samples *t*-tests objective and subjective measures showed a significant difference in sleep timing between weekdays and freedays. With sleep onset, wake time, and midpoint all being approximately 1 hour later on free days than weekdays, both objectively and subjectively. Objective measures showed a freeday sleep onset of 1:38 a.m., wake up of 9:28 a.m., and midpoint of 5:33 a.m. Adolescents had an average objective total sleep time of 6.86 hours on freedays.

Table 3.1

Participant Characteristics

Variable	Sample	N and % of sample	Range	Mean and Standard Deviation
Age	19		17-20 years	M = 19.0, SD = 1.0
BMI	17		16.7-30.8	M = 23.2, SD = 3.3
Underweight		1 (5.3%)		
Normal		12 (63.2%)		
Overweight		3 (15.8%)		
Obese		1 (5.3%)		
(Unknown)		2 (10.5%)		
Ethnicity				
Caucasian		10 (52.6%)		
Asian		6 (31.6%)		
Indian		2 (10.5%)		
Pacific Islander		1 (5.3%)		
Highest qualification				
High school		15 (78.9%)		
Undergrad degree		4 (21.1%)		
Objective daily MVPA (10 min bout) averaged over week (in minutes)	19		0.0 - 82.7	M = 21.8, SD = 24.8
How important is this reason for exercising? [a]				
To improve mood	18		3-7	M = 5.5, SD = 1.3
To cope with sadness, depression	18		1-7	M = 3.8, SD = 1.8
To cope with stress, anxiety	18		1-7	M = 4.7, SD = 1.9
DASS21 scores				
Depression	19		0-14	M = 6.1, SD = 4.5
Anxiety	19		0-17	M = 5.2, SD = 5.5
Stress	19		0-18	M = 7.2, SD = 5.4

Note. DASS21 = Depression Anxiety and Stress Scale (Lovibond & Lovibond, 1995). Higher scores indicate greater levels of depression, anxiety, and stress.

[a] Reasons for Exercise Inventory (Silberstein et al., 1988). Rating scale: 1 = not at all important, 4 = moderately important, 7 = extremely important.

Table 3.2

Sleep Descriptives and Paired Sample t-tests

Sleep Variable	Weekdays		Freedays				
	M	*SD*	*M*	*SD*	*t*	*p*	Cohen's *d*
Objective							
Midpoint	**4.56 (4:34 a.m.)**	**0.99**	**5.55 (5:33 a.m.)**	**1.44**	**4.736**	**<.001**	**1.09**
TST	6.93 hours	0.71	6.86 hours	1.11	-.273	.788	-.063
Bedtime/SOT	**24.58 (12:35 a.m.)**	**1.15**	**25.63 (1:38 a.m.)**	**1.61**	**-4.405**	**<.001**	**-1.01**
Wake time	**8.54 (8:32 a.m.)**	**0.98**	**9.46 (9:28 a.m.)**	**1.49**	**-3.506**	**.003**	**-0.80**
Subjective							
Midpoint	**4.32 (4:19 a.m.)**	**1.01**	**5.43 (5:26 a.m.)**	**1.37**	**-5.260**	**<.001**	**-1.21**
TST	8.03 hours	0.83	7.97 hours	0.99	.293	.773	0.07
Bedtime/SOT	**0.30 (12:18 a.m.)**	**1.19**	**1.45 (1:27 a.m.)**	**1.40**	**-5.350**	**<.001**	**-1.23**
Wake time	**8.33 (8:20 a.m.)**	**0.99**	**9.42 (9:25 a.m.)**	**1.53**	**-4.253**	**<.001**	**-0.98**

Note. N = 19. TST = Total sleep time; SOT = sleep onset time.
Bold = Significant (*p* <.001)

3.4.1 Total Sleep Time and Physical Activity During the Day

3.4.1.1 Aggregated Data

The hypothesis that total sleep time (TST) mediates the relationship between moderate or vigorous physical activity (MVPA) during the day, and mood, was first tested with aggregated data for two basic mediation models

- More MVPA → longer TST → more positive affect, and
- More MVPA → longer TST → less negative affect.

The mixed-model analysis found one significant direct effect for MVPA and positive affect, all other direct effects were non-significant (see Table 3.3). As there was only one significant direct effect, it is unsurprising that Sobel's test did not find evidence of mediation between physical activity, sleep, and positive affect, Z = 0.78, *p* = 0.43. Nevertheless, the relationship between physical activity and positive affect was such that, for each 33 minutes of MVPA during the day, the adolescents had a 1-point increase in their positive affect score.

Table 3.3

Model Coefficients (Direct Effects) for the Mixed-Model Analysis of the Effect of Physical Activity During the Day on Affect through Total Sleep Time - Aggregated Data

	b	SE_b	*F*	*df*	95% CI
Positive affect					
MVPA → TST	-0.002	0.002	1.42	451	[-0.005, 0.001]
TST → Positive affect	-0.299	0.236	1.60	450	[-0.76, 0.17]
MVPA → Positive affect	**0.029**	**0.008**	**14.20**	**450**	**[0.01, 0.04]**
Negative affect					
MVPA → TST	-0.002	0.002	1.42	451	[-0.005, 0.001]
TST → Negative affect	-0.036	0.139	0.068	450	[-0.31, 0.24]
MVPA → Negative affect	0.005	0.005	1.372	450	[-0.004, 0.014]

Note. b's are unstandardised regression coefficients. TST = Total sleep time; measured in hours. MVPA = Moderate or vigorous physical activity during the day; measured in minutes. Positive and negative affect measured by the Positive and Negative Affect Scale; each subscale score range is 10-50.
Bold = Significant (*p* < .001).

3.4.1.2 Individual Days

A mixed-model analysis was used to test if there was a difference in the “effect” of MVPA on TST depending upon the day of the week (see Table 3.4). A significant interaction was found between MVPA and day of the week, $F(6, 439) = 5.41$, $p < .001$. MVPA had a significant relationship with TST on Wednesday, Friday, and Sunday, such that on each of the three days more MVPA was associated with less TST.

Additional mixed-model analyses were used to see if the “effect” of TST on positive affect and negative affect varied by day (see Table 3.4). These showed significant interactions between TST and day of the week for positive affect, $F(6, 432) = 5.88$, $p < .001$, and negative affect, $F(6, 432) = 9.16$, $p < .001$. Significant relationships were found between TST and negative affect on Tuesday, Wednesday, Friday, and Sunday, and between TST and positive affect on Sunday.

There was sufficient evidence to test the data from Wednesday and Friday for mediation of the relationship between MVPA and negative affect by TST. On Sunday there was sufficient evidence to test for TST’s role as a mediator between both, MVPA and positive affect, and MVPA and negative affect.

Wednesday: Sobel’s test found that TST mediated the relationship between MVPA and negative affect, Z = 2.51, $p = 0.01$. One more minute of moderate or vigorous physical activity during the day on Wednesday was associated with 1 minute less TST, and a lost hour of TST was associated with a 1.7-point increase in negative affect score the following day.

Friday: Sobel’s test found that TST mediated the relationship between MVPA and negative affect, Z = -2.77, $p > 0.01$. One more minute of moderate or vigorous physical activity during Friday was associated with 1 minute less TST, and 1 less hour of TST was associated with a 1.4-point decrease in negative affect score the following day.

Sunday: Sobel’s test found that TST mediated the relationship between MVPA and positive affect, Z = 1.92, $p = 0.05$, but did not mediate the relationship between MVPA and negative affect, Z = 1.45, $p = 0.15$. More MVPA was associated with less TST, but 2.8 minutes of moderate or vigorous physical activity during the day on Sunday were required for 1 minute less TST, and a 1 hour less TST was associated with a 7.6-point increase in positive affect score on Monday. Although this large increase in positive affect following shorter TST seems unusual, no outliers were detected from inspection of histograms.

Table 3.4

Model Coefficients (Direct Effects) for the Mixed-Model Analysis of the Effect of Physical Activity on Positive and Negative Affect through Total Sleep Time - Individual Days

	b	SE_b	*F*	*df*	95% CI
Monday					
MVPA → TST	0.003	0.003	1.42	36	[-0.002, 0.009]
TST → Positive affect	-0.032	0.884	.001	35	[-1.83, 1.76]
TST → Negative affect	0.720	0.660	1.192	35	[-0.62, 2.06]
Tuesday					
MVPA → TST	-0.013	0.009	1.76	33	[-0.03, 0.01]
TST → Positive affect	-0.477	1.435	.110	32	[-3.40, 2.45]
TST → Negative affect	**-2.390**	**0.709**	**11.38**	**32**	**[-3.83, -0.95]**
Wednesday					
MVPA → TST	**-0.017**	**0.005**	**11.57**	**72**	**[-0.03, -0.01]**
TST → Positive affect	-0.875	0.586	2.234	71	[-2.04, 0.29]
TST → Negative affect	**-1.655**	**0.446**	**13.751**	**71**	**[-2.55, -0.77]**
Thursday					
MVPA → TST	0.004	0.002	2.55	90	[-0.001, 0.008]
TST → Positive affect	0.813	0.611	1.77	89	[-0.40, 2.03]
TST → Negative affect	0.547	0.276	3.92	89	[-0.002, 1.095]
Friday					
MVPA → TST	**-0.012**	**0.003**	**13.94**	**89**	**[-0.02, -0.01]**
TST → Positive affect	-0.671	0.657	1.04	88	[-1.98, 0.64]
TST → Negative affect	**1.430**	**0.372**	**14.77**	**88**	**[0.69, 2.17]**
Saturday					
MVPA → TST	0.011	0.008	2.15	66	[-0.004, 0.027]
TST → Positive affect	-0.403	0.403	1.00	65	[-1.21, 0.40]
TST → Negative affect	0.262	0.207	1.60	65	[-0.15, 0.68]
Sunday					
MVPA → TST	**-0.006**	**0.003**	**4.45**	**53**	**[-0.0122, -0.0003]**
TST → Positive affect	**-7.573**	**1.099**	**47.44**	**52**	**[-9.78, -5.37]**
TST → Negative affect	**-1.457**	**0.697**	**4.37**	**52**	**[-2.86, -0.06]**

Note. b's are unstandardised regression coefficients. TST = Total sleep time; measured in hours. MVPA = Moderate or vigorous physical activity during the day; measured in minutes. Positive and negative affect measured by the Positive and Negative Affect Scale; each subscale score range is 10-50.

Bold = Significant (*p* <.05).

3.4.1.3 Time of Day

Mixed-model analysis was used to test if the “time of day” of affect measurement (morning, afternoon, evening) would influence the potential for a mediating relationship between MVPA during the day and positive or negative affect by TST. No evidence was found for a significant interaction between time of day and positive affect, *F*(2, 444) = 1.09, *p* = .34, or negative affect, *F*(2, 450) = 0.07, *p* = .80.

3.4.2 Chronotype and Evening Physical Activity - 3 Hours Before Sleep

3.4.2.1 Aggregated Data

The hypothesis that chronotype mediates the relationship between evening MVPA and mood was also tested with aggregated data from Friday and Saturday night (as these are the nights before ‘freedays’ which allow determination of the circadian rhythm, see 3.3.3.3 Sleep). The two basic mediation models for testing were thus;

- More evening MVPA → later sleep midpoint → less positive affect, and
- More evening MVPA → later sleep midpoint → more negative affect.

The mixed-model analysis found significant direct effects for all relationships in both basic mediation models (see Table 3.5). More MVPA in the 3 hours prior to sleep was associated with an *earlier* sleep midpoint, which was unexpected. For 1 extra minute of evening MVPA, sleep midpoint was 2 minutes earlier. A 1 hour earlier sleep midpoint was associated with a 0.9-point increase in positive affect score (which is in the expected direction), and a 0.4-point increase in negative affect score (which is not in the expected direction).

Each mediation was tested with Sobel’s test. Sleep midpoint significantly mediated the relationship between evening MVPA 3 hours before sleep onset and positive affect, Z = 1.95, *p* = 0.05, but did not mediate the relationship between evening MVPA and negative affect, Z = -1.75, *p* = 0.08.

Table 3.5

Model Coefficients (Direct Effects) for the Mixed-Model Analysis of the Effect of Evening Physical Activity (Measured as 3 Hours Before Sleep) on Affect through Sleep Midpoint - Aggregated Data

	b	SE_b	*F*	*df*	95% CI
Positive affect					
Evening MVPA → Sleep midpoint	**-0.027**	**0.009**	**8.52**	**157**	**[-0.05, -0.01]**
Midpoint → Positive affect	**-0.887**	**0.347**	**6.55**	**156**	**[-1.57, -0.20]**
Evening MVPA → Positive affect	**-0.089**	**0.042**	**4.49**	**156**	**[-0.17, -0.01]**
Negative affect					
Evening MVPA → Sleep midpoint	**-0.027**	**0.009**	**8.52**	**157**	**[-0.05, -0.01]**
Midpoint → Negative affect	**0.424**	**0.197**	**4.61**	**156**	**[0.03, 0.81]**
Evening MVPA → Negative affect	**0.097**	**0.024**	**16.41**	**156**	**[0.05, 0.14]**

Note. b’s are unstandardised regression coefficients. Sleep midpoint measured in decimal hours. Positive and negative affect measured by the Positive and Negative Affect Scale; each subscale score range is 10-50. Evening MVPA = Evening moderate or vigorous physical activity; measured in minutes.
Bold = Significant (*p* = .05).

3.4.2.2 Time of Day

Mixed-model analysis found that the time of day of affect measurement (morning, afternoon, evening) did not significantly impact the relationship between evening physical activity, sleep midpoint, and positive/negative affect. When controlling for the effect of MVPA in the 3 hours before sleep, the effect of sleep midpoint on positive affect was nonsignificant, $F(2, 150) = 2.45$, $p = .09$, and the effect of sleep midpoint on negative affect was also nonsignificant, $F(2, 150) = 0.08$, $p = .93$.

3.4.3 Chronotype and Evening Physical Activity - After 6 p.m.

3.4.3.1 Aggregated Data

For the sake of comparison to a previous study, evening moderate or vigorous physical activity (MVPA) was also calculated as activity occurring between 6 p.m. and sleep onset. Only one direct effect was significant; later sleep midpoint was associated with a lower positive affect score. For each hour that sleep midpoint was later, positive affect score was lower by 0.7 points. See Table 3.6.

Table 3.6

Model Coefficients (Direct Effects) for the Mixed-Model Analysis of the Effect of Evening Physical Activity (Measured as 6 p.m. Onwards) on Affect through Sleep Midpoint - Aggregated Data

	b	SE_b	*F*	*df*	95% CI
Positive affect					
Evening MVPA → Sleep midpoint	0.010	0.006	2.27	157	[-0.003, 0.022]
Midpoint → Positive affect	**-0.737**	**0.345**	**4.58**	**156**	**[-1.42, -0.06]**
Evening MVPA → Positive affect	0.011	0.028	0.16	156	[-0.04, 0.07]
Negative affect					
Evening MVPA → Sleep midpoint	0.010	0.006	2.27	157	[-0.003, 0.022]
Midpoint → Negative affect	0.196	0.201	0.95	156	[-0.20, 0.59]
Evening MVPA → Negative affect	0.031	0.016	3.72	156	[-0.001, 0.063]

Note. b's are unstandardised regression coefficients. Sleep midpoint measured in decimal hours. Positive and negative affect measured by the Positive and Negative Affect Scale; each subscale score range is 10-50. Evening MVPA = Evening moderate or vigorous physical activity; measured in minutes.
Bold = Significant (*p* = .03).

3.4.3.2 Time of Day

As with the previous measure of evening physical activity, mixed-model analysis once again found that the time of day of affect measurement (morning, afternoon, evening) did not significantly impact the relationship between evening physical activity, sleep midpoint, and positive/negative affect. When controlling for the effect of MVPA after 6 p.m., the effect of sleep midpoint on positive affect was nonsignificant, *F*(2, 150) = 2.35, *p* = .10, and the effect of sleep midpoint on negative affect was also nonsignificant, *F*(2, 150) = 0.54, *p* = .58.

3.5 Discussion

Ecological momentary assessment was used to assess the temporal relationships of physical activity, sleep, and mood, and the role of sleep as a mediator, in 19 adolescent girls over the course of one week. Strong evidence was found for a beneficial impact of evening physical activity on sleep and mood. Greater levels of physical activity in the 3 hours before sleep was associated with earlier chronotype and better mood. Evidence was also found for TST as a mediator between physical activity during the day and mood. In contrast to much research in this space physical activity was consistently associated with less TST, and the impact of both on mood varied. Elaboration of the study's findings and consideration of the mechanisms involved are discussed below.

3.5.1 Sleep Descriptives

The sleep data of this adolescent sample partially confirms the pattern of results typically seen in adolescent research. Subjective sleep duration was ~8 hours, which is comparative to other adolescent studies (Galland et al., 2018), indicating that adolescents do not meet their sleep need of 9 hours or more (Crowley et al., 2018; Short et al., 2018). Objective measures were more conservative, at ~7 hours total sleep time. It is possible that this low measure of total sleep time is due to the use of accelerometry where sleep movements may have been scored as wake (Meltzer et al., 2018; Short et al., 2012).

Interestingly, there was no difference in sleep duration between weekdays or freedays. Neither subjective nor objective sleep duration changed significantly between the different types of days. This was unexpected as research shows a pattern where adolescents often obtain more sleep on freedays than weekdays, regardless of whether they are university age adolescents (Forquer et al., 2008; Liu et al., 2018; Sivertsen et al., 2019) or school age adolescents (Gariepy et al., 2020). The adolescents' sleep timing however, matched the expected pattern of results; sleep onset, wake up time and sleep midpoint all occurred ~1 hour later on freedays than weekdays (Liu et al., 2018; Lund et al., 2010; Sivertsen et al., 2019).

