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LIFESTYLE, COPING, AND PSYCHOPATHOLOGY SYMPTOMS IN GENERAL POPULATION ADOLESCENTS

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Abbreviations

BSI = Brief Symptom Inventory

CI = confidence interval

ESM = Experience Sampling Method

PA = physical activity

LPA = light physical activity

MVPA = moderate-vigorous physical activity

MSPE = Mean Squared Prediction Error

SD = standard deviation

SE = standard error

WHO = World Health Organisation

Author statement

This thesis is a compilation of research articles, which are all published or under review for publication in different research outlets. As each chapter is an individual research study using similar datasets, there are some unavoidable repetitions in some sections of the chapters. Reference lists for a single chapter are presented at the end of each chapter and a reference list for other sections of this doctoral dissertation is provided at the end of the thesis. Throughout the thesis, the term ‘we’ is consistently been used to reflect the collaborative work of all co-authors. The doctoral candidate has been responsible for the acquisition of data, drafting of the research manuscripts, statistical analysis, and interpretation of results included in the dissertation. Supervisors, co-supervisors, and co-authors have provided feedback and study supervision in all stages of the research.

Summary

Lifestyle factors, such as physical activity, sedentary behaviour, diet, tobacco smoking, and sleep, may represent a risk factor, subthreshold symptom, inherent part of, or consequence of psychopathology symptoms. Due to the scope of the SIGMA study, this PhD research project focuses on the lifestyle factors physical activity and sleep.

In the *first chapter*, we situate the study of *early* lifestyle – psychopathology relationship in the period of adolescence, as it represents the emerging phase of first psychopathology symptoms. We further elaborate on the relationships' State of the Art, but also their gaps and limitations within the *second chapter*. We summarize that, firstly, current evidence on the relationship is inconclusive and mainly based on less reliable, subjective data, whereas objective data studies are lacking. Secondly, it is unclear which correlates of sleep quality exist, and if coping relates to sleep quality in youth. We conclude that if we better understand the associations between coping and sleep quality, and which psychological mechanisms may explain such a potential relationship, it may provide opportunities of early intervention. Therefore, this doctoral thesis includes three empirical studies investigating early associations between both lifestyle and psychopathology, and coping and sleep quality.

In the *third chapter*, we explore within an observational study if a cross-sectional relationship exists between objectively measured light physical activity, moderate-vigorous physical activity, and symptoms of general psychopathology, depression, anxiety, and psychosis in general population adolescents. Additionally, we are interested to understand the *nature* of this potential relationship – if it is either linear, where more physical activity consistently relates to fewer symptoms of psychopathology, or non-linear, where a certain minimum amount of physical activity is needed until effects on psychopathology symptoms emerge. Our findings of the selected linear model do not suggest a linear relationship between objectively measured light and moderate-vigorous physical activity and symptoms of psychopathology.

In the *fourth chapter*, we investigate in an observational study the potential non-linear, cross-sectional relationship between objectively measured sleep duration, sleep quality, and symptoms of general psychopathology, depression, anxiety, and psychosis. Our findings do not provide evidence that sleep duration relates to fewer symptoms of psychopathology in adolescents. Further, our results do not suggest that compliance with sleep duration guidelines is related to fewer symptoms of psychopathology. Counterintuitively, we find that objectively

measured sleep quality relates to more symptoms of depression, psychosis, and general psychopathology, whereas associations with anxiety remain non-significant.

In the *fifth chapter*, we examine in an observational study if coping is cross-sectionally linked with subjective sleep quality when measured in daily life. Our results provide evidence for negative associations between 'passive reaction' coping, 'emotion-focused' coping, disengagement coping and subjective sleep quality in youth. Our suggested hypothesis that locus of control may represent a mediating factor of the relationship is not confirmed.

In the *sixth chapter*, we discuss the outcomes of this PhD project, highlighting that research on lifestyle and psychopathology currently stands at a cross-road. Our findings challenge the current, mainly subjective data literature by showing that findings on the lifestyle – psychopathology relationship are not robust when lifestyle is measured with objective measures. Potentially, our diverging findings suggest that subjective and objective measures capture different concepts of lifestyle. Within our discussion, we provide an extensive interpretation and potential explanation of these findings.

We conclude that this PhD project invites researchers to carefully re-investigate the previous assumption that lifestyle represents a protective factor in the early stages of psychopathology. Novel research approaches, which combine both subjective and objective measures, may add value to understand the lifestyle-psychopathology relationship. Our findings regarding the coping – sleep quality relationship suggest that in order to improve sleep quality, efforts should be directed at reducing disengagement and emotion-focused coping in youth, yet longitudinal studies are needed to support this conclusion. We suggest that interventions directed at short-term distraction from and acceptance of acute stressors might provide alternative coping strategies in those youth high in disengagement and emotion-focused coping.

Chapter 1 - General introduction

1. Mental health in adolescence

Approximately half of mental health disorders begin during adolescence (Solmi et al., 2021). Mental health disorders are characterized by significant cognitive, emotional, or behavioural disturbances, leading to impairment at the social or occupational level. Dysfunctional psychological, biological or developmental processes may underlie mental disorders (American Psychiatric Association, 2013). Worldwide, it is estimated that about one in seven adolescents (14%) aged 10-19 years old has a diagnosed mental disorder (Global Health Data Exchange, 2019). Emotional disorders are the most common in adolescence, including anxiety (5%) and depression (2%), followed by behavioural disorders, such as Attention Deficit Hyperactivity Disorder (ADHD) (2.5%), eating disorders, and disorders including psychotic symptoms (Global Health Data Exchange, 2019).

Before individuals reach the threshold of meeting the diagnostic criteria for a mental disorder, individuals can experience a broad range of general sub-threshold psychopathology symptoms, such as low mood, psychotic experiences, or obsessive thoughts (McGorry et al., 2018; Van Os, 2013). These early symptoms, experienced by one in four adolescents (S. A. Silva et al., 2020), may be either transient - and resolve as a part of normal development (Grootendorst-van Mil et al., 2021) - or persist and precede mental health disorders (Solmi et al., 2021).

Whether general, individual psychopathology symptoms develop into mental disorders depends on several factors, such as duration, intensity (Patton et al., 2014), interaction between symptoms, and context (Myin-Germeys et al., 2018; Van Os, 2013). However, which factors are relevant in early adolescence and how they relate to future mental disorder onset, remains partially unclear (Dalgleish et al., 2020; Fusar-Poli et al., 2019; McGorry et al., 2018). Therefore, it is crucial for research on the early stages of psychopathology to consider a diverse array of symptoms (i.e. general psychopathology) (Hartmann et al., 2021; McGorry et al., 2018). Understanding which factors are relevant for later psychopathology development would allow us to intervene early (Evans et al., 2021; Hartmann et al., 2021; McGorry et al., 2018), and prevent the functional impairment (Asselmann et al., 2018) and mortality associated with mental health disorders in youth (Gore et al., 2011) and adulthood (Rehm & Shield, 2019).

2. How does lifestyle relate to mental health during adolescence?

An individual's lifestyle could represent a risk factor, sub-threshold symptom (Hartmann et al., 2021; McGorry et al., 2018), inherent part, or a consequence of psychopathology (**Fig. 1**). Indeed, all of these are possible, yet current evidence is inconclusive. 'Lifestyle' is an umbrella term for several health-related behaviours and includes, but is not limited to, physical activity, sedentary behaviour, tobacco smoking, diet, and sleep (Firth et al., 2020). This PhD research project focuses on physical activity and sleep since more lifestyle facets would have been beyond the practical scope of the SIGMA study. Physical activity is technically defined as 'any bodily movement produced by skeletal muscles that results in energy expenditure' (p.126) (Caspersen et al., 1985), and holistically as 'moving, acting and performing within culturally specific spaces and contexts, and influenced by a unique array of interests, emotions, ideas, instructions and relationships' (Piggin, 2020).

Sedentary behaviour is defined as 'any waking behaviour characterized by an energy expenditure ≤1.5 metabolic equivalents (METs), while in a sitting, reclining or lying posture' (Sedentary Behavior Research Network, 2021). METs are an indicator of required energy for a physical activity related to the basic metabolic functioning of the body at rest (Jetté et al., 1990). Adequate sleep refers to age-specific sleep duration needs (Hirshkowitz et al., 2015), while good sleep quality is characterized by continuous, uninterrupted sleep, and feelings of refreshment upon awakening (Kline, 2013). Importantly, lifestyle factors are potentially modifiable and could be translated to low-threshold mental health prevention or intervention strategies in the context of adolescents' everyday lives.