3.5.2 Total Sleep Time

It was hypothesised that the relationship between physical activity and mood would be mediated by total sleep time (TST). Analysis of the aggregated data did not find sufficient evidence for a mediation, however as anticipated, more moderate to vigorous physical activity (MVPA) during the day was associated with more positive affect the next day. No other significant direct effects were found in the analysis of the aggregated data. The finding that more objectively measured MVPA during the day was subsequently followed by more positive affect matches the research findings of studies in adults and young adults (Giurgiu et al., 2019; Schultchen et al., 2019). In adolescent cohorts, similar findings have noted that more MVPA predicted lower negative affect (Langguth et al., 2016).

In order to explore the hypothesis temporally, each day was also analysed individually. On three days, Wednesday, Friday, and Sunday, TST significantly mediated the relationship between physical activity and affect. Yet, on each of these three days more MVPA during the day was associated with less TST that night, an unexpected finding which will be discussed presently. However, this was not the only unexpected finding, as on Friday and Sunday, not only was more MVPA was associated with less TST, but less TST was associated with *less* negative affect and more *positive* affect, respectively. This relationship between less sleep and "better" mood will be discussed following the consideration of the association between physical activity and sleep duration.

3.5.2.1 Physical Activity and Sleep Duration

Although it was not predicted that on days in which sleep mediated the relationship between MVPA and mood, that more MVPA during the day would be related to less TST the following night, a connection between more physical activity and shorter TST has been noted in two recent meta-analyses, one in adults (Atoui et al., 2021), and one in university students (Memon et al., 2021). Notably, Atoui's meta-analysis found that more physical activity during the day was associated with shorter TST that night. One theory that has been put forward for the relationship between more physical activity during the day and lower sleep duration is that the time taken to participate in physical activity may be displacing the time used for sleep (Antczak et al., 2020; Matricciani et al., 2018; Memon et al., 2021). That is, there is only so much time in a 24-hour day that can be used for different activities, thus it is possible that on days when a person participates in more physical activity, they have less time available to sleep that night.

Another possible explanation for the connection between more MVPA and shorter TST found in this study is that it may represent a connection between more MVPA and more time awake during the night (where a decrease in total sleep time is occurring due to an increase in wake after sleep onset [WASO]). Evidence for a linear relationship between physical activity and WASO has been identified previously. In a review, Youngstedt (2005) noted that although light physical activity was associated with a reduction in WASO, higher levels of physical activity were associated with an increase in WASO. This suggests that the amount of physical activity is important to the direction of the relationship, as although lighter or less physical activity might be beneficial to sleep, higher levels of physical activity may reverse this relationship. Evidence to support the differing impact of physical activity amount on TST and WASO can be seen in a study of 54 young adults (Mead et al., 2019). Mead and colleagues found that young adults had less TST, due to an increase in WASO, on nights after they had spent more time being active during the day than their normal daily average.

It is possible that this study's finding that more MVPA is associated with less TST is a mismeasuring of more MVPA being associaed with more *movement* during sleep, where this movement during sleep has been misattributed as WASO by the accelerometry used. Indeed, in 2017, Vitale and colleagues looked at 23 young adult athletes and found that the first night after an evening session of moderate and vigorous intensity physical activity participants with a morning chronotype spent a greater percentage of time moving during the night as measured by actigraphy. Another study into 46 athletes and 20 controls found that, compared to controls, athletes had more moving time during sleep, and a longer WASO, 1 hr 15 mins vs 50 mins, also measured using actigraphy (Leeder et al., 2012). The results of both these studies show that more activity during the day is associated with more movement at night, and as such it is possible that the accelerometry in the current study has categorised increased movement after physical activity as increased WASO, and therefore less TST.

More research is needed into the relationship between physical activity and sleep duration using traditional polysomnography or other sleep measurement devices to determine if more activity during the day is related to increased WASO or movement during sleep. Distinct to polysomnography, a number of devices have been independently validated as more accurate than actigraphy at identifying sleep versus wake (Chinoy et al., 2020). These sleep measurement devices could offer an opportunity to further explore the 'physical activity – TST' connection whilst being less expensive and logistically challenging than polysomnography (Hirshkowitz, 2016), particularly in similarly designed repeated measures studies. Further examination is certainly needed in order to determine if greater levels of physical activity during the day produce greater WASO during the night resulting in less TST, or more movement during sleep, as these two outcomes would be expected to have very different consequences for physical activity recommendations.

It is interesting that the relationship found between more MVPA during the day and less TST the following night was consistent and cyclical. The relationship reached significance every 2-3 days (Wednesday, Friday, and Sunday). It is difficult to say why this cycle occurred as it was not anticipated. Further verification and investigation of this cyclical pattern will need to be conducted by future EMA studies.

3.5.2.2 Sleep Duration and Mood

On both the days in which sleep mediated the relationship between MVPA and affect, and days on which it did not, the relationship between TST and negative affect fluctuated. The relationship between TST and negative affect was statistically significant on 4 days of the week. On Friday less TST was significantly associated with less negative affect, yet on the three other days with significant results, Tuesday, Wednesday, and Sunday, less TST was significantly related to an *increase* in negative affect the next day. Statistically there was greater evidence in this dataset for an association between less TST and *more* negative affect the next day, yet it is interesting that the relationship between TST and negative affect differed. Although shorter TST was significantly associated with increased negative affect on three days (Tuesday, Wednesday, Sunday), there was also a trend for shorter TST to be associated with decreased negative affect on three days (Monday, Thursday, Saturday), and significantly associated with decreased negative affect on Friday. Clearly trends do not represent evidence, however it is curious that the relationship would vary such that shorter sleep duration would be associated with worse mood on some days and better mood on other days.

The finding of greater evidence for significant associations between less TST and *more* negative affect the next day, matches the results of some studies. In a sample of 419 adolescents Fuligni and colleagues (2019) found less self-reported sleep the night before was associated with a higher level of psychological distress (anxiety and depression symptoms) the next day. Similarly, Kouros et al. (2022) found that less than usual self-reported sleep duration was related to more negative mood the next day in 311 adolescents. The current study's results also match Konjarski et al.'s review finding (2018) that across different age groups worse sleep quality is associated with more negative affect the next day. Furthermore, the inconsistent nature of the current results, in that the relationship between TST and negative affect was significant on some days of the week and not on others, also matches recent patterns of research. Konjarski et al.'s review (2018) found that 5 of 10 studies found a significant temporal relationship between shorter subjective TST and increased negative affect the next day. This suggests that while TST is indeed related to negative affect, that there are other factors involved in the relationship.

It is possible that one of the aspects missing from research into sleep duration and mood are the contributing factors to the sleep duration from the night before, and these factors may moderate the impact of reduced sleep duration on negative affect. For example, in the current study a shorter TST on Tuesday night and Wednesday night lead to feeling worse on Wednesday and Thursday, whereas a shorter sleep time on Friday night, led to *reduced* negative affect on Saturday. The fact that shorter sleep during the week was linked with worse on mood, yet a shorter sleep on Friday night at the beginning of the weekend was associated with better mood could indicate reduced sleep the night before and mood improvement the next day due to enjoyable activities of the night before.

There was also one day of the week in which the relationship between TST and positive affect reached statistical significance. On Sunday, less TST was found to be associated with more positive affect. Although this was unexpected, no outliers were detected during screening. Indeed, 5 of the 6 nonsignificant trends for the rest of the week between TST and positive affect also linked shorter sleep time with more positive affect.

It was hypothesised that less TST would be associated with less positive affect, indeed Konjarski et al.'s review (2018) and Short et al.'s meta-analysis (2020) indicate that overall less TST is associated with less positive affect. However, to date, only 4 studies have used adolescents to test the immediate effect of sleep duration on next day mood in a naturalistic setting (without experimentally manipulating sleep duration to induce a large sleep restriction), and the outcomes of these studies are mixed. Two studies found no significant relationship between TST and positive affect (Doane & Thurston, 2014; Randler & Weber, 2015), and two studies found significant relationships, each in a different direction (Chue et al., 2018; Takano et al., 2014). One found that *longer* TST was linked to more positive affect in the morning (Chue et al., 2018), and the other found that *shorter* TST was related to more positive affect (Takano et al., 2014). The lack of prior research in this area, and the unexpected nature of the finding, makes it difficult to interpret this result. Clearly more research is needed to investigate the elements involved. Nevertheless, both the current study and that of Takano et al. indicate that a shorter sleep duration can lead to more positive affect in adolescents.

3.5.3 Chronotype

It was hypothesised that the relationship between evening physical activity and affect would be mediated by chronotype, such that more moderate to vigorous physical activity (MVPA) in the 3 hours before sleep would result in a later midpoint of sleep which would result in worse affect (positive and negative) the next day. As predicted, MVPA in the 3 hours prior to sleep, sleep midpoint, and positive/negative affect were all significantly related, and sleep midpoint was found to mediate the relationship between MVPA and positive affect. Unexpectedly, it was found that MVPA in the 3 hours before sleep was associated with an earlier sleep midpoint, indicating that physical activity shortly prior to sleep is beneficial - not detrimental to sleep as anticipated. Thus, the direct effects were such that more MVPA was associated with earlier midpoint, which was associated with less negative affect and more positive affect.

These results indicate that in addition to the absence of a detrimental impact of physical activity on sleep timing (by pushing it later as predicted), physical activity is in fact beneficial for sleep and mood even if conducted in the 3 hours before sleep. This result matches the findings of **Chapter 2** where more evening physical activity was also found to be associated with earlier sleep timing, and both were associated with better mood. It also matches findings that evening physical activity was not detrimental to sleep parameters in adults (Myllymäki et al., 2011), young adults (Miller et al., 2020), and children (Dworak et al., 2008). Miller (2020) and Myllymaki (2011) both found that 30 minutes of physical activity concluding 1.5-3 hours before bed did not disturb sleep (sleep onset latency [SOL], TST, and WASO). Similarly, Dworak and colleagues (2008) found that 30 minutes of cycling concluding 3-4 hours prior to bedtime had no effect on TST, and in fact had reduced SOL compared to a control condition. Research into the impact of evening physical activity on sleep parameters shows mixed results (Alley et al., 2015; Buman & King, 2010; Chennaoui et al., 2015). Indeed, two reviews have noted opposing impacts of evening physical activity. One review (Chennaoui et al., 2015) indicated that physical activity in the 4 hours before sleep increases SOL and WASO, whereas the other (Kredlow et al., 2015) found that physical activity in the 3 hours before sleep reduced WASO and did not impact other parameters. The continued mixed findings in this area indicate other variables are involved.

Some studies indicate that chronotype may have a role in the relationship between evening physical activity and sleep. Both Thomas et al. (2020) and Vitale et al. (2017) have noted that those with an early chronotype are impacted differently by evening physical activity than those with a late chronotype. In a sample of 52 adults, Thomas et al. (2020) found that participants with a late chronotype experienced a phase advance (46 minutes) after evening physical activity, whereas those with an early chronotype experienced a phase delay (41 minutes) after evening physical activity. Similarly, Vitale and colleagues (2017) noted that in a sample of 23 young adults those with a late chronotype were not negatively impacted by evening physical activity. In comparison, participants with an early chronotype had lower sleep efficiency due to less TST and more WASO after evening physical activity. This is an area which requires more research, however if late chronotypes benefit from late physical activity and early chronotypes do not, this would explain the mixed results of prior research and why the current sample found late physical activity beneficial, as they have late chronotypes (average freeday sleep midpoint ~ 4:30 a.m., Roenneberg et al., 2004).

A strength of this study is the use of two definitions of late physical activity in order to make the study results more easily comparable. Late physical activity was defined as 3 hours before sleep in order to allow an individualised measure of physical activity prior to sleep for each participant. Late physical activity was also defined as activity occurring from 6 p.m. onwards in order to allow the study results to be more comparable to studies which have used a time of day cut off for physical activity, such as that used in **Chapter 2**. The analysis for the mediation of evening physical activity and mood by sleep midpoint, where evening physical activity was defined as occurring after 6 p.m., only showed a significant direct effect for later sleep midpoint being associated with lower positive affect. Although there was no association between evening physical activity after 6 p.m. with sleep, the finding that earlier or later sleep midpoint is associated with better and worse mood, respectively, is the same in both analyses of the different definitions of late physical activity. In MVPA 3 hours before sleep, *earlier* midpoint was associated with *less* negative affect and *more* positive affect. In MVPA 6 p.m. onwards, *later* sleep midpoint was associated with *less* positive affect. These results all indicate that earlier sleep midpoint improves mood, and later midpoint worsens mood. These results match previous research that earlier and later chronotype in adolescents are associated with better and worse mood, respectively (Gariépy et al., 2019; Haraden et al., 2019; Simon et al., 2020).

It is of note that the measure of physical activity from 6 p.m. onwards also includes the physical activity data measured in the 3 hours prior to sleep, as the earliest time an adolescent fell asleep was 9 p.m. and average SOT was after midnight on weekdays. It is therefore interesting that although there was a direct relationship between MVPA 3 hours before sleep and sleep midpoint, MVPA 6 p.m. onwards was not significantly related to sleep midpoint. It is possible that the more individualised measure of MVPA 3 hours before sleep is more closely related to each adolescent's circadian rhythm, as compared to physical activity from 6 p.m. onwards which is directly related to time of day. MVPA 3 hours prior to sleep provides data specific to the impact of physical activity on an adolescent's circadian rhythm regardless of their circadian rhythm's current timing (i.e. delayed or advanced) in relation to time of day. This is particularly pertinent in an adolescent sample which has a later sleep timing than that of adults (Roenneberg et al., 2004).

3.5.3.1 Time of Day

When time of day of the mood measure (morning, afternoon, evening) was taken into account, later sleep midpoint was associated with lower positive affect in the morning. This finding is similar to that of Takano et al. (2014), who found that worse sleep quality was associated with reduced positive affect the next morning. There are many pathways through which sleep and mood may be related in this way, one of which is repetitive negative thinking and rumination. Previous research in adolescents has found that poor sleep is associated with higher levels of repetitive negative thinking (Danielsson et al., 2013; Stewart et al., 2020), and that repetitive negative thinking is associated with lower mood (Krause et al., 2017). It is interesting that this study's finding that later chronotype (sleep midpoint) is associated with lower positive mood the next morning is similar to the results of Takano et al., as these researchers not only found that worse sleep quality was associated with reduced positive affect the next morning, but that this in turn was associated with increased repetitive thought in the evening. Further to this, repetitive negative thinking is associated with poorer sleep in young adults, typified by later sleep timing, shorter sleep duration, and longer sleep latency (Nota & Coles, 2015; Takano et al., 2014). This study's results demonstrate a possible element of the sleep-mood relationship, where poorer sleep, possibly due to repetitive negative thinking in the evening results in lower mood the next day, which results in more negative thinking and rumination again. This also shows how improvements to sleep by physical activity can also impact mood through sleep as a mediator.

3.6 Conclusion

Evidence was found for a temporal mediation of the 'physical activity – mood' relationship via sleep, through the mechanisms of total sleep time and chronotype (measured by sleep midpoint on freedays). Interestingly, more MVPA during the day was detrimental to sleep, resulting in shorter TST that night. Due to the presence of this finding in studies using accelerometry, more research is needed using polysomnography to determine if the relationship between greater physical activity and shorter TST is due to measurement error by accelerometry calculating increased movement during the night as WASO. This study also found that MVPA in the 3 hours prior to sleep was beneficial to sleep, resulting in earlier sleep timing that night. This further demonstrates that despite the persistence of recommendations to avoid physical activity too close to sleep (Breus, 2022), recent evidence indicates that physical activity in the hours before bedtime does not push sleep later and can instead be used to aid sleep.

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Appendix A
GGIR Shell Function Code

```
rm(list=ls())
library(GGIR)
mode= c(1,2,3,4,5)
datadir= "C:/Users/melan/Documents/21Apr/bin"
outputdir= "C:/Users/melan/Documents/21Apr"
#studyname="KR"
f0 = c() #file to start with
f1 = c() #file to end with
g.shell.GGIR(#-------------------------------
        # General parameters
        #-------------------------------
        mode=mode,
        datadir=datadir,
        outputdir=outputdir,
        f0=f0,
        f1=f1,
        overwrite = TRUE,
        do.imp=TRUE,
        idloc=2,
        print.filename=TRUE,
        storefolderstructure = FALSE,
        desiredtz = "Australia/Adelaide",
        #-------------------------------
        # Part 1 parameters:
        #-------------------------------
        windowsizes = c(5,900,3600), #5 s epoch, 15 min non-wear detection resolution, 60 min non-wear evaluation window
        do.cal=TRUE,
        do.enmo = TRUE, #ENMO physical activity metric
        do.anglez=TRUE, # for sleep analysis
        chunksize=1,
        printsummary=TRUE,
        #-------------------------------
        # Part 2 parameters:
```

```
#-------------------------------
strategy = 1,
#ndayswindow=7,
hrs.del.start = 0,
hrs.del.end = 0,
maxdur = 9, #maximum number of days
includedaycrit = 16, # min valid hours per day of measurement
# L5M5window = c(0,6,12,18,24),
M5L5res = 10,
winhr = c(5),
qlevels = c(c(1380/1440),c(1410/1440)), #quantiles to calculate
qwindow=c(0,6,12,18,24), #window for calculation of quantiles
ilevels = c(0,46,93,418), #gives acceleration distribution in 50 mg resolution calculates the
time spent in those intensities of accelerations.
mvpathreshold =c(93), #thresholds for MVPA, total and bouts 5 & 10 min
acceleration>threshold for >80% of time
boutcriter = c(0.8), #at least 80% MVPA in the time period to be classified as a bout
mvpadur = c(1,5,10), #min duration of a bout
bout.metric = 4,
closedbout = FALSE,
#-------------------------------
# Part 3 parameters:
#-------------------------------
timethreshold= c(5),
anglethreshold=5,
ignorenonwear = TRUE,
do.part3.pdf = TRUE,
#-------------------------------
# Part 4 parameters:
#-------------------------------
excludefirstlast = FALSE,
includenightcrit = 16,
def.noc.sleep = c(1),
# loglocation = "C:/Users/melan/Documents/21Apr/SleepLog/GGIRSleepLog.csv",
outliers.only = FALSE,
relyonguider = FALSE,
```

```
        # criterror = 4,
        sleeplogidnum = FALSE,
        colid=1,
        coln1=3,
        do.visual = TRUE,
        nnights = 6,
        #====================
        # Part 5
        #====================
        threshold.lig = c(46), threshold.mod = c(93),  threshold.vig = c(418),
        boutcriter = 0.8,      boutcriter.in = 0.9,     boutcriter.lig = 0.8,
        boutcriter.mvpa = 0.8, boutdur.in = c(30), boutdur.lig = c(10),
        boutdur.mvpa = c(10),
        includedaycrit.part5 = 2/3,
        #====================
        # Visual report
        #====================
        #timewindow = c("WW","MM"),
        #dayborder = 18,
        visualreport=TRUE,
        do.report=c(2,4,5),
        dofirstpage = TRUE,
        viewingwindow=1
)
## End(Not run)
```

Appendix B

A Note on the Determination of the Time Cut-Offs Between Morning, Afternoon, and Evening

A search of previous literature did not find a set definition for the cut-off between afternoon and evening in adolescent sleep research. Initially the definitions used in the 2013 National Sleep Foundation (NSF) Poll (Buman et al., 2014) were considered for this study, however they did not appear appropriate for this sample. The NSF Poll defined morning as > 8 hours before bed, afternoon as 4-8 hours before bed, and evening as < 4 hours before bed. As the current sample had an average sleep onset time of 1 a.m. the parameters used in the 2013 NSF Poll would have resulted in morning being defined as prior to 5 p.m., afternoon as 5-9 p.m., and evening as 9 p.m. - 1 a.m. As these cut offs did not seem suitable it was determined that for the current sample morning would be from 6 a.m. until midday, afternoon 12 p.m. until 6 p.m., and evening 6 p.m. and later.

The choice of a 6 a.m. as the beginning of morning segment was due to the earliest participant wake-time (6:04 a.m.) and latest sleep-onset time (5:14 a.m.). This was also an appropriate cut-off for mood as there were no mood data points between 1 a.m. and 7 a.m. The delineation of 6 p.m. – 6 a.m. as evening was due to the adolescents' sleep onset times which ranged from 8:53 p.m. to 5:14 a.m. The selection of these times ensured that physical activity was attributed to the correct day. That is, physical activity taking place in the early morning *prior to falling asleep* was captured as 'evening' activity at the end of the day, while physical activity occurring in the early morning *after waking* was captured at the start of the day. The choice of 6 p.m. as the beginning of the evening segment also made the results of this study more easily comparable to **Study 1**, which also classified physical activity after 6 p.m. as evening physical activity.

CHAPTER 4 -

COME INTO THE LAB: A CONTROLLED EXPERIMENTAL STUDY OF PHYSICAL ACTIVITY, SLEEP, AND MOOD IN ADOLESCENT BOYS

4.1 Abstract

The interrelationships between physical activity, sleep, and mood in adolescents make physical activity interventions a possible option to address sleep and mood problems in this population. The aim of this study was to assess how light-intensity morning physical activity affects sleep and mood in adolescents with a late chronotype in a controlled laboratory setting. This was anticipated to also provide further evidence for sleep's role as a mediator between physical activity and mood. Eighteen adolescent boys (aged 15-18 years) completed a 45-minute intervention over 5 mornings in a sleep laboratory. The boys were randomised to either sedentary sitting, or light-intensity treadmill walking. Physical activity intensity was monitored by heart rate (via chest strap and actigraphy watch [Polar rs100]) and intensity cut-offs were calculated using the Karvonen formula (Karvonen & Vuorimaa, 1988). Circadian rhythm timing was measured through saliva assay to determine dim light melatonin onset. Mood was measured by the Depression Anxiety and Stress Scale 21 (DASS) and the Short Mood and Feelings Questionnaire (SMFQ). Results showed a 47-minute difference in circadian timing between the intervention groups. Boys in the walking group experienced a 28-minute circadian advance over the course of the intervention, while those in the sitting group had a 19-minute circadian delay. No significant results were found between physical activity and mood (SMFQ and depression subscale of DASS) or circadian timing and mood. Although trends indicated that the *sedentary* boys had a greater mood improvement than those in the walking group. This goes against the findings of other studies, that physical activity and earlier sleep timing are both beneficial for mood (Carter et al., 2016; Gariépy et al., 2019). These results provide support for the use of physical activity interventions to treat delayed sleep timing in adolescents. Future research with later follow-ups of mood data could provide insight into when mood improvements occur following a circadian rhythm advance.

4.2 Introduction

A multitude of connections exist between physical activity, sleep, and mood in adolescents. The current available research, as summarised in meta-analyses and reviews, is that participating in more physical activity is associated with better sleep parameters (Atoui et al., 2021; Dolezal et al., 2017; Memon et al., 2021), and that both more physical activity and healthier sleep, are associated with better mood (Carter et al., 2016; Rodriguez-Ayllon et al., 2019; Short et al., 2020; Short & Chee, 2019). Whilst these relationships are certainly bidirectional (Atoui et al., 2021; Lovato & Gradisar, 2014), investigations into the directionality of these relationships have shown that to a large degree changes in physical activity precede the abovementioned sleep benefits (Atoui et al., 2021), and changes in sleep precede changes in mood (Goldstone et al., 2020; Lovato & Gradisar, 2014; Orchard et al., 2020). Thus, it seems likely that sleep mediates the relationship between physical activity and mood.

Both **Chapter 2** and **Chapter 3** of this thesis have found evidence for the mediating role of sleep between physical activity and mood. Using a large cross-sectional sample of 1,367 adolescents, **Chapter 2** found that in the three mediation models tested, the relationships were consistent with sleep mediating the physical activity-mood association. More physical activity, regardless of whether it was performed during the day or during the evening, was associated with better sleep parameters (longer sleep duration, shorter sleep onset latency, and earlier chronotype) which were also associated with better mood. **Chapter 3** found further evidence of sleep’s role as a mediator of the physical activity-mood relationship through ecological momentary assessment monitoring of 19 adolescent girls over 1 week. Again, the sleep parameters measured (total sleep time and chronotype) were found to mediate the relationship between physical activity (during the day and evening) and mood (positive and negative affect). Owing to the temporal nature of the study design, a number of variations were found for the mediation of physical activity and mood by total sleep time. Such as the days of the week on which the mediation occurred, and whether positive or negative affect were mediated. However, **Chapter 3** noted the same unexpected finding for evening physical activity as **Chapter 2**. Once again, more evening physical activity was associated with better sleep (earlier sleep midpoint) which was associated with better mood (more positive affect). Despite the expectation that evening physical activity would be detrimental to sleep (Chennaoui et al., 2015), in both **Chapter 2** and **Chapter 3** it was found that evening physical activity was actually beneficial to sleep and mood.

Reviews of research with adults show mixed results when testing the impact of evening physical activity on sleep (Buman & King, 2010; Chennaoui et al., 2015). Results range widely from evening physical activity having a beneficial impact, as discussed above (increased sleep efficiency, reduced sleep onset latency [SOL] (Dworak et al., 2008); reduced wake after sleep onset [WASO]

(Alley et al., 2015)), to evening physical activity having no impact (Miller et al., 2020; Myllymäki et al., 2011), or having a detrimental impact (longer SOL (Alley et al., 2015); a later bedtime (Glavin et al., 2020); or a circadian phase delay (Youngstedt et al., 2019)). Recent results suggest that an explanation for the differing impact of evening physical activity on sleep may come from the role of chronotype. In response to evening physical activity, early chronotypes have been seen to experience stronger negative sleep consequences (less total sleep time [TST], more WASO (Vitale et al., 2017) and a bigger circadian rhythm delay (Glavin et al., 2020)) than late chronotypes.

Comparatively, morning physical activity elicits a similar sleep response irrespective of chronotype (Glavin et al., 2020; Thomas et al., 2020; Vitale et al., 2017). Comparisons between morning and evening physical activity have also shown morning physical activity to have a stronger beneficial impact on sleep (Alley et al., 2015; Wendt et al., 2020). Adult studies show that morning physical activity is associated with circadian phase advances (Thomas et al., 2020) and earlier in-to- and out-of-bedtimes (Quante et al., 2019). Young adult studies show associations with shorter SOL (Alley et al., 2015), and longer TST and higher sleep efficiency (Wendt et al., 2020). Lastly, adolescent research has found morning physical activity to be associated with shorter SOL (Baldursdottir et al., 2017; Kalak et al., 2012), less number of awakenings (Baldursdottir et al., 2017) and better subjective sleep quality (Kalak et al., 2012). Due to the beneficial association of morning physical activity with sleep in adolescents, physical activity scheduled in the morning could further improve confidence in the physical activity-sleep-mood connections, as well as provide an effective intervention for sleep and mood problems in this population.

Relatively few studies have conducted controlled experiments of morning physical activity on sleep. One such laboratory study by Thomas and colleagues (2020) assessed the relationship between chronotype and physical activity in 52 adults who completed five mornings or evenings of physical activity (30mins, 70% VO_2 max[5]). It was found that morning physical activity (timed at dim light melatonin onset [DLMO][6] +10hrs) resulted in comparable responses for late chronotypes (i.e., 32-minute phase advance) and early chronotypes (i.e., 29-minute advance). However the response to *evening* physical activity (DLMO +20hrs) was discrepant between late chronotypes (28-minute advance) and early chronotypes (25-minute *delay*). One of the biggest strengths of this study are the robust measures used for physical activity (VO_2 max) and 'sleep' (DLMO), as they provide a more precise measurement in a controlled environment (i.e., sleep laboratory). Unfortunately, the study did

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[5] VO_2 max is a measure of the maximum amount of oxygen intake per kilogram of bodyweight per minute, and therefore % of VO_2 max can be used as a measure of exercise intensity (She et al., 2015).

[6] Dim light melatonin onset (DLMO) is the clock time at which endogenous melatonin rises above a pre-determined level. DLMO +10hrs refers to the clock time 10 hours after DLMO. Therefore, if DLMO occurs at 10 p.m., DLMO +10hrs is at 8 a.m.

not control for light exposure, which has been shown to confound results on circadian timing (Atkinson et al., 2007).

A similar physical activity intervention was conducted in a cross-over trial by Saidi and colleagues (2020) in a sample of 16 obese adolescent girls. The morning physical activity intervention was a single 40-minute session of cycling at 70% VO_2 max. Saidi et al. found that the single pulse of morning physical activity improved the adolescent girls' subsequent sleep, resulting in longer TST, decreased WASO, and increased sleep efficiency. A strength of this study was the use of objective measures of physical activity (VO_2 max) and sleep (multi-sensor armband), however the study did not measure mood outcomes. In fact, neither Thomas' (2020) or Saidi's study (2020) included mood measures, and considering the close relationship between both physical activity and sleep with mood, it would be beneficial for future research to experiment with how mood is interrelated.

The results of Thomas et al. and Saidi et al.'s experimental studies demonstrate that morning physical activity is beneficial to sleep, and that this relationship is also present in adolescents. The current study intends to build upon these results by incorporating mood into the model of the physical activity-sleep model tested thus far in this thesis. In this case, 'sleep' will be measured as circadian timing (i.e., DLMO) – a measure that is considered more precise than self-reported chronotype (Bauducco et al., 2020). The present study will also control for the impact of light on sleep by conducting the research in a dimly lit laboratory.

Research has shown that adolescents with a late chronotype are more susceptible to sleep and mood problems than those with an early chronotype or neither chronotype (Gariépy et al., 2019; Glavin et al., 2020; Haraden et al., 2017, 2019; Simon et al., 2020). This higher likelihood of sleep and mood problems amongst adolescents with late chronotypes makes them an ideal group for physical activity interventions targeting these areas. However, when developing a physical activity intervention to improve the sleep and mood of adolescents it is important to consider the characteristics of this population. Despite the benefits that physical activity can offer, adolescents with a late chronotype do less physical activity than their peers (Kauderer & Randler, 2013; Merikanto et al., 2020; Schaal et al., 2010; Urbán et al., 2011). Indeed, adolescents with a late chronotype do not identify as many positive effects from physical activity as those with an early chronotype (Schaal et al., 2010), which may indicate that those with a late chronotype find it more difficult to participate. These details must be taken into account to increase the likelihood of a successful and practical intervention. To this end, the present study will not employ an exercise intervention of moderate or high intensity, but will instead assess the utility of a light-intensity walking intervention, which is anticipated to be more amenable to a population which does not typically engage in physical activity.

A previous analysis of the dataset used in this study was recently conducted by Lang and colleagues (2022). This analysis looked at the relationship between physical activity and circadian timing in 18 adolescents with a late chronotype. The adolescents were divided into a physical activity intervention group and a sedentary group. The physical activity group participated in 45 minutes of treadmill walking at a light intensity (30-40% heart rate reserve[7]) over 5 consecutive mornings, meanwhile the sedentary group remained seated while watching TV. The sleep laboratory remained lit at <10 lux to control the impact of light exposure on both groups during their time in the laboratory and during the intervention. It was found that adolescents from the walking group experienced a circadian phase advance of 27.5 minutes, and adolescents in the sedentary group experienced a circadian phase delay of 18.5 minutes. Mood measures showed that mood improved for both groups across the intervention (decreased anxiety and stress on DASS-21) however there was no significant difference in depression score. Although this examination of the data included measures of physical activity, sleep, and mood, the analysis did not consider the physical activity-sleep-mood mediation as the research question was different (i.e., can morning physical activity advance circadian timing). As such, the current study plans to assess the possibility of sleep's role as a mediator in this relationship model.

The connections between physical activity, sleep, and mood in adolescents affords an opportunity to develop interventions that could address both sleep and mood problems in this population. To develop interventions for this unique group, a greater understanding is needed of the connections between these three areas. This study will assess how light-intensity morning physical activity affects sleep and mood in adolescents with a late chronotype.

4.2.1 Hypothesis

It is hypothesised that a change in circadian timing will mediate the relationship between physical activity and mood. That is, after the intervention the walking group will have an earlier timed circadian rhythm (measured by DLMO) and better mood (measured by SMFQ and DASS-21), compared to the sedentary group.

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[7] Heart rate reserve is the difference between an individual's resting heart rate and their maximum heart rate. Heart rate reserve is calculated using the Karvonen formula and can be used to calculate exercise intensity cut-offs (Davis & Convertino, 1975; Ignaszewski et al., 2017). For a description of the Karvonen formula see Section 4.3.3.3.

4.3 Method

4.3.1 Participants

The study protocol was completed by 18 adolescent males (self-reported sex), aged 15-18 years. In order to be eligible adolescents were required to be sedentary (defined as < 60 minutes of physical activity per week (Bennett et al., 2006)) and have a late chronotype (defined by the Munich Chronotype Questionnaire (Roenneberg et al., 2003)).

Exclusion criteria included; travel across time zones within 2 months of data collection, sleep apnoea or other paediatric sleep disorders (measured by Paediatric Sleep Questionnaire (Chervin et al., 2000)), psychological disorders associated with altered circadian rhythm (i.e. bipolar (Gold & Kinrys, 2019), autism (Pinato et al., 2019), and ADHD (Coogan & McGowan, 2017)), a physical condition requiring medical advice before undertaking physical activity (e.g. resting heart rate > 90 beats per minute), or use of psychopharmaceuticals (some antidepressants impact the biotransformation of melatonin (Antonioli et al., 2012; Hartter et al., 2001)). Females were not recruited due to the impact of menstrual phase on circadian rhythm assessment (Shechter et al., 2010).

Participants were recruited via social media advertising. Of the 62 responses received, 28 met the inclusion/exclusion criteria. Consent to participate was obtained from both the adolescent and their parent/guardian, and consent was received from 23 participants. Participants received a reimbursement of AUD$50 for their time. Ethical permission was obtained from Adelaide Clinical Human Research Ethics Committee (SAC HREC Application Number OFR 100.16 – HREC/16/SAC/90).

4.3.2 Design

The study used a between-subjects design to test a 5-day physical activity intervention. Data were collected during the school holiday periods from July 2016 to April 2017. Data collection for each adolescent occurred over two weeks. Following screening, participants completed one baseline week at home (Monday to Sunday) where they adhered to fixed bedtimes and risetimes and were not physically active. This was immediately followed by one intervention week (6 nights/5 days; Sunday to Saturday) at the Flinders University sleep laboratory. Adolescents completed baseline measures on the Sunday night before the intervention began, and post-intervention measures on the Friday night after the intervention was complete. See Figure 4.1 for a representation of the laboratory protocol.

4.3.2.1 Baseline Week

Participants first completed a baseline week at home, during which they adhered to a fixed sleep schedule (constant bedtime and risetime) and did not participate in physical activity (< 60 minutes MVPA during the entire week). Participants completed a sleep diary, physical activity diary, and wore actigraphy watches on their non-dominant wrist (ActiGraph GT3X+; ActiGraph, Pensacola, USA) during the baseline week to ensure they adhered to the protocol.

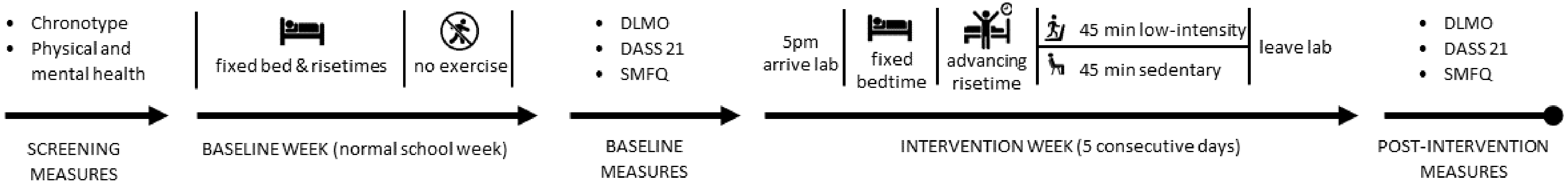
4.3.2.2 Intervention Week

The intervention week involved attending the sleep laboratory for 6 consecutive nights (Sunday-Saturday) and participating in the allocated intervention on 5 consecutive mornings (Monday-Friday). The adolescents arrived at the laboratory at 5 p.m. each day and were permitted to leave in the morning after completing their allocated intervention activity. During the intervention week the adolescents continued to complete a sleep diary and physical activity diary (see Sections 4.3.3.2 and 4.3.3.4). Whilst in the laboratory the adolescents were offered meals and snacks at set times and were not permitted access to mobile phones. Adolescents were only permitted to consume one caffeinated beverage a day, in the morning after the intervention activity.