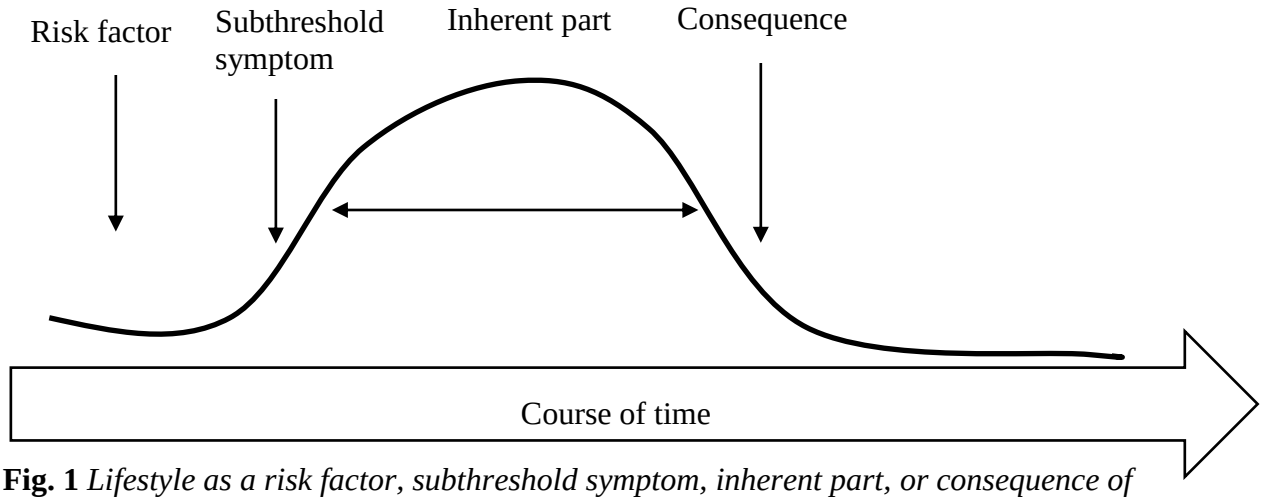

Fig. 1 *Lifestyle as a risk factor, subthreshold symptom, inherent part, or consequence of psychopathology*

2.1. Lifestyle change before psychopathology onset – a potential risk factor?

Physical activity may be a risk factor for mental health problems as it starts to deteriorate before the peak of psychopathology onset – around the age of 15 (Solmi et al., 2021). Physical activity durations continuously drop in every year of adolescence from 10 years onwards, culminating in a 38% activity decrease in both boys and girls between the age of 10 and 15 (Farooq et al., 2020). Indeed, longitudinal studies of subjective physical activity suggest that increased physical activity levels may predict a reduced risk of developing psychopathology symptoms over time (Koivukangas et al., 2010; Schuch et al., 2018, 2019). However, worldwide, and in Flanders (Belgium), 80% of the child and adolescent population does not meet the physical activity recommendations of the World Health Organization (WHO), and is therefore considered physically inactive (Dierckens et al., 2019; Guthold et al., 2020).

To improve cognitive, physical and mental health outcomes, the WHO recommends that adolescents aged 11-17 years old spend on average 60 minutes in moderate-vigorous physical activity per day (Bull et al., 2020). Moderate physical activity includes activities such as walking and cycling, which allow talking during the activity, whereas vigorous physical activity includes playing soccer or running, for example, and limits talking to saying a few words in between taking breaths (Centers for Disease Control and Prevention, 2021).

Likewise, sleep patterns shift dramatically towards later bedtimes and shorter sleep durations during adolescence (Colrain & Baker, 2011). One third of adolescents sleep less than the

recommended duration of at least 8-9 hours per night on a school night (K. Delaruelle et al., 2019; Michaud & Chaput, 2016). Altered sleep patterns are also often accompanied by decreased sleep quality. Today, one in three adolescents experiences decreased sleep quality (Li et al., 2020). In a longitudinal cohort, adolescents reported more depressive symptoms when having much shorter or longer sleep durations than what is recommended (i.e. 8-9 hours) (Liu et al., 2020). Similarly, longitudinal research shows that adolescents experiencing low quality sleep suffer more often from symptoms of depression and anxiety over time (Kaneita et al., 2009; Pigeon et al., 2017).

The 24-Hour Movement Guidelines - developed more recently than the updated version of the physical activity guidelines from the WHO (Bull et al., 2020) - consider not only one isolated aspect of lifestyle for an individual's health, but all three of them together (i.e. physical activity, sedentary behaviour, and sleep) within a 24-hour day, since emerging evidence suggests that these behaviours influence each other (Falck et al., 2021; Tremblay et al., 2016). Tapia-Serrano et al. (2021) showed that only 5.4% of adolescents (N=1465) met all three 24-Hour Movement Guidelines, whereas 10.2% of this sample did not meet any of these guidelines.

Overall, lifestyle is considered an important contributor for health and well-being, as expressed in the guidelines by the WHO (Bull et al., 2020). However, lifestyle changes negatively during early adolescence - a period that precedes or coincides with the peak time of psychopathology onset (Solmi et al., 2021). Given the co-occurrence of alterations in lifestyle and psychopathology symptoms, and their suggested dynamic and potentially interactive nature (McGorry et al., 2018; Van Os, 2013), investigating if lifestyle is a risk factor for psychopathology is relevant.

2.2. Lifestyle change as an inherent part or consequence of psychopathology?

In the course of mental illness development, lifestyle alterations such as sleep problems, may present as a subthreshold symptom (Van Os, 2013). Also, in many mental disorders - such as generalized anxiety disorder, major depressive disorder, and psychotic disorders - alterations in sleep duration, sleep quality, and physical activity can be found (American Psychiatric Association, 2013). This suggests that lifestyle could be an inherent part of psychopathology symptoms. However, mental illness and related medications can also either exacerbate sleep problems or induce sleep (i.e. 'somnolence') (Fang et al., 2016), and eventually reduce physical

activity (Kaskie et al., 2017; Vancampfort et al., 2017; Verwimp et al., 2013), implying that lifestyle changes may be a consequence of psychiatric illness.

It is challenging, however, to distinguish whether lifestyle changes precede, follow, or are an inherent part of psychopathology. If studies demonstrate the beneficial effects of lifestyle on psychopathology, this would indicate that lifestyle plays an important role in early intervention and prevention. Vice versa, if studies show that lifestyle changes are rather an inherent characteristic of the illness or a consequence of the mental state, physical activity interventions will likely not prevent mental illness, but may help to reduce the mental health burden and improve quality of life (Vancampfort et al., 2016; Walker et al., 2015). For example, addressing decreased physical activity levels and sleep problems within intervention studies in adolescents with psychiatric disorders diminishes symptom severity, increases social functioning, and physical health (Corbett et al., 2021; Correll et al., 2018; Firth et al., 2018).

Therefore, disentangling the directionality of the associations is important to inform future prevention and intervention. In the following, we will introduce the behavioural epidemiological framework, in which the study of the lifestyle-psychopathology relationship can be integrated. Afterwards, we will provide an overview of the previous prospective literature, which may give indications about the directionality of the lifestyle-psychopathology relationship.

3. Studying lifestyle and psychopathology in the context of the behavioural epidemiological framework

The study of lifestyle factors and psychopathology can be situated within the field of behavioural epidemiology, which studies the distribution and aetiology of health behaviours in populations to prevent disease and promote health (Sallis et al., 2000). Applied to the study of lifestyle and psychopathology, the behavioural epidemiological framework (Sallis et al., 2000) includes the following processes:

- (1) Establishing a link between lifestyle and psychopathology,
- (2) Developing methods to measure lifestyle,
- (3) Identifying factors that influence/ relate to lifestyle,
- (4) Evaluating interventions to change lifestyle, and
- (5) Translating research into practice.

Importantly, the processes within the behavioural epidemiological framework build on each other, but also continuously develop alongside each other (Biddle et al., 2015; Sallis et al., 2000). For example, the association between lifestyle and psychopathology may be re-investigated due to the continuous development of measurement techniques (Biddle et al., 2015; Sallis et al., 2000). It becomes an iterative process, where novel findings in every phase stimulate the development in other phases (Biddle et al., 2015).

In this PhD research project, the focus lies on the first three processes of the behavioural epidemiological framework outlined above, while processes on intervention and implementation will not be covered. In the following, we will provide an overview of the state of the art of the lifestyle – psychopathology symptoms relationship (i.e. process 1, 'Establishing a link between lifestyle and psychopathology'). Then, we will introduce methods for measuring lifestyle, which reflect process 2 ('Developing methods to measure lifestyle'). Lastly, we will provide an overview of factors that influence/relate to lifestyle, which is part of process 3 in the framework ('Identifying factors that influence/relate to lifestyle').

3.1. Effects of physical activity on psychopathology symptom

Within this section, we review the literature on previously established links between physical activity, sleep, and psychopathology symptoms in adolescence (i.e. process 1). According to prospective studies, adolescents with higher levels of physical activity have a reduced risk of developing depression (Schuch et al., 2018), anxiety (Schuch et al., 2019), and psychosis symptoms (Koivukangas et al., 2010; Suetani, et al., 2017) over a period of five to seven years compared to adolescents with low levels of physical activity. Evidence from interventional studies suggests beneficial effects of aerobic, supervised exercise on symptom reduction in depression (Bailey et al., 2018; T. Carter et al., 2016), anxiety (Gordon et al., 2020; LeBouthillier & Asmundson, 2017), and psychosis (Dean et al., 2017; Firth et al., 2018; Fisher et al., 2020).

These relationships may be explained via psychosocial, behavioural, and neurobiological mechanisms (Lubans et al., 2016). Lubans and colleagues (2016) suggest that *psychosocially*, physical activity provides an opportunity for adolescents to socially interact, experience mastery, improve their perception of appearance, and feel independent (Deci & Ryan, 2002; Lubans et al., 2016; Ryff & Keyes, 1995). Additionally, physical activity can involve contact with nature (Coon et al., 2011), which can also improve mental well-being due to its restorative

effects (Pearson & Craig, 2014). *Behaviourally*, physical activity may affect mental well-being positively by improving sleep indirectly in terms of sleep duration, sleep efficiency, and sleep onset latency (Kredlow et al., 2015). Additionally, physical activity may stimulate self-regulation and coping skills (Galantino et al., 2008; Lubans et al., 2012). On a *neurobiological* level, physical-activity related changes in the nervous system may explain boosts in cognitive functioning (Scheffer & Latini, 2020; Severinsen & Pedersen, 2020), mood, and mental well-being (Gujral et al., 2017; Siebers et al., 2021).