During the intervention week the adolescents adhered to their fixed bedtime from baseline week and followed increasingly earlier risetimes to begin their allocated intervention. Adolescents were randomised to the physical activity group or sedentary group. Both groups took part in a morning schedule which gradually advanced by 30 minutes each day, over the 5 mornings of the intervention (e.g., wake up Monday 9 a.m., Tuesday 8:30 a.m., Wednesday 8 a.m., etc). Although participants’ rise times advanced earlier by 30 minutes each day, bedtimes did not change. Twenty minutes after waking, the physical activity group performed 45 minutes of light intensity physical activity (walking on a treadmill), and the sedentary group watched TV for 45 minutes while sitting. Both groups performed their intervention in the sleep laboratory. Post-hoc analyses showed that exercise timing occurred on average 12 hours after baseline DLMO.

Figure 4.1

Overview of Study Protocol



Note. DLMO = dim light melatonin onset; DASS 21 = Depression and Anxiety Stress Scale; SMFQ = Short Mood and Feelings Questionnaire.

4.3.3 Measures

4.3.3.1 Chronotype Screening

Chronotype was assessed by the Munich Chronotype Questionnaire (MCTQ) (Roenneberg et al., 2003). The MCTQ measures sleep timing on freedays versus workdays over the previous 4 weeks to determine chronotype.

4.3.3.2 Physical Activity - Diary

A physical activity diary was used during the baseline and intervention weeks to ensure adherence to the study protocol. Adolescents recorded if they participated in any activity during the day for longer than 10 minutes. Each intensity level of physical activity was recorded separately and included walking, e.g. "*how many times have you walked continuously for at least 10 minutes?*", and "*what was the total time that you spent walking in this way?*".

4.3.3.3 Physical Activity - Walking Intervention

The physical activity group participated in a 45-minute light-intensity treadmill walking intervention over 5 consecutive days. The intensity of the walking intervention was determined using the Karvonen formula to calculate the heart rate cut-offs for light intensity physical activity (Karvonen & Vuorimaa, 1988). Each participant's heart rate was measured using a chest strap linked to an actigraphy watch (Polar rs100). The Karvonen formula categorises light-intensity physical activity as activity inducing a heart rate of 30-40% of the heart rate (HR) reserve. Heart rate reserve is calculated by first determining HR maximum (220 – age), then calculating HR reserve (HR maximum – resting HR). The lower and upper limits of this HR reserve are then both calculated to determine heart rate cut-off points in beats per minute. The lower limit of 30% is calculated by ([HR reserve * 0.3] + resting HR), and the upper limit of 40% by ([HR reserve * 0.4] + resting HR).

4.3.3.4 Sleep - Diary

A sleep diary was used during the baseline and intervention weeks. Participants recorded their bedtimes and wake times, sleep onset latency, and number of awakenings. They also rated their sleep quality on an 8-item Likert scale each morning (1 = very bad, 8 = very good).

4.3.3.5 Sleep - Dim Light Melatonin Onset

The adolescents' circadian rhythms were calculated through dim light melatonin onset (DLMO) which was measured via saliva assay. DLMO data were collected and calculated on two occasions, at (1) baseline on the first night of the laboratory week, and (2) post-intervention on the last night of the laboratory week. Saliva samples were collected from 4 hours before bedtime until 2 hours after bedtime and collection took place every 30 minutes during this window. During collection, participants remained seated for at least 5 minutes prior to sample collection to ensure there was minimal artefact on melatonin production from gross movements. The adolescents remained sitting in dim light during saliva collection and lightly chewed the salivette swab for 2 minutes (salivettes used were Sarstedt, Newton, NC, USA). Participants were allowed to consume food and water shortly after saliva collection. In the 72 hours before saliva collection participants also abstained from caffeine, nicotine, alcohol, and foods thought to impede habitual melatonin secretion (e.g., chocolate, bananas, tomatoes (Peuhkuri et al., 2012)).

The saliva samples were stored at -20°C. For analysis, the assays were thawed then centrifuged at 2500 rpm for 10 minutes, then the supernatant was retained for use in radioimmunoassay. Finally, saliva melatonin was measured using reagents from Buhlmann Laboratories AG (Allschwil, Switzerland) in a sensitive (4.3 pM) direct radioimmunoassay. The mean intra-assay coefficient was 4.5%. The inter-assay coefficients of variation for low and high levels of salivary melatonin were 8.8% (5.2 – 12.9) and 88.3% (50.7 – 104.5), respectively. The functional least detectable dose of the assay was 1.0 pg/ml. DLMO was calculated by linear interpolation across time-points when melatonin concentration increased to 4.0 pg mL or above 58.

4.3.3.6 Mood – Depression, Anxiety, and Stress Scale

Mood was measured using the Depression, Anxiety, and Stress Scale (DASS 21) (Lovibond & Lovibond, 1995). The DASS 21 is comprised of 21 items which are grouped into 3 subscales, depression, anxiety, and stress, each subscale consists of 7 items. Each item is scored on a 4-point Likert scale where participants indicate how much each item applied to them over the past week (0 = did not apply to me at all, 3 = applied to me very much or most of the time). Higher scores indicate worse mood. Adolescents completed the DASS 21 at baseline (Sunday night), and post intervention (Friday night).

4.3.3.7 Mood – Short Mood and Feelings Questionnaire

Mood was also measured using the short version of the Mood and Feelings Questionnaire (SMFQ) for children (Messer et al., 1995). Two mood measures were used to gain a more comprehensive indication of depression symptoms, through increased opportunity of the items mapping onto different depression criteria (*Diagnostic and statistical manual of mental disorders: DSM-5-TR*, 2022). The SMFQ is a 13-item self-report questionnaire which screens for depression in ages 6-19 years. The child or adolescent answers how much each of the 13 items has applied to them over the last two weeks (0 = not true, 1 = sometimes true, 2 = true). Higher scores indicate worse mood. Adolescents completed the SMFQ at baseline (Sunday night), and post intervention (Friday night).

4.4 Statistics

The descriptive sleep data were analysed using paired samples *t*-tests after looking for outliers using boxplots and passing Shapiro-Wilk's test of normality. One outlier was detected in the sleep diary data for TST, and sensitivity analyses were run with and without this data point with very similar outcomes, see Table 4.5 and Table 4.6 respectively. Descriptive mood data were analysed using a Mann Whitney U test; as the distribution of scores was not similar, mean ranks were used for comparison.

Descriptive DLMO data were analysed using independent samples *t*-tests. The baseline DLMO data met assumptions for outliers, normality (Shapiro-Wilk), and homogeneity (Levene's test). One outlier was found in the post-intervention DLMO data. After removal of the outlier, the data passed Shapiro-Wilk's test of normality but homogeneity was violated (Levene's test p = .01) and so Welch's *t*-test was used. An outlier was also found in the DLMO change data. After removal of the outlier the data met assumptions for outliers (boxplots), normality (Shapiro-Wilk) and homogeneity (Levene's test).

The 'sleep-mood' relationship was assessed using Pearson product-moment correlation, and point biserial correlation was used to assess the relationships between 'physical activity-sleep' and 'physical activity-mood'. The appropriate preconditions for each type of correlation analyses were conducted, testing for outliers (boxplots or scatterplots), linearity (scatterplots), homogeneity of variances (Levene's test), and normality (Shapiro-Wilk's test). All preconditions were met, except for one outlier detected in the DLMO change data. Upon removal of the outlier, the precondition tests were re-run and all were passed. The following analyses were run both with and without the DLMO change outlier.

4.4.1 Change Variables

'Change' variables were calculated for use in the correlation analyses of the sleep-mood relationship. These variables were calculated by finding the difference in each measure between the baseline and post-intervention data points (e.g., change variable = baseline score – post-intervention score). As such, a negative DLMO change score represented a delay in DLMO, and a positive DLMO change score represented an advance in DLMO (e.g., 20:00 – 22:00 = -2 hours, a delay of 2 hours). A negative DASS change score represented an increase in DASS score which indicates a worsening of mood, while a positive DASS change score represented a decrease in score and improvement in mood (e.g., 7 – 10 = -3, a higher score at post-intervention and thus a worsening of mood).

4.5 Results

The 18 adolescents who completed data collection had an average age of 16.4 years (Table 4.1). BMI scores ranged from 17-34, with most adolescents having a BMI in the normal range (N = 10). All participants had a late chronotype as defined by the Munich Chronotype Questionnaire, with an average freeday midsleep time of approximately 6 a.m.

Table 4.1

Participant Characteristics

Variable	Sample	N and %	Range	Mean (Standard Deviation)	Clock Time
Age	18		15 – 18	16.44 (1.04)	
BMI	18		17.28 – 33.81	23.50 (5.13)	
Underweight (< 18.5)		2 (11.1%)			
Normal (18.5-24.9)		10 (55.6%)			
Overweight (25-29.9)		3 (16.7%)			
Obese (30-39.9)		3 (16.7%)			
Midsleep time on free days (MCTQ)	18		4.25 – 8.21	6.10 (1.11)	6:06 a.m.
Midsleep time on free days corrected for sleep debt	18		4.25 – 8.27	5.57 (1.24)	5:34 a.m.
DLMO	17		20.51 – 26.51	23.13 (1.65)	11:08 p.m.

Note. MCTQ = Munich Chronotype Questionnaire; DLMO = Dim Light Melatonin Onset.

Actigraphy and sleep diary measures of the adolescents' sleep during the home baseline week were comparable. As is often seen in this population, the adolescents had a significantly later bedtime and waketime on freedays compared to weekdays (Crowley et al., 2014). Both actigraphy and diary data showed that on freedays bedtime was ~1.5 hours later and waketime was 1.5-2.5 hours later. Although actigraphy total sleep time was comparable between weekdays and freedays, sleep diary data indicated that TST was longer on freedays compared to weekdays. See Table 4.2.

Table 4.3 shows the descriptive data for the DASS and SMFQ measures of mood at baseline and post-intervention. The difference in DASS scores at baseline between the sedentary and walking groups was tested with a Mann-Whitney U test. This difference was not found to be significant (sedentary group mean rank = 11.44, walking group mean rank = 7.95, $U = 24.5$, $z = -1.40$, $p = .16$).

Table 4.2

Sleep Descriptives of Weekdays and Freedays Using Paired Sample t-tests

Sleep Variable	Weekdays		Freedays				
	Clock Time	*M (SD)*	*Clock Time*	*M (SD)*	*t*	*p*	Cohen's *d*
Actigraphy							
Bedtime	**12:21 a.m.**	**24.35 (0.98)**	**1:39 a.m.**	**25.65 (1.61)**	**-4.34**	**<.001**	**0.97**
Waketime	**8:56 a.m.**	**8.94 (1.36)**	**10:37 a.m.**	**10.63 (1.08)**	**-5.49**	**<.001**	**1.38**
TST		7.30 hrs (1.07)		7.64 hrs (0.98)	-1.25	.23	0.33
Diary							
Bedtime	**12:03 a.m.**	**24.06 (1.09)**	**1:35 a.m.**	**25.59 (1.67)**	**-5.32**	**<.001**	**1.09**
Waketime	**7:54 a.m.**	**7.90 (1.59)**	**10:29 a.m.**	**10.49 (0.99)**	**-7.62**	**<.001**	**1.96**
TST[a]		**7.78 hrs (1.65)**		**9.00 hrs (1.43)**	**-5.14**	**<.001**	**0.96**

Note. N = 18. TST = Total sleep time.
[a] = outlier removed (N = 17).
Bold = significant (*p* <.001).

Table 4.3

Descriptive Statistics for Mood Variables of Both Intervention Groups at Baseline and Post-Intervention

Variable and Group	Baseline			Post-Intervention		
	N	*Range*	*M (SD)*	*N*	*Range*	*M (SD)*
DASS – Depression subscale						
Sedentary	8	8-24	12.00 (5.45)	7	0-8	2.57 (2.51)
Physical Activity	10	0-16	4.60 (5.74)	10	0-14	7.80 (5.53)
SMFQ						
Sedentary	8	1-14	5.38 (4.14)	8	0-5	2.75 (2.05)
Physical Activity	10	0-14	6.00 (4.67)	10	0-14	3.40 (4.48)

Note. DASS = Depression Anxiety and Stress Scale; SMFQ = Short Mood and Feelings Questionnaire.

Descriptive analyses of the timing of dim light melatonin onset during the study are shown in Table 4.4. Independent samples *t*-tests were used to compare DLMO between the two groups at baseline and post-intervention. At baseline the sedentary and walking groups were not statistically different from each other, *t*(15) = -0.15, *p* = .44. By the post-intervention follow-up there was a statistically significant difference between groups, *t*(9.02) = 2.17, *p* = .03, Cohen’s *d* = 1.08.

The change in DLMO for each group was also significantly different, *t*(14) = -2.81, *p* = .01, Cohen’s *d* = 1.41. Measurement of DLMO after the intervention week showed that the sedentary group had delayed by 34 minutes and the walking group advanced by 27.5 minutes. When the analysis was repeated after removal of an outlier it was found that the sedentary group experienced a phase delay of 18.5 minutes, *t*(13) = -2.79, *p* = .01, Cohen’s *d* = 1.45.

Table 4.4

Descriptive Statistics for DLMO for Both Intervention Groups from Baseline to Post-Intervention

DLMO Variable and Group	Sedentary				Physical Activity			
	N	*Range*	*Clock Time or Phase Change*	*M (SD)*	*N*	*Range*	*Clock Time or Phase Change*	*M (SD)*
Baseline	8	20.51–26.51	11:03 p.m.	23.06 (2.04)	9	21.43–24.82	11:10 p.m.	23.18 (1.34)
Post-Intervention	8	20.51–27.00	11:45 p.m.	23.76 (2.05)	8	20.90–24.64	10:04 p.m.	22.07 (0.79)
Change	8	-144–31	34.25 minute delay	-34.25 (53.15)	8	-13–79	27.5 minute advance	27.50 (32.04)
Change – no outlier	7	-57–31	18.57 minute delay	-18.57 (31.65)	8	-13–79	27.5 minute advance	27.50 (32.04)

Note. DLMO = Dim light melatonin onset.

Change scores: a negative DLMO change score represents a delay, and a positive DLMO change score represents an advance, a negative DASS change score represents a worsening of mood, and a positive DASS change score represents an improvement in mood. See Section 4.4.1 for explanation of change variable calculation.

4.5.1 Correlations

Correlations were run to assess the strength of connections between physical activity, sleep, and mood (see Table 4.5). ‘Sleep’ was measured by the change in DLMO (dim light melatonin onset), and mood was measured by the DASS (Depression Anxiety and Stress Scale) and SMFQ (Short Mood and Feelings Questionnaire). Only one significant relationship was found, between physical activity group and change in DLMO, such that allocation to the physical activity group was associated with DLMO change in a positive direction (see discussion of change variable calculation in Section 4.4.1), meaning physical activity participation was related to earlier DLMO (circadian phase advance). The correlations between sleep-mood and physical activity-mood were non-significant.

Table 4.5

Physical Activity, Sleep, and Mood Correlations (including DLMO outlier)

Variables	*r*	*p (two tailed)*	Variability %
Physical activity group – DLMO change	**.60**	**.01**	**36.1%**
DLMO change – DASS change	-.41	.15	-
DLMO change – SMFQ change	--------------- Not linear ---------------		
Physical activity group – DASS change	-.48	.07	-
Physical activity group – SMFQ change	-.004	.99	-

Note. DLMO = Dim light melatonin onset; DASS = Depression Anxiety and Stress Scale; SMFQ = Short Mood and Feelings Questionnaire.
Change scores: a negative DLMO change score represents a delay, and a positive DLMO change score represents an advance, a negative DASS change score represents a worsening of mood, and a positive DASS change score represents an improvement in mood. See Section 4.4.1 for explanation of change variable calculation.
Bold = significant (*p* = .01).

When the correlations were rerun *without* the outlier from the DLMO data, the results were similar (see Table 4.6). Once again, the only significant relationship was found between physical activity group and change in DLMO timing, however those in the sedentary group had a circadian phase delay of 19 minutes, which is a slightly smaller delay than found in the analyses including the outlier. All other relationships and significance testing were comparable between analyses with and without the outlier.

Table 4.6

Physical Activity, Sleep, and Mood Correlations (excluding DLMO outlier)

Variables	*r*	*p (two tailed)*	Variability %
Physical activity group – DLMO change	**.61**	**.02**	**37.6%**
DLMO change – DASS change	-.36	.23	-
DLMO change – SMFQ change	-.35	.21	-
Physical activity group – DASS change	-.48	.07	-
Physical activity group – SMFQ change	-.004	.99	-

Note. DLMO = Dim light melatonin onset; DASS = Depression Anxiety and Stress Scale; SMFQ = Short Mood and Feelings Questionnaire.

Change scores: a negative DLMO change score represents a delay, and a positive DLMO change score represents an advance, a negative DASS change score represents a worsening of mood, and a positive DASS change score represents an improvement in mood. See Section 4.4.1 for explanation of change variable calculation.

Bold = significant (*p* = .02).

4.6 Discussion

A controlled laboratory setting was used to test the impact of a walking intervention on the mediation of the relationship between physical activity and mood by sleep in 18 adolescent boys. As predicted, it was found that the walking intervention was associated with earlier circadian timing (DLMO) compared to the sedentary group. However the relationships between ‘physical activity – mood’ and ‘sleep – mood’ did not reach significance and thus there was not sufficient evidence for the proposed mediation. A more detailed examination of these findings is discussed below.