3.2. Effects of sleep on psychopathology symptoms

Evidence from cross-sectional (Morishima et al., 2020; Ojio et al., 2016) and prospective (Liu et al., 2020) studies suggests that adolescents who report much shorter or longer sleep durations than what is recommended (i.e. 8-9 hours) are more likely to report symptoms of depression, anxiety (Kaneita et al., 2007; Liu et al., 2020; Ojio et al., 2016), and psychosis (Morishima et al., 2020). Similarly, longitudinal research shows that adolescents experiencing low quality sleep suffer more often from symptoms of depression and anxiety (Kaneita et al., 2009; Pigeon et al., 2017). Evidence from interventional studies suggests that improving insomnia symptoms in students reduces depression (Clarke et al., 2015), hallucination, and paranoia symptoms (Freeman et al., 2009).

One mechanism that may explain the sleep and psychopathology relationship is emotion regulation. The intimate, bidirectional relationship between emotion and sleep is well-established in adults (Palmer & Alfano, 2017; Vandekerckhove & Wang, 2018), and similar evidence in adolescents is emerging. Experiential studies in adolescents suggest that sleep deprivation leads to weakened regulation of negative emotions and worse mood (Baum et al., 2014; Vriend et al., 2013). Vice versa, poor emotion regulation strategies such as avoidance, impulsivity, suppression, and rumination have been related to poor sleep quality in nationally representative samples in university students – which in turn was associated with mood, anxiety disorders, and PTSD symptoms (Nicholson et al., 2021; Palmer et al., 2018).

Psychopathology, and depression in particular, is linked with an increased inflammatory state (Dowlati et al., 2010; Soczynska et al., 2011), which is also developing in those with sleep disturbances (Grandner et al., 2013; Prather et al., 2015). Therefore, another potential mechanisms linking sleep and psychopathology is inflammation (Tubbs et al., 2020; Weinberger et al., 2015).

3.3. Effects of psychopathology symptoms on physical activity

The current literature on prospective effects of psychopathology on physical activity levels is limited and presents a mixed picture. Some studies suggest that scoring high on internalizing (i.e. anxiety disorders, depressive disorders) (Sabiston et al., 2013) and externalizing symptoms (i.e., attention hyperactivity deficit disorders) (Pinto Pereira et al., 2014) in adolescence is related to lower physical activity levels at age 20 (Pinto Pereira et al., 2014; Sabiston et al., 2013), 30, and 40 (Pinto Pereira et al., 2014). In contrast, other studies do not find any supportive evidence that general psychopathology (Suetani et al., 2017), symptoms of depression (Birkeland et al., 2009; Pinto Pereira et al., 2014), and externalizing symptoms (Pinto Pereira et al., 2014) affect levels of physical activity later in life. Given the limited and mixed literature regarding the effects of psychopathology on lifestyle, future research is warranted.

As potential explanations for these associations, Suetani and colleagues suggest that adolescents experiencing higher levels of psychopathology are less physically active due to decreased social connectedness and social isolation (Suetani et al., 2016; Suetani, Saha, et al., 2017). Those adolescents may worry more about peer scrutiny (Seime & Vickers, 2006) and experience higher self-negativity (Dow & Craighead, 1987), making them avoid physical activity contexts to avoid feeling athletically and socially inadequate (Sabiston et al., 2013).

3.4. Effects of psychopathology symptoms on sleep

To date, prospective evidence provides stronger evidence for sleep duration predicting the development of psychopathology, such as depression and anxiety, rather than vice versa, however few studies have investigated the potential longitudinal effects of depressive symptoms on sleep duration (Liu et al., 2020; Lovato & Gradisar, 2014; Patten et al., 2000; Roberts & Duong, 2014). In contrast, the prospective relationships between lower sleep quality and more symptoms of depression and anxiety is considered bi-directional (Kaneita et al., 2009).

3.5. A suggested bidirectional lifestyle-psychopathology relationship

In order to disentangle whether lifestyle aspects precede, are inherent to, or follow psychopathology symptoms, we have provided an overview of the literature. Overall, the current prospective and interventional literature investigating the relationship between lifestyle factors and psychopathology symptoms in adolescents provides (a) stronger effects of lifestyle

on psychopathology than vice versa, and (b) cautious support for a reciprocal relationship (**Fig. 2**). The cautious support is mainly based on the very limited number of longitudinal studies on the effects of psychopathology *on* lifestyle.

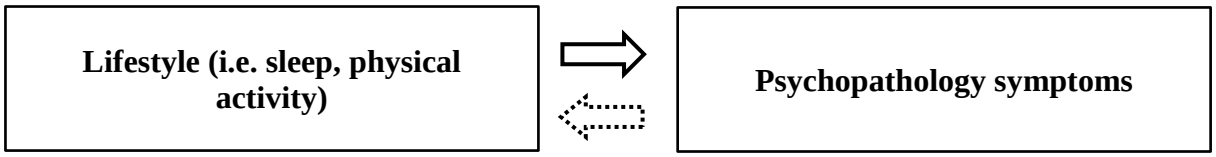

Fig. 2 *Suggested bidirectional relationship between lifestyle and psychopathology symptoms*

Note: Continuous lines suggest stronger evidence, dashed lines indicate weaker evidence for the relationship

3.6. Gaps and limitations in research on the physical activity – psychopathology relationship

Despite the established longitudinal effects of physical activity on psychopathology, many gaps and shortcomings remain. First, the established effects are based on self-report measures (LeBlanc & Janssen, 2010; Manios et al., 2013; Sullivan et al., 2012) and may include questionable conclusions, while studies applying objective, more valid measures are scarce (Kandola et al., 2020; Toseeb et al., 2014; Wiles et al., 2012). Second, previous objective studies have focused on the effects of moderate-vigorous physical activity on depression, but the effects of lower intensity levels of physical activity on depression and other psychopathologies are unknown – but suggest equal effects (Kandola et al., 2020). Third, previous studies have assumed a linear physical activity - psychopathology relationship, whereas literature in adults suggests that a non-linear relationship provides a better fit (Bernard et al., 2018).

Therefore, given the current limitations in the literature, we aim to (1) investigate in chapter 3 what kind of model (e.g. linear or non-linear) represents the nature of the objectively measured physical activity-general psychopathology relationship in adolescents best. Additionally, we will explore (2) if a relationship exists between objectively measured light, moderate-vigorous physical activity, and general psychopathology symptoms in adolescents.

3.7. Gaps and limitations in the sleep – psychopathology relationship

Although longitudinal studies support a sleep – psychopathology relationship (Liu et al., 2020), shortcomings and gaps remain. First, the longitudinal literature is mainly based on questionnaire data (Guedes et al., 2016; Matthews et al., 2018), therefore concerns around the validity of the study conclusions still exist. But studies applying objectively measured sleep duration (Ranum

et al., 2019; Slykerman et al., 2020) and sleep quality (Koopman-Verhoeff et al., 2019) are lacking. Second, self-report data studies suggest a non-linear relationship between sleep duration and psychopathology (Liu et al., 2020; Morishima et al., 2020; Ojio et al., 2016) – but the non-linear relationship has never been investigated in objective data.

That is why we will explore in chapter 4 if there is (1) a non-linear association between objectively measured derived sleep duration and symptoms of psychopathology. (2) Second, we will explore if not complying with sleep duration recommendations is associated with more symptoms of psychopathology. (3) Lastly, we assess whether objective sleep quality is associated with general symptoms of psychopathology, depression, anxiety, and psychoticism in adolescents.

3.8. The SIGMA Study

Ideally, the study of the lifestyle – psychopathology relationship occurs within a phase when early symptoms of psychopathology are just evolving – during adolescence. The SIGMA study, an ongoing, accelerated longitudinal cohort study (N= 1913) of adolescent mental health in Flanders, Belgium, investigates how contextual risk factors, such as childhood trauma, parenting style, exposure to bullying, and lack of social support, translate via everyday social processes to early mental health symptoms over the course of adolescence (Kirtley et al., 2021). Given its setting in early adolescence, SIGMA offers a unique opportunity to study lifestyle factors in a phase when early psychopathology symptoms emerge.

4. How to measure lifestyle?

In the previous section, we outlined the literature regarding process 1 ('Establishing a link between lifestyle and psychopathology') of the behavioural epidemiological framework. Next, we will introduce methods of measuring lifestyle, which reflects process 2 ('Developing methods to measure lifestyle') of the behavioural epidemiological framework.

4.1. Physical activity measurement

One aspect that is closely related to establishing the lifestyle-psychopathology link and implemented in the behavioural epidemiological framework, is the process of developing accurate assessment of lifestyle factors (Sallis et al., 2000). In physical activity measurement, one aims to quantify the duration, frequency, intensity, and type of activity of the individual (Caspersen et al., 1985). However, assessing these aspects may be particularly challenging to

capture with questionnaires, since daily physical activity durations are variable from day to day (Telford et al., 2013), and activity bouts can be short-lived (i.e. seconds to 5 minutes) (Sanders et al., 2014; Willis et al., 2015), making it challenging to remember and report them.

Until recently, self-report measures have been the method of choice in large-sized adolescent samples. Given their cost-effectiveness, low burden to both participant and researchers, and their ability to capture the physical activity domain (e.g. leisure time), they present a very practical assessment option (Hagströmer et al., 2008; Sirard & Pate, 2001). However, one main downside of self-report measures is that – even when adapted to adolescents - they tend to be less valid when compared to objective assessment of physical activity, particularly in younger adolescents (Hagströmer et al., 2008). Low correlations between questionnaires and objective measurement have been explained by difficulties for younger adolescents to understand the concepts and different questionnaire design for adults and older adolescents (> 14 years).

Additionally, higher proportions of spontaneous activity types are particularly prevalent in younger compared to older adolescents, which are more difficult to capture in questionnaires compared to structured, vigorous physical activity (Hagströmer et al., 2008), leading to significant underestimation of low (Sullivan et al., 2012), and overestimation of moderate-vigorous physical activity (LeBlanc & Janssen, 2010; Manios et al., 2013) when compared to objective measures (e.g. accelerometery).

A solution to the adolescent-specific challenges outlined above could be objective measures, which are hip- or wrist-worn devices that continuously capture physical activity (Sirard & Pate, 2001). More complex devices, such as multi-sensor devices, asses physical activity by combining accelerometery with heart rate measurement, for example. This combined measure has several benefits to the single-use of accelerometery or heart rate monitors. For example, heart rate sensors support catching activities that involve little torso movement required for accelerometery assessment (e.g., cycling) through an elevated heart rate whilst being in a static position (Fitbit, 2021b), thereby preventing underestimating physical activity levels (Sirard & Pate, 2001). Vice versa, accelerometery measurement ensures capturing physical activity when it actually occurs, since heart-rate measurement may be inaccurate when influenced by other factors than bodily movement, such as psychological or environmental distress (e.g., caffeine or medication) (Emons et al., 1992). The use of consumer multi-sensor devices, such as Fitbit, in research, was previously criticized for not reaching comparable validity as research-grade

device (e.g., Actigraph) so that consequently, false study conclusions may eventually inform public health guidelines (Feehan et al., 2018). This worry was particularly relevant for consumer devices which did not include additional sensors, such as heart rate, which have shown decreased accuracy compared to those that use the additional input for assessing physical activity (Feehan et al., 2018).

Yet, today, multi-sensor consumer devices, such as the Fitbit Charge 2, have reached a comparable standard for measuring light and moderate-vigorous physical activity in adults, children, and adolescents when compared to research devices (Brewer et al., 2017; Godino et al., 2020; Roberts et al., 2020). This is promising, since consumer devices are more cost-effective than research grade devices, which allows greater sample sizes in objectively measured lifestyle studies.

4.2. Sleep measurement

The measurement of sleep requires precise assessment in order to understand its role in relation to health and psychopathology. Polysomnography offers direct, objective assessment and is therefore considered the gold standard in laboratory research and sleep medicine for the last 50 years (Chinoy et al., 2021). However, polysomnography is less well suited for large-scale epidemiological studies, since it is applied in a controlled, laboratory setting, is time- and cost-intensive, requires specialised trainings, and can be disruptive for sleep itself, particularly in children and adolescent populations (Nascimento-Ferreira et al., 2016).

In contrast, objective wrist-worn accelerometers which translate bodily movement captured by in-built accelerometers into sleep-wake scores (Sadeh, 2011), provide the opportunity of measuring sleep behaviour in an uncontrolled environment (Hyde et al., 2007), allowing spontaneous assessment of bed times and sleep duration behaviour in free-living environments at home, are less time and cost-intensive, do not require specific training, and represent less disruption of sleep for the individual (Meltzer et al., 2012; Nascimento-Ferreira et al., 2016). That is why research-grade accelerometers have been applied as a standard measure for free-living conditions (Kinder et al., 2012).

In recent years, consumer devices, such as Fitbit, have been increasingly used in research, as opposed to research-grade accelerometer (e.g. Actigraph). However, despite the initial validity concerns regarding consumer devices, newly developed devices partially address the two main

limitations of actigraphy: single-sensor measurement and high costs. Compared to actigraphy, multi-sensor consumer devices, such as Fitbit for example, consist of both an accelerometer and heart rate sensors, that can be used as physiological, additional input for the proprietary algorithm (Chinoy et al., 2021). Due to this double-assessment, recent studies have already shown that some multi-sensor consumer devices (i.e. Fitbit HR) assess sleep duration at least equally well as research-grade Actigraphs in adolescents (Lee et al., 2019), or even outperform them (Menghini et al., 2021).

However, accuracy concerns about sleep staging identification are still relevant, since the Fitbit Charge 3 showed only low (59-69%) proportions of correct classification of sleep stages compared with PSG (Lee et al., 2019; Menghini et al., 2021), requiring cautious interpretation of findings. Overall, consumer multi-sensor devices (e.g. Fitbit Charge 2) are at least comparable to research-grade devices in sleep duration measurement, involve lower costs, and may be better accepted by adolescents (Dunne et al., 2014).

An alternative way of measuring sleep *subjectively* whilst addressing the limitations of single-timepoint questionnaires - such as recall bias and insufficient ecological validity - is assessing sleep by means of the Experience Sampling Method (ESM). ESM is a structured diary method, in which participants report their daily life experiences, in the moment that it occurs, using, for example, their smartphone (Csikszentmihalyi & Larson, 1987; Myin-Germeys et al., 2018). Several previous studies have used ESM to assess sleep (Block et al., 2020; Kasanova et al., 2020; Mulligan et al., 2016; Takano et al., 2014), as well as psychosocial risk and protective factors for psychopathology in daily life (Rauschenberg et al., 2021; Zaki et al., 2013), in both adolescents, and adults.

While this section provided an overview of measuring lifestyle, the following section will cover potential factors that may influence lifestyle.

5. What impacts lifestyle?

In the previous section, we provided a summary of measuring lifestyle, reflecting process 2 (‘Developing methods to measure lifestyle’) of the behavioural epidemiological framework. Next, we move to the last section of this PhD thesis: Factors that influence/relate to lifestyle. This section is part of process 3 in the behavioural epidemiological framework (‘Identifying factors that influence/relate to lifestyle’).

Next to establishing a link between lifestyle and psychopathology, it is also a crucial process within the behavioural epidemiological framework to investigate the factors that are related to lifestyle, so that these findings can guide the design choices in future interventional studies and implementation programs (Sallis et al., 2000). Generally speaking, factors presenting a barrier or a facilitator to lifestyle are considered 'correlates', and can be classified by a psychological, environmental, behavioural, socio-demographic, biological, or social dimension (Bauman et al., 2012). Further, correlates may be changeable (i.e. mediators) or unmodifiable (i.e. moderators). For example, late-night caffeine use might be a mediator for poor sleep, while age and gender would be unchangeable moderators (Biddle et al., 2015).

While correlates refer to the cross-sectional nature of the associations, 'determinants' represent longitudinal, causal relationships (Bauman et al., 2012). Determinants are particularly relevant for designing physical activity interventions, as it is expected that changing these would also affect the lifestyle variable (Biddle et al., 2015). Correlates and determinants of physical activity have been well-explored so far (Biddle et al., 2015): There is consensus that boys tend to be more physically active than girls, and that healthy diet, low sedentary behaviour, parental support for physical activity, and higher perceived competence are positivity related with physical activity (Biddle et al., 2015). In the following, we will provide an overview of correlates and determinants of *sleep* in adolescents, a field of evidence that is still establishing.

5.1. Sleep duration and sleep quality correlates

The evidence around cross-sectional factors associated with sleep (i.e. *correlates*) is currently limited due to this being a relatively 'young' field of research. *Socio-demographically*, boys and younger adolescents tend to get more hours of sleep during the *week* compared to girls and older adolescents (Sousa-Sá et al., 2021). Overall, those adolescents with a medium or low *socio-economic status* are least likely to meet the sleep guidelines (Sousa-Sá et al., 2021). During early adolescence, we see that girls tend to have better sleep quality, but as girls progress through puberty, their sleep becomes more fragmented and delayed when compared to boys (Franco et al., 2020). Additionally, early school times present an important *environmental* factor leading to decreased sleep duration and sleep deprivation (Bei et al., 2014).

Genetically, it has been suggest that sleep disorders such as insomnia have a certain heritability as predisposing factor (Palagini et al., 2014). *Behavioural* aspects have been well-researched in adolescent sleep. For example, adolescents with poor sleep hygiene, which includes frequent

and late-evening tobacco, caffeine, and digital technology use, and low physical activity, tend to sleep shorter than those with better sleep hygiene (Lang et al., 2016). *Psychosocial* mechanisms could influence poor quality sleep when experiencing work/school pressure (Delaruelle et al., 2021) or social distress, such as being bullied (Donoghue & Meltzer, 2018).

Despite the intimate link between stress and sleep in adolescence (Bauducco et al., 2016; Doane & Thurston, 2014), only limited and mixed findings exist around coping and sleep (Matthews et al., 2016; Sadeh et al., 2004; van Schalkwijk et al., 2015). Coping is defined as cognitive and behavioural strategies consciously employed in response to the appraisal of stress and related to well-being (Lazarus & Folkman, 1984) has been considered a behavioural moderator in the context of stress and sleep (Kalmbach et al., 2018).Overall, many open questions regarding this topic remain. While research on coping and sleep is generally limited, it is unclear if differential effects of coping exist for younger or older youth. To date, studies have either investigated the effects of coping in younger or older youth, but have not compared how associations may differ between age groups, although developmental evidence suggests that coping abilities are age-dependent (Zimmer-Gembeck & Skinner, 2011). Second, the underlying mechanisms of the potential coping - sleep relationship are unknown.