4.6.1 Sleep Descriptives

The baseline sleep of the adolescents in this study matched the standard features of adolescent sleep reported in reviews (Alfonsi et al., 2020; August & Rosen, 2020; Tarokh et al., 2019). The sleep patterns showed the characteristic adolescent sleep delay on freedays compared to weekdays. Freeday sleep was timed ~1.5 hours later than weekday sleep, and average freeday bedtime was 1 a.m. Measurement of DLMO at baseline found that DLMO occurred on average at 11:08 p.m. All aspects of sleep were comparable between objective and subjective measures, however measurement of total sleep time diverged. Sleep diary data showed an average TST of 7.5 hours on weekdays, and 9 hours on freedays, which is similar to the majority of adolescent sleep research (Saxvig et al., 2020; Tarokh et al., 2016). Comparatively, actigraphy data measured a TST of 7.5 hours on both weekdays and freedays, which was unexpected. It is possible that the discrepancy between the sleep diary and actigraphy data indicates a mismeasurement of sleep by the actigraphy software, during which some of the freeday sleep was miscategorised as wake, possibly due to movement during sleep (Meltzer et al., 2018). Previous research has shown that actigraphy measures of sleep can underreport TST in adolescent populations (Meltzer et al., 2012; Short et al., 2012). Alternately this TST discrepancy could be a misinterpretation of sleep on the sleep diary measure. However, the pattern of sleep recorded by the sleep diary measure matches that typically seen in adolescents, where sleep time is shorter on school days than freedays (Gariepy et al., 2020). Despite this discrepancy, all other sleep measures indicated the adolescents had typical sleep at baseline for their stage of life.

4.6.2 Physical Activity and DLMO Timing

Physical activity group allocation was significantly associated with DLMO timing. As mentioned in a previous publication of this study's data, participating in 45 minutes of light physical activity in the morning, immediately after waking, was associated with a circadian phase *advance* of 28 minutes, while remaining sedentary was associated with a *delay* of 19 minutes (Lang et al., 2022). Very minimal research has been conducted in adolescents to test the effect of morning physical activity on circadian timing. These results are similar to that of an adult sample in a similar study design (Thomas et al., 2020). Thomas et al. found that after 5 mornings of moderate-vigorous physical activity participants with late chronotypes experienced a 32-minute circadian advance. It is notable that the adolescents in the current study experienced a similar circadian advance after 5 mornings of light physical activity following a gradually advancing wake schedule compared to the adults' 5 mornings of moderate-vigorous physical activity on a fixed schedule. This indicates that a gradually advancing wake schedule could augment the use of physical activity to advance the circadian rhythm, which is helpful for populations that find physical activity undesirable. The circadian advances and delays experienced by the adolescents match the circadian phase response curve to physical activity found in adult research (Youngstedt et al., 2019). In particular, the finding that morning physical activity can elicit a circadian phase advance in adolescents is valuable information for a group that often struggles with delayed circadian rhythms (August & Rosen, 2020; Dutil et al., 2022).

4.6.3 The Relationship Between DLMO Timing and Mood

Contrary to expectations, the association between DLMO change and mood change was not found to be significant for either mood measure. However, cautious consideration of data trends showed a tendency for a bigger DLMO delay to be associated with a bigger decrease in SMFQ and DASS depression score. That is, a larger circadian rhythm delay was associated with a stronger mood improvement. Whereas, a larger circadian advance was associated with a smaller or no mood improvement.

Although minimal conclusions can be drawn from these results as they represent trends and not significant findings, it is curious that these results do not match those of previous research.

Typically a later circadian rhythm in adolescents is associated with worse mood (Dolsen & Harvey, 2018; Simon et al., 2020; Wilson et al., 2019). However, the results of the current study do not pertain to the impact of circadian rhythm timing on mood, which has been the focus of most research, but instead to the impact of a circadian rhythm phase *shift* on mood. It is possible that the experience of undergoing a phase advance is unpleasant and thus was detrimental to the adolescents' mood. This explanation would match the findings of Richardson et al. (2022) that no significant mood improvements were found 1 week after a light exposure intervention to advance the circadian rhythm (during the phase shift), but mood improvements became significant at the 1 month follow up of Richardson et al.'s study (after completion of the phase shift to a new established circadian timing). If the experience of a phase advance itself is unpleasant this could explain why the results do not match those of previous research showing that those who already have earlier timed circadian rhythms have better mood than those with later circadian rhythms. Nevertheless, it is important to be mindful that these results represent data trends and not significant findings.

4.6.4 Physical Activity and Mood

It was predicted that the walking group would have improved mood following the physical activity intervention, compared to the sedentary control group. There was no relationship identified between physical activity group allocation and SMFQ ($p = .99$). Yet, there was a trending relationship between physical activity group and DASS depression score, although this did not reach significance ($p = .07$). This non-significant trend showed that the sedentary group experienced a larger DASS improvement (reduction of 7 points) than the walking group (reduction of 3 points). It is interesting that following the week in the lab both groups experienced improved DASS depression scores, however the walking group did not experience the same improvement as the sedentary group. As the only difference between groups was physical activity allocation, this indicates that the mood improvement participants experienced was counteracted if participating in the walking intervention. The idea that participating in physical activity could be detrimental to mood is contrary to the majority of research in both adults and adolescents. Physical activity is consistently beneficial for mood (Chan et al., 2019; Rodriguez-Ayllon et al., 2019; Zhang et al., 2020) and sedentary activity is detrimental to mood (Giurgiu et al., 2019). Nevertheless, recent systematic review and meta-analysis (Bourke et al., 2021; Buecker et al., 2021) have found that there is a stronger relationship between physical activity and positive affect than negative affect. Bourke et al. reviewed child and adolescent research and noted that there was stable evidence for improvements to positive affect following physical activity but mixed results for the impact of physical activity on negative affect. Therefore, it is possible that although no significant relationship was found between the walking group and negative affect, a significant relationship may have been found between physical activity and positive affect had it been included as a measure. Though once again it emphasised that these results represent a trend and not significant findings.

Given the lack of a significant 'physical activity – mood' relationship, it is necessary to consider whether the light intensity walking intervention was of sufficient strength to alter mood. However, given that the intervention had a strong impact on sleep, creating a difference in DLMO timing of 45 minutes between groups, it seems unlikely that the walking intervention was not "strong enough". Indeed, due to the close connection between sleep and mood (Clarke & Harvey, 2012; Shochat et al., 2014), it would be expected that even if the physical activity intervention itself did not impact mood, that the large difference in sleep between the groups would result in mood changes regardless. Thus it is more likely that the lack of significant mood change is due to the measurement of mood, possibly indicating poor timing of mood follow-up. More discussion of this point continues in Section 4.6.6.

4.6.5 Mediation of Physical Activity – Sleep – Mood

It was hypothesised that 'sleep' would mediate the relationship between physical activity and mood, in that after the intervention the walking group would have an earlier circadian rhythm which would in turn result in better mood for the adolescents. However, only one of the three required preconditions for this mediation was significant. Physical activity participation was associated with earlier DLMO timing. However, the relationships between physical activity and mood, and DLMO timing and mood were non-significant. As such, this study did not find evidence for a mediation of the physical activity – sleep – mood relationship.

It is interesting that while the association between physical activity and sleep occurred as anticipated, the two correlations involving mood measures (physical activity – mood, sleep – mood) were non-significant and trended in a non-hypothesised direction. There were trends for the sedentary group to have a larger mood improvement than the walking group, and a bigger DLMO delay was associated with greater improvement in mood, whereas a bigger DLMO advance was associated with little-to-no-improvement. Regarding the unexpected and non-significant mood results it is noteworthy that the study took place during the adolescents' transition from the school term into school holidays, and the beginning of the intervention week in the sleep laboratory was also the first week of holidays for the adolescents. The data collection was timed in this way to ensure that the morning intervention activity and school start times would not impact each other. However it did result in the baseline mood measure being taken only 2 days after school term finished and the follow-up mood measure was taken at the end of the first week of school holidays. It is possible that all participants experienced an improvement in mood due to the beginning of the school holidays.

Yet, the walking group showed less mood improvement than the sedentary group, despite research indicating that physical activity participation improves mood (Rodriguez-Ayllon et al., 2019). The present study specifically recruited sedentary participants with a late chronotype, in order to target the development of a physical activity intervention towards a population in need of its benefits for sleep and mood. It is possible that the very characteristics targeted by this study - sedentary adolescents with a late chronotype - made elements of the study protocol unpleasant for those allocated to the walking group. The adolescents were required to get up early in the morning on their holidays and walk for 45 minutes for 5 days, sometimes next to a participant from the sedentary group that was sitting on a couch. Research shows that late chronotypes rate submaximal morning physical activity as requiring more effort than earlier chronotypes (Vitale et al., 2017) and also attribute less positive aspects to physical activity than earlier chronotypes (Schaal et al., 2010). Thus, it is possible that although all participants experienced an improvement of mood due to the beginning of school holidays, a smaller improvement was experienced by the walking group due to their dislike of participating in physical activity, which produced non-significant results.

Another possibility is that any mood benefits typically reported by those with earlier circadian rhythm timing are not present directly after advancing the rhythm, but occur some weeks later. Evidence for this is possibly seen in a study into the circadian rhythm advancing effects of a light exposure intervention. Mood was measured weekly and although there was no significant change to mood during the 3-week treatment period, significant changes in mood were reported at the 1-month follow-up, such that mood improved following an advance in circadian rhythm (Richardson & Gradisar, 2022). Richardson and Gradisar’s (2022) results support the explanation that undergoing a circadian advance is unpleasant and thus mood improvements seen in advanced circadian rhythms likely occur after the rhythm timing is stabilised. Unfortunately, as the current study did not perform follow-up mood measurements at later time points it cannot be determined if mood began to improve subsequent to the circadian phase advance.

4.6.6 Strengths, Limitations, and Future Research

One of the biggest strengths of this study was the use of a laboratory setting to control for external factors while testing the effect of a physical activity intervention on sleep and mood. Controlling for other factors in this way allowed the impact of physical activity on sleep to be isolated from the additional impact of light on sleep. Light exposure has a substantial effect on sleep, and different elements of light exposure, such as intensity, timing, and duration, alter the effect of light on the circadian rhythm (Tähkämö et al., 2019). By removing the variable impact of light on the circadian rhythm, the results indicate to what extent physical activity impacts the circadian rhythm in a variety of settings irrespective of lighting conditions, e.g. indoors and outside. Thus, the results show that morning physical activity can advance the circadian rhythm even if conducted in minimal light conditions, such as outside during the early morning or inside under dim lighting.

Although significant results were found between physical activity and sleep, no significant results were found for the relationships involving mood. One of the studies limitations was the lack of a further mood follow-up subsequent to the initial post-treatment mood measurement. This lack of a follow-up possibly led to the absence of significant mood findings. No significant change in mood was observed immediately following the physical activity intervention, however as discussed previously, findings by Richardson and Gradisar (2022) indicate that mood changes do not immediately follow a circadian rhythm advance but instead occur a few weeks later. The use of multiple follow-up data collection points in future research would be beneficial in determining if mood changes occurring following a circadian shift only become significant after cessation of the intervention and completion of the circadian phase shift. The results of Richardson and colleagues indicate that this mood change reaches significance 1 month following the intervention, highlighting the need for circadian and mood research to include mood measurements until this time point at a minimum.

A further limitation of this study was the timing of data collection. From a practical perspective, running data collection over the transition to school holidays allowed for easier stabilisation of bed and rise times during the baseline week, and ease of intervention administration and study measures during the intervention week. However, the drawback to this study design was the potentially confounding nature of the beginning of school holidays which occurred concurrently with the intervention. It is thus difficult to determine to what degree the adolescents' mood changes, particularly those in the sedentary group, represent mood changes due to the physical activity intervention versus the beginning of school holidays. It is difficult to design an experimental protocol to suit all constraints, however it would be beneficial for future research to take into account the impact of school holidays on mood and design the study or measurement timings with this in mind. Indeed, continued collection of mood measures at later data points could also be beneficial in separating mood changes occurring from physical activity and sleep, from mood changes occurring due to school holidays.

Further research is needed into physical activity interventions for sedentary, late chronotype adolescents. This population is at risk of sleep and mood problems (Crowley et al., 2018; Polanczyk et al., 2015) and thus would greatly benefit from the development of interventions for this purpose. Although it was found that morning physical activity advanced the adolescents' circadian rhythms, the lack of a significant mood improvement in this group signals the need for a more appropriate intervention for this population. Morning physical activity was used in the current study as it has been found to have a stronger effect on advancing the circadian rhythm of adolescents than evening physical activity (Alley et al., 2015; Wendt et al., 2020). Nevertheless, evening physical activity may be a more suitable intervention for a group of sedentary adolescents with late chronotypes, as evening physical activity is less difficult than morning activity for those with late chronotypes (Bonato et al., 2017), and evening physical activity is also less detrimental to sleep for late chronotypes than it is for early chronotypes (Glavin et al., 2020). Due to the risk of sleep and mood difficulties in the adolescent population, particularly those who are sedentary with a late chronotype, further research into the appropriate characteristics of a physical activity intervention to serve as prevention or treatment for sleep and mood problems is beneficial.

4.7 Conclusion

This study investigated the presence of a physical activity – sleep – mood mediation in adolescents following a physical activity intervention. As seen in Lang and colleagues (2022) a strong relationship was found for ‘physical activity – sleep’. Participation in the walking intervention resulted in a circadian advance of 28 minutes, whereas those allocated to the sedentary group experienced a circadian delay of 19 minutes. Conversely, the relationships involving mood, ‘sleep – mood’ and ‘physical activity – mood’ were not significant, and the relationship trends were in the opposite direction than expected. The trend was for sedentary behaviour and circadian delay to be associated with better mood (using the depression subscale of the DASS), and physical activity and circadian advance were associated with less mood improvement. The lack of change in mood was surprising, considering the large change in sleep between the different physical activity groups. Further research is warranted to find out why the mood relationships were non-significant and trended in the opposite direction. The results of the present study - that physical activity is able to advance adolescent circadian rhythm - is helpful, but the lack of benefit to mood from the physical activity and circadian rhythm advance indicate that sedentary late chronotype adolescents may be difficult to treat clinically. More research is needed to find appropriate interventions for this unique population of adolescents.

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CHAPTER 5 -
DISCUSSION

5.1 Thesis Aims

The aim of this thesis was to investigate if sleep mediates the relationship between physical activity and mood in adolescents. This was accomplished by looking at different elements of sleep (sleep timing, total sleep time, and sleep onset latency), different physical activity timing (physical activity during the day, and physical activity during the evening [after 6 p.m., or in the 3 hours before sleep]), and using different study designs (cross-sectional, ecological momentary assessment, and an experimental intervention in a sleep laboratory).

5.2 Brief Summary of Findings

Evidence was found for sleep's role as a mediator between physical activity and mood for all three aspects of sleep (sleep timing, TST, and SOL), and evidence for each of these proposed mediations was as follows.

5.2.1 Mediation by Sleep Timing

The mediation of physical activity and mood by sleep timing (chronotype/circadian rhythm timing) was tested in **Chapters 2**, **3**, and **4**. The mediation was found to be significant in **Chapter 2** and **Chapter 3**, where more physical activity, regardless of time of day was associated with better mood, and this relationship was mediated by *earlier* sleep timing. More physical activity was also associated with earlier sleep timing in **Chapter 4**, however the mood measures had no significant relationship with sleep or physical activity, and so mediation could not be tested. Across these chapters, physical activity was performed at different times of day, after 6 p.m. (**Chapter 2**), in the 3 hours before sleep (**Chapter 3**), and immediately after waking (**Chapter 4**), and it was found that regardless of the timing, more physical activity was associated with an earlier sleep timing in the adolescents.

Chapter 2 found that the relationship between evening physical activity after 6 p.m. and mood was significantly mediated by chronotype, and **Chapter 3** offered the opportunity to replicate this finding. However, **Chapter 3** found that physical activity after 6 p.m. was not related to chronotype, although physical activity in the 3 hours before sleep was.

A distinct sex difference was noticed across the three chapters, such that the mediation of physical activity and mood by sleep timing was significant in girls but not in boys. **Chapter 2** contained a sample of both sexes, and found the mediation was only significant for the total sample and for the girls, not for the boys. This pattern was repeated in the subsequent chapters where the mediation by chronotype was significant in an exclusively female sample (**Chapter 3**), but was not significant in a solely male sample (**Chapter 4**). When the results of the different sexes were compared in **Chapter 2** it was identified that the adolescent boys did not have the same range of mood scores as the girls, which may have prevented the mediation model from reaching significance. Similarly, in **Chapter 4** the boys' mood scores were not significantly associated with sleep or physical activity.

5.2.2 Mediation by Total Sleep Time

Chapter 2 and **Chapter 3** tested for the mediation of physical activity and mood by total sleep time. In both instances the mediation model was significant, however the direction of the associations differed between the two studies. In **Chapter 2** more physical activity overall, and during free time, were related to better mood and this relationship was mediated by longer total sleep time. The results of **Chapter 3** however were more varied. The relationships between physical activity, sleep, and mood in this chapter were assessed on a daily scale which allowed a more detailed examination of the data but also more variability. Although total sleep time was not a significant mediator overall, it did significantly mediate the relationship between physical activity and mood on three alternating days - Wednesday, Friday, and Sunday. On all three days, more moderate to vigorous physical activity (MVPA) during the day was associated with *shorter* total sleep time (this will be discussed further in Section 5.3.2.1). For two of these three significant mediations (Friday and Sunday) shorter total sleep time mediated the relationship between more MVPA and better mood (less negative affect, or more positive affect, respectively), in the third mediation (Wednesday) shorter total sleep time mediated the relationship between more MVPA and *worse* mood (more negative affect). So although the significance and directions of the tested relationships varied between days, sleep duration did indeed mediate the relationship between physical activity and mood on a daily scale in **Chapter 3**.

The significance of the relationships in **Chapter 3** was intermittent, and the directions were changeable. The relationship between physical activity and mood was significant in 5 instances, and in 3 of these, more physical activity was beneficial to mood (more positive affect, or less negative affect), and in 2 instances it was detrimental to mood (less positive affect, or more negative affect). Similarly, there were also 5 significant relationships between TST and mood. In 3 of these relationships more TST was beneficial to mood (less negative affect), and in 2 cases it was detrimental to mood (less positive affect, or more negative affect). These findings in **Chapter 3** highlight the potential complex inter-relationships of these three key variables when examined over a daily basis.