One such psychological factor linking coping and sleep is locus of control. Locus of control is defined as a trait (Rotter, 1954) and a state (Bandura, 1977; Lazarus & Folkman, 1984), describing the degree to which an individual cross-situationally attributes outcomes and events in their life to their own behaviour (internal locus), as opposed to external forces (external locus). Since coping and locus of control are bidirectionally linked (Bandura, 1977; Zimmer-Gembeck & Skinner, 2011), and control has been linked with sleep, it may present an underlying mechanism in the coping-sleep relationship (Alfano, Zakem, Costa, Taylor, & Weems, 2009; DeAngelis, Escobar, Ruiz, & Acevedo, 2019). However, this has never been investigated in adolescents so far.

To address the current gaps in the literature, we will investigate in chapter 5 (1) how trait coping styles relate to sleep at the daily level in youth. Furthermore, we investigate (2) if state locus of control mediates the association between trait coping style and quality of sleep.

6. Aims of this PhD project

To summarise, there are three aims in this PhD project:

- (1) To investigate what kind of model (e.g. linear or non-linear) represents the nature of the objectively measured physical activity-general psychopathology relationship best, and if a relationship exists between objectively measured light, moderate-vigorous physical activity, and general psychopathology symptoms,
- (2) to explore if there is a non-linear association between objectively measured derived sleep duration, sleep quality, and symptoms of psychopathology, and if not complying with sleep duration recommendations is associated with more symptoms of psychopathology, and
- (3) to disentangle if trait coping styles relate to sleep in youth, and if this potential relationship is mediated by locus of control.

Chapter 2 – Objectives

This doctoral research project aims to unravel the early lifestyle – psychopathology symptoms relationship in general population adolescents and disentangle factors related to poor-quality sleep in adolescents.

More specifically, the objective in **chapter 3** is to determine (1) what kind of model (e.g. linear or non-linear) represents the nature of the objectively measured physical activity-general psychopathology symptoms relationship in adolescents best. Additionally, we will explore (2) if a relationship exists between objectively measured light, moderate-vigorous physical activity, and general psychopathology symptoms in adolescents.

In **chapter 4**, we will explore if there is (1) a non-linear association between objectively measured derived sleep duration and symptoms of psychopathology. (2) Second, we will explore if not complying with sleep duration recommendations is associated with more symptoms of psychopathology. (3) Lastly, we assess whether objective sleep quality is associated with general symptoms of psychopathology, depression, anxiety, and psychoticism in adolescents.

In **chapter 5**, we will investigate (1) how trait coping styles relate to sleep at the daily level in youth. Furthermore, we investigate (2) if state locus of control mediates the association between trait coping style and quality of sleep.

Chapter 3 - Objectively measured physical activity and symptoms of psychopathology in general population adolescents from the SIGMA cohort

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Abstract

Background: Less physical activity (PA) has been associated with the development of psychopathology in adolescence. Few studies, however, have focused on understanding the nature of the PA – psychopathology relationship and existing research relies mostly on self-report PA measures, which are less reliable. In this study, we investigated the nature of the relationships between objectively measured light physical activity (LPA) and moderate-vigorous physical activity (MVPA), and psychopathology symptoms in adolescents.

Methods: 934 adolescents (63% female) aged 11-19 years from the SIGMA cohort wore the Fitbit Charge 2 measuring LPA and MVPA during at least three days. Participants completed the Brief Symptom Inventory-53, assessing general symptoms of psychopathology, depression, anxiety, and psychoticism. Model selection was conducted in a subset of the dataset (n = 464) to determine the best fit. The optimal model was then fitted to the remainder of the dataset (n= 470).

Results: The results from the selected linear model indicated a non-significant relationship between LPA, MVPA, and symptoms of general psychopathology, depression, anxiety, and psychoticism.

Conclusions: This study does not provide evidence that higher durations of LPA and MVPA alone relate to reduced symptoms of general psychopathology, depression, anxiety, and psychoticism in the general adolescent population. A more integrative approach considering the interdependency of multiple lifestyle factors, as well as the domain, context, and individual experience of PA may add value to the understanding of the PA- psychopathology relationship.

1. Introduction

The transitional period of adolescence represents a phase of rapid growth and development, during which the individual grows towards more independence and adulthood (Esnaola et al., 2020; Farooq et al., 2020; Spear, 2013). In this challenging phase, adolescents are particularly vulnerable to developing symptoms of psychopathology (Kessler et al., 2007). One of the potential risk factors for the development of psychopathology is adolescents' physical inactivity (Schuch et al., 2018, 2019). Current physical activity (PA) guidelines recommend that adolescents should spend on average at least 60 minutes in moderate-vigorous physical activity (MVPA) on a daily basis to receive health benefits, such as reducing symptoms of depression (World Health Organization, 2020). Yet more than 80% of the adolescent population worldwide does not meet these recommendations (Guthold et al., 2020).

Recent literature suggests that more PA is associated with lower psychopathology symptoms among children and adolescents, independently of other lifestyle factors (e.g. sedentary behaviour). There is, for example, supportive evidence from longitudinal studies indicating that more PA is associated with a lower risk for depression (Schuch et al., 2018), anxiety (Schuch et al., 2019) and psychosis (Koivukangas et al., 2010; Shuichi Suetani, Mamun, et al., 2017). Potential underlying mechanisms for the mental health benefits of PA in adolescents include psychosocial factors (e.g., improved self-esteem, better social connectedness), behavioural factors (e.g., improved sleep volume, better coping strategies), and neurobiological mechanisms (e.g., higher neuroplasticity, decreased inflammation) (Lubans et al., 2016).

Despite this seemingly convincing evidence for an association between PA and psychopathology, the existing literature exploring associations between PA and psychopathology is hampered by shortcomings. First, the majority of studies rely on single-timepoint self-report surveys. Subjective measures are less reliable, as adolescents underestimate durations of low physical activity (LPA) (Sullivan et al., 2012), and overestimate durations of MVPA (LeBlanc & Janssen, 2010; Manios et al., 2013), as compared to objective measures (e.g. accelerometery). Consequently, objective measures (e.g. Fitbit Charge 2) may provide more accurate and higher quality evidence. Fitbit Charge 2 devices do not only overcome the limitations of subjective measures by continuously capturing PA as it occurs in daily life, they are also less cost-intensive than research-grade devices (e.g. Actigrapgh) - which

could allow greater sample size - while achieving comparable measurement validity (Brewer et al., 2017).

Second, studies investigating associations between objectively measured PA duration and psychopathology have mainly focused on the effects of higher intensity PA, i.e. MVPA. Yet, lower intensity PA, (LPA), may also relate to symptoms psychopathology independently of MVPA (Kandola et al., 2020). Given that adolescents spent at least 50% of their daily activity in LPA (Hoos et al., 2004), and that LPA may provide a lower threshold for being active than MVPA to reach activity goals, it is important to better understand the associations between LPA and the development of psychopathology symptoms. Further, previous prospective studies on objectively measured PA have focused on effects of PA on symptoms of depression in adolescents (Kandola et al., 2020; Toseeb et al., 2014; Wiles et al., 2012), while associations with anxiety, psychoticism, and general psychopathology need further exploration.

Third, knowledge regarding the *nature* of the PA - psychopathology relationship between objectively measured LPA and MVPA and psychopathology, is missing in adolescents. It is unclear if there is a consistent, linear relationship, where more LPA and MVPA relates to fewer symptoms of psychopathology, or if the associations are non-linear, and only emerge after a certain threshold of LPA and MVPA has been reached. In a study in adults (n=8150), for example, objectively measured LPA was only associated with symptoms of psychopathology after a threshold of 400 min/day of LPA had been reached (Bernard et al., 2018). Therefore, understanding the nature of the relationship more clearly in adolescents may be relevant for providing evidence- based, psychopathology-informed PA guidelines in the long-term.

Considering these shortcomings in the literature, the current study aims to examine, in adolescents, (1) what kind of model (e.g. linear or non-linear) represents the nature of the objectively PA- general psychopathology relationship best, and (2) if a relationship exists between objectively measured LPA, MVPA and general psychopathology symptoms. The registered confirmatory analyses investigated the relationship between LPA, MVPA, and general psychopathology. We hypothesise that more objectively measured LPA and MVPA are linearly associated with fewer symptoms of general psychopathology. Further exploratory analyses were conducted to examine the relationships between LPA, MVPA, depression, anxiety, and psychoticism, subscales of the general psychopathology measure.

2. Methods

2.1. Sample and recruitment

Data from Wave 1 of the SIGMA study, a large-scale, ongoing, longitudinal study of adolescent mental health in Flanders, Belgium, are used in this study. In total, 1913 adolescents were included in Wave 1 (age range 11-19 at enrolment). Full details of the methods, measures and sample have been described elsewhere (Kirtley et al., 2021). The participants in the SIGMA study were recruited from the general population via schools, with an opt-in consent procedure. Students at each school were invited to take part in the study, regardless of sociodemographic or psychological factors, e.g. known presence/absence of psychological disorder. The inclusion criteria were: (a) being a current student in the first, third or fifth year at a participating school; and (b) being able to read and write in Dutch. Ethical approval for this study was obtained from the UZ/KU Leuven Medical Ethics Committee (Ref: S6 1395). This study was post-registered on the Open Science Framework (a form of pre-registration that occurs following data collection, but before conducting the analyses; (Benning et al., 2019)) available via https://osf.io/jt8zb/?view_only=0b80007da3af473bbfca83a22f1a27ac. Deviations from the post-registration are reported in *Supplement 1*.