5.2.3 Mediation by Sleep Onset Latency

The role of sleep onset latency as a mediator was only able to be tested in **Chapter 2**. Nevertheless, in the large sample of 1,367 adolescents involved in this study, the data matched a model where once again sleep mediated the relationship between physical activity and mood. Again, this was only found to be the case for the total sample and for girls - but not for boys. It was found that evening physical activity after 6 p.m. was linked with better mood, and this relationship was mediated by *shorter* sleep onset latency. Once again it was found that an improved aspect of sleep mediated the effect of evening physical activity on mood.

An additional element of the sleep onset latency model was also tested. It was found that the data also matched a model where repetitive negative thinking significantly moderated the aforementioned mediation between SOL and mood. Girls with lower levels of repetitive negative thinking had a stronger relationship between shorter SOL and better mood. Indicating that those with a longer SOL and worse mood have less repetitive negative thinking, contrary to expectations.

5.3 How do Findings Sit in the Body of Literature?

5.3.1 Sleep Timing Mediation

5.3.1.1 Physical Activity and Sleep Timing

The finding that evening physical activity was related to earlier chronotype, was not anticipated at the beginning of this thesis. Yet, the observation of evening physical activity having no effect, or even a beneficial effect on sleep is not unique (Frimpong et al., 2021). For example, Miller et al. (2020) found that 30 minutes of evening exercise (cycling or resistance) did not impact sleep measures in a group of 12 young males. Similar results have been seen by Myllymaki et al. (2011) in a sample of 11 young adults, where the only measure of sleep impacted by ~35 minutes of vigorous cycling in the evening was an increase in the percentage of non-REM sleep. Alley et al. (2015) also found no difference in the majority of sleep measures between ~30 minutes of resistance exercise at 7 p.m. versus no exercise in 24 university students. The only differences found were that the evening exercise condition had a shorter WASO and also less number of times woken during the night compared to the control condition. In all three of these young adult studies evening physical activity had either no effect or some beneficial effect on sleep. When considering the results of these studies in conjunction with the results of **Chapters 2** and **3** it is acknowledged that the three studies did not measure sleep timing and thus their results cannot be directly compared to the finding in **Chapters 2** and **3** that evening activity was associated with earlier chronotype. Nevertheless, it remains that the results of **Chapters 2** and **3** are not the first time that evening physical activity has been found to have, not only no adverse impact on sleep, but to be associated with better sleep.

This is not to say that evening physical activity does not have the capacity to delay the circadian rhythm. Reviews confirm that physical activity can both delay and advance the circadian rhythm (Montaruli et al., 2017; Richardson et al., 2017) and a phase response curve of the circadian rhythm to physical activity has been identified in a young adult sample (Youngstedt et al., 2019). Indeed, the adolescents' circadian response to physical activity in **Chapter 4** is consistent with this phase response curve. Youngstedt et al. ascertained that 1 hour of moderate treadmill exercise elicits a circadian phase advance if conducted at 7 a.m. or between 1-4 p.m. In accordance with this, **Chapter 4** found that 45 minutes of physical activity conducted immediately after waking for 5 days resulted in a phase advance of DLMO. It could seem at first glance that the physical activity in **Chapter 4** does not match the phase response curve of physical activity ~7 a.m., as although the exercise was timed immediately after waking, it ranged between participants from 8:30 a.m. to 1:30 p.m. However, the times of Youngstedt's phase response curve refers to an individual's intrinsic circadian time and not the clock time, and the timing of the physical activity was individualised to each adolescent's sleep schedule. Therefore, regardless of the clock time of each individual adolescent's wake time in **Chapter 4**, from the reference point of internal circadian timing, the physical activity was likely occurring near the 7 a.m. time noted by Youngstedt et al. (2019).

As much as the results of **Chapter 4** fit Youngstedt's phase response curve (2019), how the results of **Chapters 2** and **3** fit with the phase response curve is not as clear. Youngstedt et al. found that physical activity between 7-10 p.m. resulted in a circadian delay, yet **Chapters 2** and **3** found physical activity after 6 p.m. and in the 3 hours before sleep were related to *earlier* sleep timing. The contradictory nature of these results cannot be disregarded. Yet despite the opposing quality of the relationships found between Youngstedt et al. and **Chapters 2** and **3**, this differing direction of the relationship between evening physical activity and sleep timing has been observed in other studies (Bonato et al., 2017; Thomas et al., 2020; Vitale et al., 2017). Studies in young adults by Thomas et al. (2020) and Vitale et al. (2017) found that different chronotypes reacted differently to evening physical activity. While both early and late chronotypes reacted similarly to morning physical activity, and this reaction matched that projected by Youngstedt's phase response curve, the reactions to evening physical activity differed between chronotypes. Early chronotypes matched the expectations of the phase response curve but later chronotypes did not. Indicating that individual differences also have a role to play in the relationship between physical activity and sleep timing.

All three studies in this thesis found a connection between physical activity and sleep timing. Despite the seeming disparity between the findings that both morning and evening physical activity were associated with earlier sleep timing, this contradiction in outcomes can also be seen in the literature, particularly when considering the role of individual differences such as chronotype.

5.3.1.2 Sleep Timing and Mood

Within the chronotype mediations in **Chapters 2** and **3** it was found that earlier chronotype was associated with better mood. This relationship fits well with the literature in this area. Reviews and meta-analysis, mainly consolidating research from adult samples, note the link between late chronotype and lower mood or depression (Au & Reece, 2017; Müller & Haag, 2018). This link is also seen in adolescent research (Chiu et al., 2017), on a daily scale (Díaz-Morales et al., 2015), longitudinally (Haraden et al., 2017, 2019), and in large samples (N = 29,635; Gariépy et al., 2019).

However **Chapter 4** found that the phase advance the adolescents experienced from participating in the physical activity intervention was not associated with a significant mood change. Indeed, there was a trend for the adolescents in the sedentary group that experienced a phase delay to experience a *bigger* mood improvement than those doing the 45-minute light intensity walking intervention. This result does not fit so clearly with the majority of literature in this area. Although **Chapter 4**'s relationship between earlier circadian rhythm and worse mood is only a trend, due to its unexpected nature, it merits further consideration.

As discussed in the previous paragraph, earlier circadian rhythm and sleep timing is consistently associated with better mood parameters than later timing (Chiu et al., 2017; Díaz-Morales et al., 2015; Gariépy et al., 2019; Haraden et al., 2017, 2019). As such, the result that a phase delay (and sedentary behaviour) caused a mood improvement and a phase advance (and morning physical activity) caused little-to-no mood improvement, does not fit with the majority of the literature in this area. Yet, an important distinction of **Chapter 4**'s results are that they represent the impact of a circadian phase *change* on mood, not the impact of current and stable circadian phase timing on mood. This stable timing of sleep is what is represented in **Chapters 2** and **3**, which do match the literature that an established earlier sleep timing is associated with better mood. Negligible research has measured the effect of the *movement* of circadian phase on mood in adolescents. To the author's knowledge only one study has done this. While testing the impact of light treatment on advancing adolescents' circadian rhythm, Richardson and colleagues (2022) found that there was no significant mood change to accompany the circadian rhythm advance during the 3 weeks of treatment, but there was a significant mood improvement at the 1 month follow up. This suggests that improvements in mood from a circadian advance do not occur immediately, and that later mood improvements were missed in **Chapter 4** due to the lack of a later follow-up.

5.3.1.3 Chronotype as a Mediator

This is the first time to the author's knowledge that chronotype has been considered as a mediating mechanism between physical activity and mood. **Chapters 2** and **3** found that chronotype did indeed mediate the 'physical activity – mood' connection, and this finding matches the wider research in this area of the relationships between physical activity, sleep, and mood. Meta-analysis and research using large samples (N = 5,000-177,000) commonly finds that more physical activity is related to better sleep (Atoui et al., 2021; Banno et al., 2018; Galland et al., 2020; Lang et al., 2016; Tambalis et al., 2019; Wang & Boros, 2021), and better sleep is related to better mood (Gwyther et al., 2022; Konjarski et al., 2018; Orchard et al., 2020; Palmer et al., 2018; Short et al., 2020).

5.3.2 Total Sleep Time Mediation

Chapter 2 and **Chapter 3** both found significant mediations of the relationship between physical activity and mood by TST, but the directions and consistency of the relationships involved differed between the two chapters. This was understandable as the research designs of each study differed greatly. **Chapter 2** utilised a cross-sectional design in a large sample of adolescents (N = 1,367) to assess if the data matched the proposed models prior to further causal consideration of the data. Building upon this, **Chapter 3** employed an ecological momentary assessment design to test these relationships from a causal perspective on a daily scale. The inherent differences of the research designs naturally returned different results, where **Chapter 2** provides insight into the general overall associations, **Chapter 3** is looking at specific daily links.

The results of the large cross-sectional study in **Chapter 2** followed the pattern expected in the literature. More physical activity (during free time and in a composite score of overall physical activity during the day), was associated with a longer TST, and this was associated with better mood. It has been previously established in reviews and meta-analysis that more physical activity is often associated with longer sleep duration (Antczak et al., 2020; Dolezal et al., 2017) and better mood (Gianfredi et al., 2020; Rodriguez-Ayllon et al., 2019; Sampasa-Kanyinga et al., 2020), and that longer sleep duration is also typically associated with better mood (Gwyther et al., 2022; Short et al., 2020). The mediation found in **Chapter 2** reflects the relationships typically seen in the literature. In addition to providing further evidence for these relationships in a large adolescent sample, the results of **Chapter 2** also create a new link in the literature, by showing that one of the mechanisms through which physical activity is connected to mood is through TST itself.

Interpretation of the results of **Chapter 3** is more complex. This is largely due to the increased detail of the data collected, which allowed consideration of daily temporal relationships between physical activity, sleep, and mood. Analysis of the overall data (aggregated over the week) did not find evidence for TST as a mediator between physical activity and mood. However separate analysis of each day of the week found a significant mediation on three days: Wednesday, Friday, and Sunday. In these three mediations more MVPA during the day was associated with *less* TST the following night, which was associated with a mood change, and the direction of the mood change differed depending on the day.

5.3.2.1 Physical Activity and Total Sleep Time in Chapter 3

The relationship between more moderate-to-vigorous physical activity (MVPA) and less TST was unanticipated and intermittent, yet the direction of this relationship remained consistent. On all three days in which MVPA was significantly related to TST, more MVPA resulted in less TST. Studies have previously linked more physical activity with less sleep (Atoui et al., 2021; Memon et al., 2021), particularly day-to-day studies of daytime exercise, and sleep that night (Atoui et al., 2021; Huang et al., 2021; Pesonen et al., 2022). As was discussed previously in Section 3.5.2.1 of **Chapter 3**, the idea has been put forward that more physical activity may be related to shorter sleep duration through displacement of the time available to sleep (Antczak et al., 2020; Matricciani et al., 2018;

Memon et al., 2021). That is, the time taken up by exercise may either occur during the time in which the person would have been sleeping, or may cause a chain reaction in which other necessary activities which were displaced by the physical activity (e.g., homework, dinner, showering) could be pushed later, thereby displacing sleep. Certainly, there are data to support this being the case in young adult athletes (Fox et al., 2020). Nonetheless, there may be an alternate explanation.

It is possible that the relationship between more physical activity during the day and shorter sleep duration the following night occurs through actigraphic measurement error. It is feasible that more physical activity during the day results in more movement during one's time in bed at night. Whilst this may be recognised as a large claim, the results from previous research support this idea. A number of studies have identified increased movement during sleep after participating in more physical activity during the day (Leeder et al., 2012; Taylor et al., 1997; Vitale et al., 2017). Further to this, a review by Youngstedt (2005) and other studies (Bernard et al., 2016; Leeder et al., 2012; Mead et al., 2019; Plekhanova et al., 2021) have also noted increased WASO the night after more physical activity during the day. Moreover, the studies that noted increased WASO were using actigraphy. So it is plausible that more physical activity causes more nocturnal movement, which can be interpreted by actigraphy as WASO, or conversely shorter TST.

5.3.2.2 Total Sleep Time and Mood in Chapter 3

The relationships between TST and mood in **Chapter 3** were somewhat inconsistent. Of the 14 possible relationships between TST and mood across the days of the week (7 days of sleep measures with positive and negative affect), there were 5 which reached statistical significance. Among these significant relationships an overall pattern seemed evident. Total sleep time was largely unrelated to positive affect, although less TST was associated with more positive affect (better mood) on one day (Sunday). The relationship between TST and negative affect reached significance on more days, and less TST lead to worse mood (more negative affect) on three days (Tuesday, Wednesday, and Sunday) compared to less TST leading to better mood (less negative affect) on only one day (Friday). The overall direction of the results is that for the most part less TST was related to worse mood, and this was via negative affect. This fits with other studies' temporal assessment of adolescents in larger samples. Both Kouros et al. (2022) and Fuligni et al. (2019) found that less subjective TST the night before was related to more negative mood or psychological distress (anxiety and depression symptoms) the next day, respectively. Nevertheless, due to the somewhat sporadic nature of the relationships found in **Chapter 3** consideration must be given to whether the relationships found between TST and mood do indeed represent a pattern - or simply occurred by chance.

A review of the daily relationships between sleep and mood by Konjarski et al. (2018) has also identified that the relationship between sleep duration and mood is not always present when analysed on a daily basis. Konjarski et al. found that more subjective TST was associated with better mood in 5 of 10 studies for negative affect, and 6 of 9 studies for positive affect. Indicating the variable nature of the relationship between sleep duration and mood on a daily scale. This is despite evidence of the finding that less TST is typically associated with worse mood when assessed on a longer time scale (Orchard et al., 2020; Short et al., 2020; Sullivan & Ordiah, 2018). Clearly the relationship between TST and mood is more complicated from day to day.

5.3.2.3 Total Sleep Time as a Mediator

The results of **Chapters 2** and **3** indicate that total sleep time is a partial mediator of the relationship between physical activity and mood in adolescents. Total sleep time's role as a mediator is not as simple as the previously discussed mediation from sleep timing. For the most part, the overall direction of the 'physical activity – sleep duration' relationship is that more physical activity is related to longer sleep, which is observed in most of the scientific literature and **Chapter 2**. This is also reflected in the wider research base that more physical activity is related to better sleep. However, **Chapter 3** demonstrates that the connection between physical activity and sleep duration is more variable on a daily scale and thus the role of total sleep time as a mediator is more complex.

5.3.3 Sleep Onset Latency Mediation

The mediation in **Chapter 2** showed evidence in the total sample, and girls subsample, for sleep onset latency mediating the 'physical activity – mood' relationship. It was found that more physical activity in the evening was associated with a shorter sleep onset latency, which in turn was associated with better mood.

5.3.3.1 Physical Activity and Sleep Onset Latency

At the beginning of this thesis the expectation was that evening physical activity would be associated with longer SOL, due to the purported alerting effects of exercise (Bonnet & Arand, 1998, 2000, 2005; Silverman & Deuster, 2014; Wenger, 1995). It was anticipated that the circadian delaying effects of late-timed physical activity (Youngstedt et al., 2019) would be seen in a longer SOL. Instead, it was found that more physical activity after 6 p.m. was associated with a shorter SOL. Indeed, despite the alerting effects of evening physical activity, most research indicates that the effects of exercise on the body are not sufficient to disrupt sleep/increase SOL (Atkinson et al., 2007; Brand et al., 2014; Miller et al., 2020; Stutz et al., 2019). Of the more recent meta-analyses and reviews, some have found that physical activity does not have an impact on SOL (Atoui et al., 2021; Bartel et al., 2015; Stutz et al., 2019), and others have found that SOL was reduced after physical activity occurred during the day (Kredlow et al., 2015) and even in the evening (Chennaoui et al., 2015). Additionally, the common finding of research in adolescents is that physical activity during the day can result in a shorter SOL (Baldursdottir, Taehtinen, et al., 2017; Brand et al., 2009; Glavin et al., 2022; Lang et al., 2013) and **Chapter 2** suggests that physical activity after 6 p.m. has a similar beneficial outcome. It may be that 6 p.m. is not late enough to see a detrimental effect of physical activity on SOL, however some studies have indicated that even late physical activity might not affect SOL (Miller et al., 2020; Myllymäki et al., 2011) which infers that the idea of late physical activity being detrimental to sleep is outdated and incorrect.

5.3.3.2 Sleep Onset Latency, Repetitive Negative Thinking, and Mood

Regarding the ‘sleep – mood’ component of the mediation with physical activity, **Chapter 2** found that shorter SOL was associated with better mood. This relationship between SOL and mood has been seen previously in adolescents. Two meta-analyses (Augustinavicius et al., 2014; Lovato & Gradisar, 2014) and a review (Wilson et al., 2019) have shown that adolescents diagnosed with depression have a longer SOL. However, the results of **Chapter 2** go further than the connection of these two variables in adolescents, with the results highlighting *how* SOL is related to mood. Specifically, repetitive negative thinking (RNT) was found to moderate the connection between SOL and mood. Girls with lower levels of repetitive negative thinking had a stronger relationship between shorter SOL and better mood, indicating that *less* repetitive negative thinking occurs in girls with longer SOL and worse mood. This was not the anticipated outcome when the role of RNT was tested in this model. Repetitive negative thinking is typically associated with lower mood and worse sleep (Krause et al., 2017; Raes, 2012; Slavish & Graham-Engeland, 2015; Takano et al., 2014; Watkins & Roberts, 2020), and thus the expectation was that RNT would have a stronger relationship with longer SOL and lower mood **-** *not* shorter SOL and better mood. For example, in a large sample of 10,148 adolescents Palmer et al. (2018) found that adolescents with greater sleep problems are more likely to qualify for a mood disorder and report more rumination (a subtype of repetitive negative thinking (Ehring & Watkins, 2008)). Indeed, Palmer and colleagues found that sleep problems were associated with mood disorders through rumination. Huang et al. (2020) also found that RNT fully mediated the association between difficulty falling sleep and depressed mood in a group of adolescents. Yet still, **Chapter 2** found that less RNT occurred in girls with longer SOL and lower mood.

In addition to RNT being typically associated with lower mood, it is also generally linked with longer SOL. A 2020 meta-analysis noted that, across 16 studies, repetitive negative thinking (termed “perseverative cognition”) was associated with longer SOL (Clancy et al., 2020). Indeed, research in young adults has shown that the relationship between repetitive negative thinking and sleep quality is mediated by pre-sleep cognitive arousal (Yeh et al., 2015), and longer SOLs have also been connected with pre-sleep cognitive arousal in adolescent research (Maskevich et al., 2020). Much previous research has linked RNT with longer SOL and worse mood, although not in the same way in which they were connected in **Chapter 2**. Yet the significance of these relationships, although not in the expected direction, still reflects the interrelated nature of these variables.

5.3.4 Sex Differences

Across **Chapters 2**, **3**, and **4**, a notable difference emerged in the results between girls and boys. The mediations and relationships, particularly those involving mood, typically reached statistical significance for girls, but not for boys. This can be seen in **Chapter 2** where the mediation mechanisms (SOL, TST, and chronotype) were significant in the total sample and, when the sexes were analysed separately, in the girls but not in the boys. In **Chapter 3**, the study was conducted in a sample of 19 girls, and the two mediation mechanisms tested (TST and chronotype) were significant. Whereas in **Chapter 4**, a sample of 18 boys was used and the mediation mechanism (circadian rhythm timing) was non-significant.

When identifying where the difference arises in these relationships between girls and boys, mood appears to be indicated. In **Chapter 2** it appeared that the relationships for boys did not reach significance due to lower mood scores, and a smaller range in these mood scores than the girls (i.e., a floor effect). Similarly in **Chapter 4**, a sample of only boys, the mood measure was not significantly related to physical activity or sleep, further indicating mood differences between girls and boys.

A meta-analysis and a large scale population study in Iceland have shown that, across the globe, the gender difference in depression diagnosis and depression symptoms reaches its peak in adolescence, in that adolescent girls have a higher incidence of both than boys (Baldursdottir, Valdimarsdottir, et al., 2017; Salk et al., 2017). Adolescent girls have also been shown to have higher rates of sleep difficulties (Baker et al., 2020; Meers et al., 2019; Oyegbile, 2020). Consequently, it stands to reason that the ‘physical activity – sleep – mood’ relationship would be stronger in adolescent girls than boys if girls are more likely to experience low mood. In accordance with this, other adolescent studies have also found significant relationships between sleep and mood in girls, but not boys. For example, in a large sample of 3,071 adolescents, Conklin et al. (2018) found that cumulative sleep restriction was related to higher depression scores in girls at 6-12 month follow-up. The same was not true for boys, as their depression scores did not differ at different levels of cumulative sleep deprivation. van Zundert et al. (2015) also found that poor sleep quality had a stronger impact on negative affect in girls. Interestingly, this stronger ‘sleep – mood’ relationship was true in van Zundert’s study for girls *and* participants higher in depressive symptoms. Similar to the pattern observed in this thesis, the findings of these two studies both show that adolescent girls have a stronger relationship between sleep and mood than boys.

Interestingly, studies also show sex differences in adolescents’ physical activity participation. Multiple studies in this population have found that girls do less physical activity than boys (Baldursdottir, Valdimarsdottir, et al., 2017; Brand et al., 2017; Lang et al., 2013; Marques et al., 2014; Nader et al., 2008; Tambalis et al., 2019). Which may highlight a potential factor contributing to sleep and mood difficulties in adolescent girls. A study by Glavin and colleagues (2022) also found that undergraduate males participated in more physical activity than females. Furthermore, amongst the female participants greater exercise frequency was associated with both better sleep parameters (earlier bedtime, higher sleep quality) and better mood (more positive affect, less depressive affect). Further demonstrating the strong link between physical activity, sleep and mood in adolescent and young adult girls.

5.4 Theoretical Implications

5.4.1 Adolescent Sleep Theories

When considering which theories would be most appropriate to apply the findings of this research there are a few broad theories of adolescent sleep to be considered.

One of these broad theories of adolescent sleep is the ‘Perfect Storm’ model, initially presented by Carskadon (2011) and updated by Crowley et al. (2018). The Perfect Storm model describes how different elements of adolescents’ lives combine in such a way as to restrict adolescent sleep duration by pushing sleep onset later and wake time earlier. Adolescents’ later sleep times are driven by bioregulatory pressure (such as a slower accumulation of sleep pressure and circadian phase delay) and psychosocial pressure (such as increased bedtime autonomy, academic pressure, screen time, and social networking), which interact with each other and form a self-reinforcing cycle to exacerbate both of these pressures (Crowley et al., 2018). In addition to this late sleep onset time, adolescents are also pushed to wake up early by societal pressures, such as school start times. Taken together, these opposing directions of pressure constrict the time available for adolescents to sleep. Although the Perfect Storm model is largely focused on the factors leading to short sleep in adolescents, Carskadon and Crowley et al.’s papers both discuss how low mood and depression can be an unfortunate outcome of adolescent’s restricted sleep, although it is not featured in the diagrammatic representations of the model.

Another broad model of the unique sleep of adolescence comes from Becker et al. (2015). This model provides an overview of how adolescents’ development, biological factors, contextual factors, and psychosocial factors all impact each other, and additionally how these three broad factors all impact sleep and are impacted by sleep. The biological factors described in this model are similar to the bioregulatory pressures from the Perfect Storm model (e.g., including elements of Borbély et al.’s (2016) two-process model of sleep pressure) but is even broader by also including adolescents’ evening preference, sleep architecture changes, and the health effects of more versus less sleep. The psychosocial factors of Becker et al.’s model include family, peer, academic, and mental health (mood and depression). The contextual factors include electronic media use, homework, employment, extracurricular activities, school start times, neighbourhood and community factors, and cultural factors. When considering the theoretical implications of this thesis’ findings, Becker et al.’s model includes, in a broad sense, the physical activity, sleep, and mood elements tested throughout this thesis, as these are encapsulated by the biological/contextual (physical activity), sleep, and psychosocial (mood) components of the model.

Both Becker et al.'s model and The Perfect Storm are broad overviews, and they provide a wider context to the multitude of factors which impact adolescent sleep. In both models, physical activity and mood are one small part of a larger factor and not an individualised factor of their own. This broad view presented by the models allows them to serve as a backdrop to other models that approach each variable with a more detailed perspective to explore the finer aspects of different relationships. Including such detail in broader models of adolescent sleep may overwhelm the model, and thus it was deemed unfitting to apply the findings of this thesis to either Becker et al.'s model or The Perfect Storm.

5.4.2 Sleep and Mood Theories

The finer detail of the connection between sleep and depression in adolescents has been described in a conceptual model by Lovato and Gradisar (2014). This model links how elements related to puberty, like decreased SWS, decreased TST, circadian delay, and evening arousal, can lead to poor sleep in adolescents. The model shows how this poor sleep, typified by elements of increased arousal, such as increased SOL, increased WASO, and decreased self-reported sleep quality, can lead to depression via rumination. A cycle then begins between depression, rumination, and poor sleep, in which they exacerbate each other. The model provides a detailed view of the link between sleep and mood, and the cognitive pathway in which they can affect each other, including rumination (similar to the repetitive negative thinking assessed in **Chapter 2**). However, the model does not include elements leading to adolescents' poor sleep, other than the consequences of puberty directly on sleep (e.g., circadian delay), and therefore the model does not include physical activity. Due to the model's focus on the pathway between sleep and mood, it is difficult to incorporate the role of physical activity and its effect on sleep and mood.

Watling et al. (2017) has also proposed a broad model of sleep and mood. This model notes the bidirectional relationship between sleep and mood, with sleep and mood both being connected directly to each other (i.e., without a mediator). The model also illustrates how sleep is connected to emotion and emotion regulation. So, in addition to the direct connections between sleep and mood, sleep is linked to emotion which also links to mood. This relationship between emotion and mood is acted upon by emotion regulation. The model essentially maps three different types of connections, the bidirectional relationship between sleep and mood, the stepping stones of sleep to emotion to mood, and the effect of sleep on emotion regulation which acts upon the relationship between emotion and mood. Unlike the previous three models discussed, Watling et al.'s model of the 'sleep – mood' connection is not made exclusively for adolescents, however it is certainly applicable to this population. Watling et al.'s model focuses largely on the emotion and mood elements of the model, and the sleep portion of the model refers to "poor sleep" in general, not the finer aspects of sleep, such as SOL and sleep timing. The model is largely built upon sleep duration and the effects of considerable sleep restriction, and as such the model does not include a detailed representation of the different ways in which sleep can be affected by other factors. This lack of detail in the sleep factor, in addition to the absence of physical activity in the model, again makes it difficult to incorporate the findings of the current thesis without introducing major changes and shifting the focus of the model.

5.4.3 Physical Activity and Sleep Theories

On the other side of the mediation model is the connection between physical activity and sleep. Research into this relationship has seen a number of stand out papers in recent years, covering the associations in adolescents and young adults (Lang et al., 2016; Memon et al., 2021), on a daily basis (Atoui et al., 2021), acute and regular exercise in relation to discrete sleep outcomes such as SOL and TST (Kredlow et al., 2015), and even a meta-review of reviews (Kline et al., 2021). However, at this stage the majority of reviews have not taken the step to provide a theoretical framework for the connections in this relationship. As such, during research for this thesis, only one theoretical framework was identified that detailed the relationship between physical activity and sleep. This model, developed by Chennaoui and colleagues (2015), is based on a summary of the available information of the impact of physical activity on sleep.

5.4.4 Chennaoui et al.'s Theory

Chennaoui et al.'s (2015) model (see Figure 1 of their review paper "Sleep and exercise: A reciprocal issue") includes not only physical activity and sleep but also mood. Chennaoui et al.'s review of the relationship between physical activity and sleep synthesised research findings from across the lifespan to cover the many possible ways in which moderate intensity physical activity might impact sleep. In the review, Chennaoui and colleagues mention that the impacts of these factors included in the model may vary due to individual characteristics (sex, age, fitness level, and presence of sleep difficulties), and elements of the physical activity itself (frequency, duration, type, timing, intensity, environment).

Chennaoui et al.'s model depicts a number of pathways in which acute and regular moderate intensity aerobic physical activity increase total sleep time and even slow wave sleep. Unlike the previous models discussed, Chennaoui et al.'s model includes all three main elements of the relationships in this thesis, physical activity, sleep, and mood. The model is also cyclical, in that improved sleep is linked back to participation in physical activity via mood. There are multiple pathways included in the model to link physical activity to sleep, and one of these pathways is supported by the results of this thesis. Chennaoui et al. modelled a probable link from regular physical activity to sleep changes via alterations to the circadian rhythm and melatonin. The results of **Chapter 4** endorse this, as 5 mornings of aerobic physical activity advanced the timing of dim light melatonin onset.

Yet, Chennaoui et al.'s model does not include some important elements of the 'physical activity – sleep – mood' mediation. Chennaoui et al.'s model includes changes to sleep duration and slow wave sleep as outcomes of physical activity participation, but not relationships with sleep onset latency nor sleep timing. The bidirectional aspects of the relationships between physical activity, sleep, and mood, are present in this model, although this presence is somewhat obscured. Mood is included in the model twice, where participation in physical activity not only leads to a change in mood, mood also influences physical activity participation itself. This illustrates the bidirectional nature of the relationship between physical activity and mood. Although the relationship between physical activity and sleep is not explicitly shown as bidirectional, physical activity is shown to impact sleep, and sleep in turn is shown to impact physical activity, albeit via mood. The model also approaches the subject matter from a biological perspective and therefore does not include the cognitive elements of these relationships, such as the potential role of repetitive negative thinking in the relationship between sleep and mood.

5.4.5 A New Model?

In order to clearly illustrate the multiple ways sleep was found to mediate physical activity and mood, and to make clear the multi-directional nature of these relationships, it was deemed appropriate to generate a new model. This model, seen in Figure 5.1, depicts the multiple bidirectional relationships between physical activity, sleep, and mood, and how this thesis found that sleep acts as a mediator between physical activity and mood in three different ways. Figure 5.1 shows how participation in physical activity can elicit changes in sleep latency (SOL), sleep timing (chronotype/circadian rhythm), and total sleep time, and how these three changes in sleep are linked to changes in mood. It also includes the bidirectional relationship between physical activity and mood (Annesi et al., 2017; Bourke et al., 2021; Pascoe & Parker, 2019) (although this was not tested in this thesis).

5.4.5.1 Sleep as a Mediator

The model depicts how more physical activity is linked with reduced sleep latency, which is linked with better mood, and this relationship between SOL and mood is moderated by repetitive negative thinking. Although these relationships were significant the causal directions of these relationships were not able to be tested as they were ascertained through cross-sectional data, therefore they are represented with dotted lines.

The model also shows that more physical activity is related to changes in sleep timing (chronotype/circadian rhythm). In this thesis physical activity was consistently related to earlier sleep timing, which was in turn related to better mood. As the connections between physical activity, sleep timing, and mood were tested in three chapters of this thesis the lines connecting these components are thicker than those in the rest of the model, as these findings are more robust.

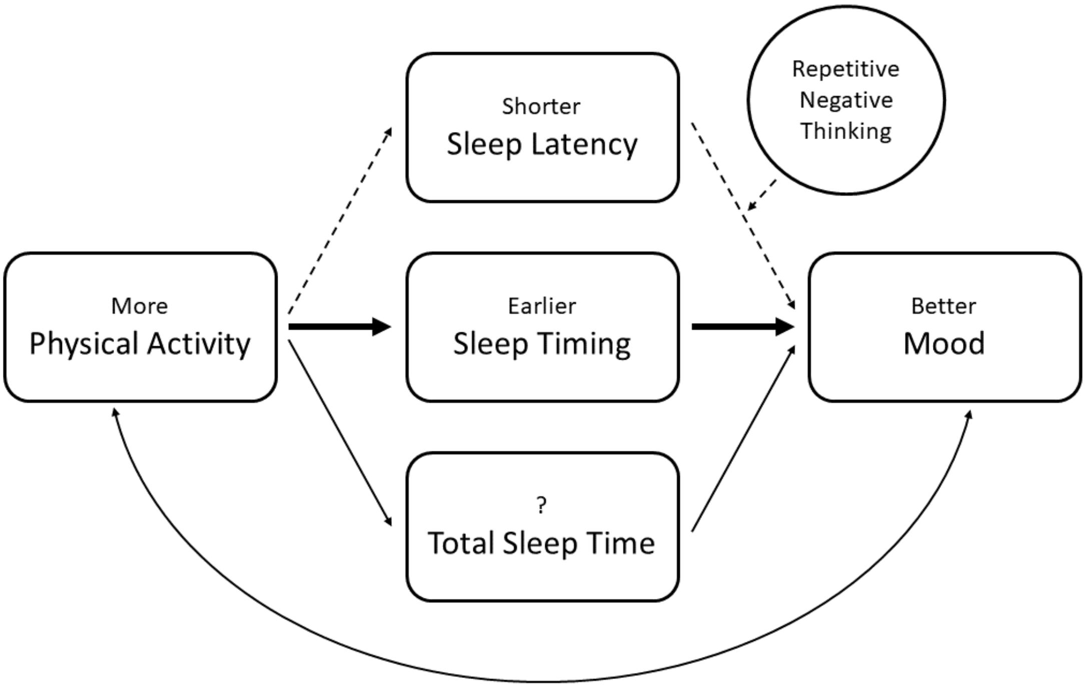
Last of the three mediations, the model shows that more physical activity is related to changes in total sleep time, and that changes in total sleep time are related to changes in mood. **Chapters 2** and **3** had differing results on the direction of the relationship between physical activity and TST, however they both found evidence to support the mediation.

5.4.5.2 Benefits

There are some potential advantages to the use of this proposed model. Firstly, the model is uncomplicated, making it easily testable for future research. The connections to and from the three sleep components of the model are clear and the simplicity of the model will readily allow the addition of extra detail. For example, incorporation of how individual characteristics and variability in physical activity (e.g., intensity, duration, frequency, type) change the relationships. The clear and simple nature of the model may also make it easier for non-scientific professionals and lay people to understand the connections between physical activity, sleep timing, and mood. Thus allowing this knowledge to be translated into everyday practice more quickly and easily. In a similar way, the straightforward connections between the different components of the model will make it easier for this knowledge to inform the clinical application of physical activity participation for sleep and mood.

Figure 5.1

Model of the Mediating Role of Sleep Between Physical Activity and Mood



Note. Dotted lines represent suggested links from cross-sectional data. Thick lines represent more robust findings.

5.5 Clinical Implications

5.5.1 Physical Activity is Beneficial to Sleep (At Any Time of Day)

For all three aspects of sleep there was evidence that physical activity improved sleep in addition to improving mood. More physical activity was related to earlier sleep timing (chronotype and circadian rhythm) in **Chapters 2**, **3**, and **4**, and it was related to more TST and shorter SOL in **Chapter 2**. Literature proximal to this area shows that physical activity benefits sleep in numerous ways. This benefit is not only limited to sleep timing, TST, and SOL as explored by this thesis. A number of studies have found that adolescents and young adults who engage in more hours of physical activity per week have more deep sleep and less time awake during the night (Baldursdottir, Taehtinen, et al., 2017; Brand et al., 2010a, 2010b; Brand et al., 2014; Kalak et al., 2012; Lang et al., 2013). The benefits that physical activity can have on multiple aspects of sleep increases the potential for physical activity to be used as a prevention and/or intervention strategy for adolescents' sleep problems. The benefits of physical activity on sleep and mood also make it a worthy consideration for clinicians, particularly as an adjunct treatment for adolescents with sleep and mood difficulties.