2.2. Procedure

Self-reported symptoms of psychopathology were assessed in an initial testing session in the classroom. Following completion, students were instructed to wear a Fitbit Charge 2 device on their wrist, during seven consecutive days and 24 hours per day. The Fitbit Charge 2 continuously collects data on the participant's light (LPA), moderate (MPA), and vigorous physical activity (VPA). Participants were asked to remove the device whenever they would be in contact with water (e.g. when swimming, showering) since the device is not water resistant. After the 7-day wear period, they returned the Fitbit at their school. Participants received a 10-euro voucher for participation in the entire SIGMA study.

2.3. Symptoms of psychopathology

The Brief Symptom Inventory-53 (BSI-53; Derogatis, 1993) was used to assess symptoms of psychopathology. It includes ten different subscales on somatization, compulsiveness, social insecurity, depression, anxiety, aggression, phobia, paranoia, psychoticism, and additional items (e.g. suicidal thoughts, sleep quality). Example items are feeling 'unworthy', 'nervous', or 'distrustful to most people' from the depression, anxiety, and psychosis subscales, respectively. For all 53 items, participants were asked to report how much they had experienced

these thoughts or feelings during the last week, including the day of assessment, on a scale ranging from 0 ('not at all') to 4 ('very much'). There was also a response option 'I do not want to answer this question'.[1]

As outcome variables, we used the Global Severity Index (GSI), which is a mean score of all 53 items, and mean values of the subscales of depression, anxiety, and psychosis. The Dutch version of the BSI-53 is sufficiently valid and reliable (Beurs & Zitman, 2006). In the current study, overall reliability was good: McDonald's Omega ω = .96, as was the reliability of the subscales depression (ω = .90), anxiety (ω =.87), and psychoticism (ω = .75). GSI scores were calculated in accordance with the BSI-53 guidelines. Therefore, participants with BSI- 53 data containing more than 3 missing values in total or more than 1 missing value per subscale were excluded.

2.4. Physical activity

We measured LPA, MPA, and VPA with the consumer wearable device Fitbit Charge 2. To create average daily minutes of LPA, MPA, and VPA, the sum of activity minutes over all valid days was divided by the number of valid measurement days. LPA, MPA, and VPA were based on an algorithm from Fitbit using metabolic equivalents (METs). The algorithm counts MPA and VPA minutes from an intensity level of 3 METs or higher and from a duration of 10 minutes or longer. Previous research demonstrates acceptable concurrent validity (r = .658) between the Fitbit Charge 2 and research-grade wearables such as Actigraph when assessing LPA, MPA, and VPA over a 7-day period (Brewer et al., 2017).

The choice of the Fitbit Charge 2 device was motivated by good assessment practice of finding a balance between validity and feasibility of measurement instruments (Corder et al., 2008). Compared to adults, adolescents would be less willing to wear a device that clashes with their idea of 'social wearability', which is defined by the degree to which adolescents perceive the visual appearance of the device as acceptable in a social setting (Corder et al., 2008; Dunne et al., 2014).

[1] This option was introduced to all questionnaires at the request of schools (see Kirtley et al., 2021 for further information).

The screen of the device was disabled to provide feedback on the participants' activity, yet the distance (km) they covered daily was displayed as this could not be turned off. We decided a priori to create a variable of MVPA, a sum of MPA and VPA. We originally planned to also include sedentary behaviour in this study, but in a deviation from our post-registration, we decided not to impute the missing SB data or proceed with analysis of sedentary behaviour due to high amounts of missing data (~58%), (see *Supplement 2* for more information).

2.5. Inclusion and exclusion of data into the final dataset

We used a threshold of at least ≥3 valid measurement days as an inclusion criterion in line with previous research (Kandola et al., 2020). Since a minimum of 4 valid days has been suggested as well (Migueles et al., 2017), we conducted an additional sensitivity analysis (see *Supplement 3*). Sufficient wear time usually includes 8-10 hours in a 24 hr day (Migueles et al., 2017). Common proxies for non-wear time (e.g. heart rate, accelerometery count) were not available for this Fitbit day-level data sample. Thus, a valid day was alternatively defined as having a measurement day with: (a) LPA for ≥60 minutes and (b) having started measurement day 1 before or the latest at 12noon, and (c) having a sleep period of more than 200 minutes and with a sleep onset after 1pm. If on all seven measurement days the participant had zero values for all measured variables of the device (LPA, MPA, VPA, minutes asleep), we assumed that the device was not worn, and data were excluded. For more details on defining missing data, non-wear time, and the rationale for in- and exclusion criteria we refer to *Supplement 2*.

2.6. Covariates

Longitudinal evidence suggests that adolescents are becoming less moderate-vigorously physically active with age, and this has been observed in both genders, although particularly in girls (Farooq et al., 2020). Further, a cross-sectional study from Germany with comparable seasonal conditions shows that adolescents are less light to moderately physically active during winter and on rainy and short sunlight days (Quante et al., 2019). Therefore, we included age (years), gender (male/female), and season (spring/summer/autumn/winter) as covariates into our analyses.

2.7. Statistical analysis

The aims of the statistical analysis were threefold. Given that there is no established 'gold standard' for handling missingness in Fitbit data, first, we wanted to explore the nature of missing data patterns and find a suitable method to deal with missing data (e.g. imputation). Second, since the nature of the relationship between PA and psychopathology is currently unclear (e.g. linear, non-linear), we wanted to investigate if the relationship between PA and psychopathology is explained better by a linear or non-linear model. In order to address these two aims, we used a random subsample, comprising 50% of the total sample, as a training set. Within the training dataset, we first explored the missing data pattern and developed a suitable technique for handling missing data. Then, we conducted a model selection procedure with four models. The lowest Bayesian information Criterion (BIC), Akaike Information Criterion (AIC), and Mean Squared Prediction Errors (MSPE) values indicated the best fitting model. Third and finally, we fitted the selected model to the remaining data from the total sample, i.e. the testing dataset.

2.7.1 Missing data exploration and imputation

We used a random 50% subsample (n=587) in order to explore the amount and pattern of missing data in the PA variables and select the best fitting model for our data. After having excluded participants who did not wear the device at all during the 7-day measurement period (N=23), and participants who had less than 3 days of valid data (N=100), the training subsample consisted of 464 participants. Based on our criteria for missing data (see *Supplement 2*), 17.87% of LPA, MPA, and VPA data, and 48.64% of sedentary behaviour data, were missing after applying our criteria for in- and exclusion. We used Little's Test for Missing Completely At Random (MCAR) (Little, 1988) within Stata Version 15.1 (StataCorp, 2017) to explore the pattern of the missingness in the dataset. The results indicated that the missing data within the training dataset were not missing completely at random (X^2= 179.96; df= 31; p= ≤.001).

There is a lack of information regarding best practices for dealing with missing Fitbit data (e.g. Feehan et al., 2018), therefore we used a multiple imputation method to impute missing data in multilevel models (van Ginkel et al., 2020). This approach is preferred since it considered that there a repeated measurements per participant. The data within this study have a multilevel structure, where accelerometery data are nested within participants, which are nested within schools. In general, a recommended approach is then to perform a multilevel multiple

imputation (van Ginkel et al., 2020). We followed this general recommendation, but did not empirically evaluate this approach, or compare approaches, within our sample.

To perform a multiple imputation technique for multilevel models, we used the 'mitml'-package (Grund et al., 2019) in R (R Core Team, 2019), which imputed the missing values for LPA, MPA, and VPA and generated ten imputed datasets. In general, three to ten imputations are considered to be sufficient (Rubin, 1987; von Hippel, 2018). We chose 10 imputations to maximise the efficiency of estimates and replicability (Rubin, 1987). The same multiple imputation technique for multilevel model was applied within all ten datasets. After data were fully cleaned and all inclusion and exclusion criteria were applied as described above, the missing data were imputed.

We did not investigate if the estimates differed significantly between imputed datasets. However, previous work has illustrated that the imputation of point estimates has good replicability even if missingness is very high (e.g. 75%), with point estimates differing only by 0.1% between the first and second imputation (von Hippel, 2018). Finally, we created a mean value for LPA, MPA, and VPA across the number of observations per participants in every imputed dataset. MPA and VPA were summed to create the MVPA variable, which we used in our analysis.

2.7.2. Model selection with the training subsample (n=464)

After imputing the missing data, we estimated for each imputed dataset the following models: (1) a linear regression, (2) a linear mixed effects model considering school differences, (3) a generalized additive model, and (4) a generalized additive mixed effect model considering school differences. Model 1 and 2 assume a linear relationship between PA and psychopathology, while model 3 and 4 assume non-linear one, to test the 'threshold' effect. Mixed effects models were included in the model selection procedure to investigate if accounting for school differences would improve the model fit. All models were estimated using the mgcv package (Wood, 2017). The linear model was estimated with the gls function (1), the linear mixed effects model by the lme function (2), and the generalized additive models (3, 4) with the gam function. To allow for comparability, the number of knots for the generalized additive models were fixed (k=3), and Maximum Likelihood (ML) Estimation was chosen for all models. For each of the four different models we wanted to compare, we computed the

Bayesian Information Criterion (BIC), Akaike Information Criterion (AIC), and mean squared prediction error (MSPE).

The MSPE represents a summary of differences between actual and predicted response values and indicates how well a model predicts in the future and is calculated by k-fold cross-validation (Hastie et al., 2008). In this approach, the sample is split into k subsets. Using all subsets except the kth subset, the model is estimated for each fold, whereby the kth subset serves a validation sample. This process is repeated until every subset has served as the validation sample. Then, the computed MSPE values are averaged across the folds (Hastie et al., 2008). In this study, we used 10-fold cross-validation in each imputed dataset to compute the MSPE value, which was later pooled across the M imputed datasets (Hastie et al., 2008). The best fit of the model was determined by the lowest AIC, BIC, and MSPE value across all imputed datasets.

2.7.3. Estimation of the selected model in the testing subsample (n=464)

After selecting the model with the better fit, we estimated the model to assess (a) our confirmatory hypothesis on the association between LPA and MVPA and general symptoms of psychopathology, and (b) exploratory hypothesis on the association between LPA and MVPA on symptoms of depression, anxiety, and psychoticism. In preparation of the analysis of the testing sample, same steps were taken as in the training sample: After the data of the testing sample (n=586) had been cleaned, 10 different imputed datasets were created. We used the same multiple imputation method for 2-level data as in the training subsample. In every imputed dataset, we created a mean value for LPA, MPA, and VPA across the number of observations per participants. MPA and VPA were summed to create an additional value; MVPA.

We used Rubin's rules for pooling effect estimates and standard errors (Rubin, 1987). The Wald test was calculated using the pooled regression coefficient and standard error. The degrees of freedom (df) and the p-value for the pooled estimate were derived from the adjusted formula version to calculate the df (Van Buuren, 2018) using the MICE package in R (van Buuren & Groothuis-Oudshoorn, 2011). In a deviation from our post-registration, we performed a sensitivity power analysis using a fixed multiple linear regression modelling R^2 increase within the testing subsample (n=464) using G*Power version 3.1.9.4. (Faul et al., 2007). Testing the hypothesis that R^2 increase is zero, the minimum effect size to achieve a power larger than 80% is f^2 = .02. Within our OLS regression, we achieved a partial R^2 value of .08. Please see *Supplement 4* for more detailed information on the power analysis calculations.

3. Results

3.1. Characteristics of the training and testing subsample

Table 1 shows the means, standard deviations, and percentages for the variables age, gender, season, LPA, MVPA, BSI-GSI, and the subscales depressiveness, anxiety, and psychoticism for both the training and the testing subset with and without data imputation. **Table 2** shows the minimum, maximum, and quartile values for light and moderate-vigorous physical activity within the unimputed and imputed training and testing subsample.

Table 1 *Means, standard deviations, and percentages within the unimputed and imputed training (n=464) and testing subsample (n=470)*

	Unimputed training subset (n=464)	Unimputed testing subset (n=470)	Imputed training subset (n=464)	Imputed testing subset (n=470)
Age (years)	13.27 (1.74)	13.20 (1.59)	13.27 (1.74)	13.20 (1.59)
Gender (% female)	65	60	65	60
Season: Spring (%)	45	40	45	40
Season: Autumn (%)	15	49	15	49
Season: Winter (%)	40	1	40	1
LPA (minutes)	255.19 (50.83)	248.45 (55.80)	253.43 (58.11)	249.52 (51.06)
MVPA (minutes)	47.51 (32.83)	50.59 (38.41)	47.25 (34.26)	50.83 (35.84)
BSI-GSI	.90 (.64)	.83 (.60)	.90 (.64)	.83 (.60)
Anxiety	.92 (.64)	.83 (.67)	.92 (.64)	.83 (.67)
Depressiveness	.85 (.64)	.72 (.80)	.85 (.64)	.72 (.80)
Psychoticism	.69 (.64)	.63 (.67)	.69 (.64)	.63 (.67)

Note: LPA= light physical activity, MVPA= moderate - vigorous physical activity, BSI-GSI= General Severity Index of the Brief Symptom Inventory-53

Table 2 *Minimum, maximum, quartile, and skewness-index values for light (LPA) and moderate-vigorous physical activity (MVPA) within the unimputed and imputed training (n=464) and testing subsample (n=470)*

Sample	Variable	Min.	Average physical activity per quartile			Max.	Skewness-Index
			1st Quartile	2nd Quartile	3rd Quartile		
Unimputed	LPA	88.25	211.96	250.33	296.58	422.00	.03
training	MVPA	0	23.94	38.45	61.67	197.00	1.58
Imputed	LPA	92.00	218.57	252.42	292.16	399.13	.05
training	MVPA	-8.91	25.10	40.64	62.03	196.37	1.49
Unimputed	LPA	66.00	208.80	273.00	320.00	501.00	-.14
testing	MVPA	0	17.00	46.50	96.75	305.00	1.34
Imputed	LPA	92.21	216.62	248.54	281.36	412.00	.04
testing	MVPA	-13.62	26.48	43.33	67.38	233.97	1.55

Note: LPA= light physical activity, MVPA= moderate - vigorous physical activity

2. Missing data and model selection in training subsample (n=464)

We determined the BIC, AIC, and MSPE values from a linear regression (LM), a linear mixed effect model (LME), a generalized additive model (GAM), and a generalized additive mixed effect model (GAMM) across 10 imputed datasets. Considering all values, we found that the linear regression model had the lowest BIC and MSPE values, while there was an equal number of datasets presenting the lowest AIC value in either a linear or a generalized additive model. Overall, we concluded that the linear model provided the best fit (**Table 3** and **Table 4**).

Table 3 *BIC and AIC values for a linear model (LM), linear mixed effects model (LME), generalized additive model (GAM), and generalized additive mixed effects model (GAMM) among ten imputed datasets of the training sample (n=464)*

Dataset	1	2	3	4	5	6	7	8	9	10
BIC										
LM	719.57	718.98	719.52	718.87	717.74	718.05	718.51	718.93	718.35	719.42
LME	725.48	724.89	725.42	724.93	723.64	723.95	724.42	724.81	724.26	725.33
GAM	727.33	726.44	729.78	725.92	725.95	726.32	725.63	725.20	726.34	727.35
GAMM	727.33	726.44	729.78	725.92	725.95	726.32	725.63	725.20	726.34	727.35
AIC										
LM	688.32	687.73	688.28	687.63	686.49	686.80	687.27	687.66	687.11	688.18
LME	690.32	689.73	690.28	689.63	688.49	688.80	689.27	689.66	689.11	690.18
GAM	688.28	687.38	690.73	686.87	686.89	687.26	686.57	686.14	687.29	688.30
GAMM	688.28	687.38	690.73	686.87	686.89	687.26	686.57	686.14	687.29	688.30

Note: BIC = Bayesian Information Criterion; AIC = Akaike Information Criterion; LM = linear model; LME = linear mixed effects model; GAM = generalized additive model; GAMM = generalized additive mixed effects model

Table 4 *Mean Squared Prediction Error (MSPE) values for a linear model (LM), linear mixed effects model (LME), generalized additive model (GAM), and generalized additive mixed effects model (GAMM) among ten imputed datasets of the training sample (n=464)*

Dataset	1	2	3	4	5	6	7	8	9	10
MSPE										
LM	.3751	.3810	.3743	.3800	.3907	.3905	.3843	.3866	.3775	.3821
LME	.3751	.3810	.3743	.3800	.3907	.3905	.3843	.3866	.3775	.3821
GAM	.3738	.3801	.3789	.3828	.3935	.3938	.3879	.3888	.3838	.3781
GAMM	.3738	.3801	.3789	.3828	.3935	.3938	.3879	.3888	.3838	.3781

Note: MSPE= Mean Squared Prediction Error; LM = linear model; LME = linear mixed effects model; GAM = generalized additive model; GAMM = generalized additive mixed effects model; Standard error values of the MSPE values are reported in Supplement 7.

3.3. Model fit values for the associations between light and moderate-vigorous physical activity and symptoms of general psychopathology in the testing sample (n=470)

Based on the training set results, we conducted a confirmatory analysis using a linear regression model in the testing subsample. The pooled results across the 10 imputed datasets can be found in Table 5. There were no significant associations between LPA and MVPA, and symptoms of general psychopathology. These findings remained unchanged when conducting a sensitivity analysis applying multilevel multiple imputation to the BSI variable.

Table 5 *Associations between light (LPA) and moderate-vigorous physical activity (MVPA) and psychopathology (GSI-BSI) estimated with a linear regression in the testing subsample (n=470)*

	Dependent variable			
Independent variables	GSI-BSI			
	β (SE)	p	b (SE)	p
LPA	.00009 (.0006)	.84	.0001 (.0007)	.81
MVPA	-.0008 (.0009)	.54	-.001 (.0009)	.15
Age	.04 (.02)	.07	.05 (.02)	**.02**
Gender	.26 (.06)	**<.001**	-	-
Season (Spring)	-.48 (.58)	.41	-.61 (.21)	.30
Season (Autumn)	-.34 (.58)	.56	-.49 (.60)	.41

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; b= standardized regression coefficient; SE= standard error, LPA= light physical activity, MVPA=moderate - vigorous physical activity

3.4. Model fit values for the associations between light (LPA) and moderate-vigorous physical activity (MVPA) and symptoms of depression, anxiety, and psychoticism in the testing subsample (n=470)

We conducted exploratory analyses using a linear regression model. The pooled results across the 10 imputed datasets can be found in **Table 6**. There are no significant associations between LPA and MVPA with symptoms of depression, anxiety, and psychoticism. These findings remained unchanged when conducting a sensitivity analysis applying multilevel multiple imputation to the BSI variable.