It was a consistent finding in all three studies in this thesis, that more physical activity was associated with earlier chronotype or circadian rhythm timing. This is a salient point for clinicians of adolescents, particularly clinicians of clients with Delayed Sleep-Wake Phase Disorder (DSWPD). DSWPD is a disorder characterised by having very delayed sleep timing, such that it has a strong negative impact on one's life (American Academy of Sleep Medicine, 2014). Treatment of DSWPD typically involves the use of bright light therapy (Bjorvatn & Pallesen, 2009; Gradisar et al., 2014). The response of the circadian rhythm to physical activity suggests that it could be used as an adjunct treatment to bright light administration. Physical activity could even be considered as a treatment option for adolescents who report light sensitivity. Additionally, the presence of a period of time in the circadian afternoon in which physical activity can elicit a phase advance (1-4 p.m. (Youngstedt et al., 2019)), presents an alternative option for adolescents that do not find it possible to wake early enough in the morning for bright light administration. Physical activity could be used to augment other first-line treatments of DSWPD in adolescents to assist with their circadian phase advance.

Further to this point, evening physical activity was associated with earlier chronotype, indicating that evening physical activity should not be discouraged. There has been a pervasive sleep hygiene message to avoid physical activity in the evening due to its' effect on sleep (Bains, 2021; Breus, 2022; Centre for Clinical Interventions, 2019; HT Correspondent, 2018; Kaur & Bhoday, 2017; timesofindia.com, 2021). Yet, the findings of this thesis and two reviews have indicated that evening physical activity is not harmful to sleep (Chennaoui et al., 2015; Stutz et al., 2019). Indeed, those with a late chronotype find physical activity more exerting when undertaken in the morning (Bonato et al., 2017; Vitale & Weydahl, 2017), and therefore it is possible that many adolescents would prefer to participate in physical activity during the evening.

The practicalities of an adolescent's day may make it difficult to find time to exercise. For some adolescents waking up in time for school is a Herculean effort, particularly those that would be targeted by a treatment to push the circadian rhythm earlier. Therefore, encouraging many of these adolescents to engage in physical activity in the morning before school would likely be challenging and thus ineffective. After the morning, the next period in an adolescent's day is during school hours for 5 days of the week, which eliminates this as a regular option. Next comes the period of time after school during which many adolescents participate in extra-curricular activities after school. These activities may preclude this time from being available for the physical activity intervention, although this time period may be an option for a student with less activities on their calendar. Consequently, once it is assumed that at this stage in the day an adolescent would need to eat dinner before being able to participate in physical activity, it appears one of the only times left in the day is during the evening. For this reason, it is fortuitous that evening physical activity is largely proving not to be detrimental to sleep. This time of day is also possibly more desirable to adolescents, as late chronotypes not only do less physical activity than earlier chronotypes (Kauderer & Randler, 2013; Merikanto et al., 2020; Olds et al., 2011; Schaal et al., 2010; Urbán et al., 2011; Wennman et al.,

2015) they also often find morning physical activity more exerting than exercise in the evening (Bonato et al., 2017; Vitale & Weydahl, 2017). The finding that physical activity is beneficial to sleep regardless of the time it is undertaken is a promising development for the adolescents seeking treatment for DSWPD.

5.5.2 Activity as an Adjunct for Treatments for Sleep Timing Delays

Throughout this thesis there was a reasonably consistent link found, using a diverse range of study designs and measures, that more physical activity was associated with earlier sleep timing. These connections to earlier sleep timing are valuable information for a population prone to later chronotypes (Roenneberg et al., 2004), and the mood difficulties typically associated with late chronotypes (Au & Reece, 2017; Gariépy et al., 2019; Haraden et al., 2019; Müller & Haag, 2018). This relatively stable link between physical activity, sleep timing, and mood provides the opportunity to consider prevention and treatment options for adolescents with late sleep timing.

Delayed sleep timing has a number of contributing factors so it is no surprise that there exist several evidence-based options to advance sleep timing. For each of these, the feasibility of using adjunct physical activity varies. For example, one existing strategy for fostering earlier sleep timing in adolescents is the use of parent-set bedtimes. Parent-set bedtimes are associated with a number of improved sleep parameters including earlier bedtimes (Khor et al., 2021; Randler et al., 2009; Short et al., 2011). Further establishing the link between earlier sleep timing (bedtimes) with better mood, one large scale study of 15,659 adolescents found that earlier bedtimes reduced the likelihood of depression and suicidal ideation (Gangwisch et al., 2010). Parent-set bedtimes is a relatively simple strategy, thus adding morning physical activity (e.g., walking to school) should not overly burden adolescents who are receptive to physical activity at this time of day. In addition to the benefits of parent-set bedtimes for moving adolescent sleep timing earlier, some studies have tested more comprehensive prevention strategies and interventions.

A number of school-based programs have been trialled and found to be beneficial for adolescent sleep parameters, including earlier bedtimes and waketimes. The programs vary widely, ranging from a single 45-minute education session followed by 2 weeks of self-directed targeting of a sleep promoting behaviour (Tamura & Tanaka, 2016), to a 12-session Sleep Smart program (Wolfson et al., 2015), a 6-week mindfulness intervention (Bei et al., 2013), and a 3-session intervention (Wing et al., 2015). All programs found that bedtimes became earlier over the intervention (Bei et al., 2013), or the intervention group had an earlier bedtime than the control group at the end of treatment (Tamura & Tanaka, 2016; Wing et al., 2015; Wolfson et al., 2015). These multi-component programs teach adolescents an array of healthy sleep practices to benefit their sleep. The addition of education about the mechanisms and benefits of physical activity, including the development of a plan, would not take much extra class time in these programs. Whether this education turns into actual behaviour change though is where the challenge would lie (Cassoff et al., 2013).

Interventions at the clinical level have also addressed late sleep timing in adolescents seeking individual professional treatment. One such intervention is Transdiagnostic Sleep and Circadian Intervention (TranS-C) developed by Harvey and Buysse (2017). This intervention includes core and optional treatment components for the treatment of sleep problems. TranS-C has been found to be an effective multi-component treatment for adolescents with a late chronotype to move their sleep timing earlier (Harvey et al., 2018). Considering the propensity for physical activity to also move sleep timing earlier, it could be used as an adjunct in TranS-C as an optional treatment component. As mentioned previously, another treatment option for the clinical treatment of DSWPD, characterised by clinically delayed sleep timing, is light therapy (Bjorvatn & Pallesen, 2009; Gradisar et al., 2014). Richardson and colleagues have assessed the phase advancing effects of morning bright light therapy (Richardson & Gradisar, 2022), and morning bright light therapy in conjunction with morning physical activity (Richardson et al., 2018). In both studies, by post-treatment and follow-up, the adolescents' sleep onset and wake up times had advanced. However in the study utilising physical activity there was no objective evidence (from wrist actigraphy) that adolescents complied with physical activity instructions. Further supporting the concept that simply informing adolescents of the benefits of physical activity may not be sufficient to result in actual behaviour change. Nonetheless, physical activity shows promise as a practice that can be used to help adolescents maintain an earlier sleep timing and supplement other techniques working towards this goal.

5.5.3 The Struggles of Adolescent Girls

The findings of this thesis indicate that there are sex differences in the 'physical activity – sleep – mood' connection. These relationships were strongest for girls (**Chapter 2** and **Chapter 3**) as the mood measures did not reach significance for the boys (**Chapter 2** and **Chapter 4**). The finding that these relationships are stronger in girls is informative when determining target populations for research in this area, and for the most effective implementation of interventions. Although this is certainly not to say that adolescent males should not be considered. Nonetheless in the face of distinct sex differences, and the broad applicability of these relationships to the majority of adolescent girls as a large overarching group, but not to the majority of adolescent boys, consideration of how these relationships can be used to benefit this large group warrants some focus.

As discussed in the previous section, prevention strategies and interventions have been successfully applied to adolescents irrespective of sex, and physical activity offers an additional technique that could be used to push sleep timing earlier. The links between more physical activity, better sleep and mood are interesting to note when considered side-by-side with the fact that adolescent girls do less physical activity (Baldursdottir, Valdimarsdottir, et al., 2017; Brand et al., 2017; Lang et al., 2013; Marques et al., 2014; Nader et al., 2008; Tambalis et al., 2019), have been reported to experience more sleep problems (Baker et al., 2020; Meers et al., 2019; Oyegbile, 2020), and often report lower mood (Baldursdottir, Valdimarsdottir, et al., 2017; Salk et al., 2017) compared to boys of the same age. The potential offered by physical activity for adolescent girls is promising. These close relationships indicate that targeting girls' physical activity directly may improve sleep and mood outcomes. It is even possible that the general promotion of girls' sport, even without attention to sleep and mood, could nevertheless have beneficial outcomes for sleep and mood in this group.

Chapter 2 indicated that physical activity was associated with reduced sleep onset latency in girls. Girls who participated in more physical activity after 6 p.m. had a shorter SOL than those who participated in less. Long sleep onset latencies are not uncommon in adolescents (Gradisar et al., 2011; Short, Gradisar, Gill, et al., 2013; Short, Gradisar, Lack, et al., 2013) and there has been some progress towards developing methods to reduce long SOLs in affected adolescents. Bartel et al. (2018) found that a mindfulness intervention was successful at reducing SOL time for those adolescents with a SOL longer than 30 minutes. Similarly, some of the previously mentioned school-based treatments which were successful for advancing sleep timing were also successful at reducing SOL (Bei et al., 2013; Tamura & Tanaka, 2016). The connection between physical activity and SOL in **Chapter 2** indicates the potential for physical activity to be a useful addition to treatments targeting long SOL, particularly in cohorts of adolescent girls.

5.6 Limitations and Future Directions

Whilst three different mediation models were tested with three different research designs, further research is still needed into the different aspects of sleep which mediate physical activity and mood. For instance, as sleep onset latency was only assessed in this thesis through the cross-sectional design in **Chapter 2**, it is important that the role of SOL as a mediator between physical activity and mood is tested using a design that can confirm causality. At this stage the results only show that the correlations match what would be expected from causal results. Also, due to the large sample, objective measurements were not practical. Thus, further clarification of this relationship is needed using objective measures of physical activity and sleep and a causal design.

More investigation is also needed into the daily relationships between TST and mood. **Chapter 3** found that, despite an overall pattern for less TST to be associated with lower negative affect, this relationship was intermittent and the direction of the relationship, towards better or worse mood, was not completely consistent. The mixed results of this study require more research to witness any replication of these intermittent findings, or whether they were random in nature.

Finally, there would be value to further confirmation of the role of sleep timing as a mediator between physical activity and mood in adolescents. Not simply to increase data in this under-researched area with this unique population, but also to inform development of physical activity interventions to assist with adolescents' often delayed sleep timing and mood difficulties.

An important aspect of future studies would also be the use of a female sample. As the relationships between physical activity, sleep, and mood are stronger in adolescent girls compared to boys, it would be beneficial to focus on how these relationships could be used in a way to alleviate girls' sleep and mood difficulties. Then, once the dynamics of the relationships between physical activity, sleep, and mood are understood in adolescent girls, these relationships from this bigger overall group could be verified in those adolescent boys who would be responsive to physical activity interventions.

Future research in the area of the links between physical activity, sleep, and mood in adolescents could take numerous forms. Further investigation of the relationship between late physical activity and sleep timing would be beneficial. The results of **Chapter 4** corresponded with Youngstedt et al.'s phase response curve (2019), morning physical activity resulted in a circadian phase advance, measured by DLMO. However, the results of **Chapters 2** and **3** did not match the phase response curve, as late physical activity was *also* associated with earlier sleep timing through early chronotype (measured by questionnaire and actigraphy in **Chapters 2** and **3** respectively). Thomas et al. (2020) and Vitale et al. (2017) found that the response to evening physical activity of the adults and young adults used in their studies differed according to chronotype. In both studies the response of participants with an early chronotype corresponded to the phase response curve (evening physical activity caused a circadian phase delay), and those with a late chronotype did not (evening physical activity caused a phase advance). It is important to check in an adolescent population for this differing relationship between chronotypes and evening physical activity, as late sleep timing is often seen in adolescents and therefore this is one of the populations in which the treatment would be applied. Due to the unique components of adolescent sleep, including their tendency for late chronotypes and sleep timing, it would be informative to establish if this relationship difference is also relevant to this population as it could inform the timing recommended for physical activity participation.

It would be important for the timing of physical activity to be aligned with each adolescent's individual circadian timing. This is to ensure that any difference in reaction is indeed due to a difference in chronotype and not the misalignment of clock time with circadian rhythm timing. The phase response curve described by Youngstedt et al. (2019) refers to the circadian rhythm timing of physical activity. It is possible that an adolescent with a late chronotype could participate in "evening" exercise at a late clock time, but that this may not occur at an evening time according to that individual's intrinsic circadian clock. For example, the phase response curve indicates that physical activity at 7 p.m. results in a circadian delay, but physical activity at 3 p.m. results in an advance. If an adolescent's sleep timing is 4 hours delayed, then physical activity occurring at a clock time of 7 p.m. would in fact be occurring at the circadian timing of 3 p.m. Which the phase response curve suggests would result in a phase advance and not a delay. Thus, it is important to determine if this difference in response to evening physical activity (Thomas et al., 2020; Vitale et al., 2017) is indeed due to the influence of chronotype or due to a misalignment of the circadian rhythm with clock time. Determining the source of this difference would inform the timing recommendations for adolescents to use physical activity interventions to assist with sleep timing.

Finally, a new study could also look at the involvement of repetitive negative thinking (RNT) in the sleep and mood relationship. **Chapter 2** of this thesis was the only section in which the role of RNT could be examined. The results supported the involvement of RNT in the relationship between SOL and mood. The cross-sectional data fit a moderated model such that RNT moderated the relationship between SOL and mood for the adolescent girls. But further study is needed to confirm this relationship, as the cross-sectional data cannot confirm causality of the model and the relationship did not go in the predicted direction. Less RNT occurred in girls with longer SOL and lower mood, and more occurred in those with shorter SOL and better mood. This is not the direction of relationship that was predicted, nor what prior research would suggest. As rumination and repetitive thinking are typically associated with longer SOL and worse mood (Clancy et al., 2020; Krause et al., 2017; Raes, 2012; Slavish & Graham-Engeland, 2015; Watkins & Roberts, 2020).

The assumption to be tested in such a study would be whether physical activity can limit adolescents' repetitive negative thinking during the time before sleep by reducing SOL, thereby reducing the opportunity for RNT. Furthermore, would this reduction in RNT result in an improvement in mood. Previous research in this area trialled the impact of 3 weeks of bright light therapy in a sample of 60 adolescents with DSWPD (Richardson et al., 2019). Prior to the intervention the adolescents with DSWPD had more RNT and longer SOLs than the comparison group of 40 good sleeping adolescents. Treatment of the adolescents with DSWPD with the light therapy reduced SOL and pushed sleep onset time earlier. Additionally, over the course of treatment the DSWPD adolescents' level of RNT reduced with the reduced SOL time. It remains to be seen whether a comparable response would be observed in adolescents from a non-clinical population.

5.7 Conclusion

Having reached the threshold of adulthood, adolescence is a time of dynamic changes in a person's life. From increasing independence, to experiencing many things for the first time, adolescents undergo many changes. Moreover, there are also many biological changes that occur through puberty, including characteristic changes in sleep that are unique to this life stage. These changes in sleep, most strongly distinguished by a delay in circadian rhythm timing, can culminate in sleep difficulties when in conjunction with societal and psychosocial factors, the process of which is largely described in Carskadon and Crowley et al.'s Perfect Storm model (2018). Sleep difficulties can also be accompanied by mood problems (Clarke & Harvey, 2012; Scott et al., 2021; Shochat et al., 2014). Both of which can take their toll, causing numerous negative consequences (Clayborne et al., 2019; Goldstein & Franzen, 2020; Shochat et al., 2014; Wickersham et al., 2021). Although adolescents and their sleep have received less research attention than adults and children, they have not been overlooked by research exploring interventions to assist with sleep problems. The unique sleep problems of adolescents have been targeted as the focus of research into treatments using CBT, light therapy, and melatonin (Blake et al., 2017; Danielsson et al., 2016, 2018; Saxvig et al., 2014; Wilhelmsen-Langeland et al., 2013). The close connections between physical activity, sleep, and mood (Bisson, 2021; Brand et al., 2010a; Raudsepp & Vink, 2019; Stubbs et al., 2018) offer the possibility that physical activity may be a lifestyle change that could help teenagers with sleep *and* mood difficulties.

This thesis used different research designs and a range of measures to test the relationships between physical activity, sleep, and mood in different adolescent cohorts. Physical activity participation was found to be consistently associated with earlier sleep timing. Sleep timing acted as a mediator in three studies (**Chapters 2**, **3**, and **4**). Total sleep time acted as a mediator in **Chapters 2** and **3**, and sleep onset latency confirmed expectations by also mediating the relationship between physical activity and mood in **Chapter 2**. A pattern in the results between the three studies of **Chapters 2**, **3**, and **4** noted apparent sex differences. The sleep variables acted as a mediator between physical activity and mood for adolescent girls but not for boys. This presents the opportunity to develop physical activity interventions for this wider population, in addition to offering such interventions to the select population of boys who also exhibit this relationship.

The next step is to develop practical and achievable physical activity interventions for this age group, an age group that may be reluctant to participate in physical activity, particularly at certain times of day (e.g., morning) (Bonato et al., 2017; Kauderer & Randler, 2013; Merikanto et al., 2020; Schaal et al., 2010; Urbán et al., 2011; Vitale & Weydahl, 2017; Wennman et al., 2015). In order to inform the development of these interventions it will be important to investigate the role of chronotype in the relationship between physical activity and mood. If chronotype impacts adolescents' circadian response to evening physical activity this will be instructive in the improvement of recommendations for physical activity timing for adolescents.

This thesis found that sleep is one of the mechanisms linking physical activity and mood in adolescents, and three ways in which this links occurs is through sleep timing, total sleep time, and sleep onset latency. Due to the ways in which physical activity, sleep, and mood are linked, physical activity has the potential to be used to combat sleep and mood problems in this vulnerable population. Implementing physical activity, either broadly in a school setting or in a specialised clinical setting, holds promise as a two-pronged approach to improving sleep and emotional health in adolescents.

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