Table 6 *Associations between light (LPA) and moderate-vigorous physical activity (MVPA) and general psychopathology (GSI-BSI-53) estimated with a linear regression (n=470)*

	Dependent variables					
Independent variables	Depression		Anxiety		Psychoticism	
	β (SE)	p	β (SE)	p	β (SE)	p
LPA	-.0002 (.0008)	.81	.0004 (.0007)	.54	-.000007 (.0007)	.99
MVPA	-.0004 (.001)	.72	-.001 (.001)	.18	-.0006 (.001)	.55
Age	.08 (.03)	**.008**	.007 (.02)	.75	.03 (.02)	**.02**
Gender	.30 (.08)	**<.001**	.24 (.07)	**<.001**	.22 (.07)	**.001**
Season (Spring)	-1.54 (.79)	.05	-.22 (.65)	.74	-.45 (.66)	.49
Season (Autumn)	-1.37 (.79)	.08	-.09 (.65)	.88	-.27 (.66)	.69

Note: in bold = alpha < 0.05; β= unstandardized regression coefficient; SE= standard error, LPA= light physical activity, MVPA= moderate - vigorous physical activity. Standardized coefficients are reported in Supplement 5.

4. Discussion

To the best of our knowledge, this is the first study investigating the nature of the relationship between objectively measured PA and symptoms of general psychopathology, depression, anxiety, and psychoticism in adolescents. We hypothesized that a linear relationship exists, where more minutes of LPA and MVPA would be negatively associated with fewer symptoms of psychopathology in adolescents. Yet, our results showed that the (standardized) effect sizes between LPA and MVPA and symptoms of general psychopathology, depression, anxiety, and psychoticism, were negligible to small, and that the associations were non-significant. Therefore, our findings do not provide evidence that more LPA and MVPA relate to fewer symptoms of psychopathology in the general adolescent population.

Our results are not in line with previous self-report data from the general adolescent population, showing significant associations between more PA and lower levels of depression and anxiety symptoms (Korczak et al., 2017; McMahon et al., 2017). However, these previous findings need to be interpreted cautiously, as self-reported PA is less reliable and prone to social desirability (Adams et al., 2005) and recall biases, meaning adolescents might either overreport MVPA (LeBlanc & Janssen, 2010) or underreport LPA (Sullivan et al., 2012).

In contrast, our observation that MVPA durations were not associated with depression is consistent with findings from other accelerometery studies in adolescents. For example, in the ROOTS study (n= 1238; 54% girls; mean age = 13.8 years) and the Avon Longitudinal Study of Parents and Children (ALSPAC) study (n= 3298, 53% girls mean age= 14.5 years) (Kandola et al., 2020; Toseeb et al., 2014; Wiles et al., 2012), objectively measured MVPA was also not associated with symptoms of depression, and reported small, (unstandardized), effect sizes of weekday MVPA (.02).

Our findings do not provide evidence that more LPA and MVPA are associated with fewer symptoms of psychopathology in the general adolescent population. Recent prospective evidence suggests that the relationship between lifestyle behaviours and psychopathology is interdependent, where multiple lifestyle factors, such as sleep, sedentary behaviour, and PA, have an integrative effect on psychopathology, as opposed to individual lifestyle factors alone (Brown et al., 2021). These findings suggest that a more inclusive, broader approach may be needed for future research and intervention. Additionally, individuals' experience of PA, the

type, domain, and context of PA need to be considered for psychopathology-informed PA recommendations (Teychenne et al., 2020).

Preliminary evidence suggests that PA is associated with fewer psychopathology symptoms when PA occurs during leisure time (White et al., 2017), in the company of others (Kleppang et al., 2017), in nature (Coon et al., 2011), and with a focus on the mind-body relationship, such as yoga (Galantino, Galbavy, & Quinn, 2008; Lubans, Plotnikoff, & Lubans, 2012). In contrast, PA during transport, household chores, and physical education classes is not associated with fewer symptoms of psychopathology (White et al., 2017). There is also evidence that PA carried out alone is associated with higher odds of developing depression compared to PA performed in a social setting (e.g. in a sports clubs) (Kleppang et al., 2018). Therefore, further research may investigate interactions of PA with domain, context, type, and experience of PA, in relation to symptoms of psychopathology in adolescents, using the Experience Sampling Method, for example.

Our finding that LPA duration and depression levels were not significantly associated is in contrast to previous research using objectively measured LPA from the ALSPAC cohort study (Kandola et al., 2020). Currently, little is known about psychopathology-related associations with LPA. Cross-sectional evidence in adults suggests that associations with LPA are threshold-dependent, showing that associations emerge only after a certain minimum duration of LPA (~400 min/day) (Bernard et al., 2018). Potentially, a similar threshold-dependent relationship exists in adolescents, where the minimum amount to affect psychopathology is reached with at least ~320 minutes of LPA per day (Kandola et al., 2020), whereas shorter durations, as in our study (~250 minutes/ day) do not. Further exploration showed that the majority of LPA values (i.e. 75%) were below an average of 320 minutes.

Following a reviewer's suggestion, because our threshold of LPA inclusion was low (60 minutes), we conducted exploratory analyses with an increased threshold (300 min) to estimate the associations of higher LPA (mean 360.28, SD 25.98) with psychopathology symptoms in a linear and non-linear model in a sample of N=332. Our results indicated that in both models the linear and non-linear relationship between both LPA and MVPA, and psychopathology, remained non-significant (see Supplement 6). Overall, given that no associations were found between general psychopathology, depression, anxiety, and psychoticism and LPA/MVPA duration, these findings also suggest that factors other than PA may be more important in

relation to psychopathology. Further research should elucidate the role of social risk factors, for example low family cohesion and adverse life events in relation to PA in adolescents (Cuffe et al., 2005).

Since the results of the linear model investigating the PA-psychopathology relationship was non-significant, this study does not enable us to conclude whether a linear or a non-linear model describes the relationship best. In the previous literature, the nature of the PA-psychopathology relationship has been much debated. Other studies in adults, using self-report data, are inconsistent in their findings, as they have been suggesting various natures of relationships: Linear (Galper et al., 2006), quasi-linear (Stephens, 1988), s-shaped (Mummery et al., 2004), and U-shaped relationships (Kim et al., 2012). The only accelerometery study to date investigating the nature of the PA- psychopathology relationship shows a non-linear (i.e. U-shaped) association in adults (Bernard et al., 2018).

Our study has several methodological strengths. First, we aimed for maximal transparency by post-registering our study on the Open Science Framework. This approach may increase replicability of future work by minimising 'researcher degrees of freedom' and counteracting questionable research practices such as p-hacking (i.e. conducting multiple analyses until a significant result is achieved) and HARKing, standing for 'Hypothesising After Results are Known, can increase the risk of type 1-errors and reduce replicability of findings. Second, we conducted a sensitivity power analyses to increase the interpretability of our findings and guide future work in sample size decisions. Third, we addressed the risk of bias related to missingness in accelerometery data by using multiple imputation methods for multilevel data (van Ginkel et al., 2020). Given the many misconceptions about multiple imputation, listwise deletion still remains a conventional method in dealing with missing data, which may bias study conclusions (van Ginkel et al., 2020). Given the absence of a "gold standard" for handling missing Fitbit data (Feehan et al., 2018) our methods may also help to increase the rigor of future research using Fitbit devices.

Our results also need to be interpreted in light of some limitations. First, common proxies of non-wear time (e.g. heart rate; accelerometery count) were unavailable in this data sample using Fitbit Charge 2. Therefore, we cannot definitively know if the included data represents sufficient wear time, which usually includes at least 8 hours in each 24-hour day. Future research using Fitbit devices may include minute-level heart rate measurement as a proxy for

non-wear time. Second, since the device is not water resistant, inconvenient to wear during contact sports (e.g. volleyball), and MVPA durations shorter than 10 consecutive minutes are not captured by the Fitbit Charge 2, full PA may not have been captured in the data. Options for participants manually logging additional non-recorded activities could be explored. Third, while including at least three valid days is common practice in accelerometery research (Kandola et al., 2020), current recommendations suggest to include at least four valid days (Migueles et al., 2017).

However, within our sensitivity analysis, in which we estimated a linear regression including at least 4 valid days, results were similar to our analyses using three valid days. Fourth, our study design did not account for the influence of additional lifestyle aspects, such as sleep and sedentary behaviour on adolescent psychopathology symptoms, although previous research suggests an interdependency and combined association of these behaviours on adolescent mental health (Brown et al., 2021). This means that the single assessment of only one lifestyle aspect (i.e. physical activity) in this study may represent an incomplete picture of the relationship (Tremblay, 2020).

To conclude, our results show that objectively measured LPA and MVPA durations are not significantly associated with symptoms of general psychopathology, depression, anxiety, and psychoticism in adolescents, and that the relationships between PA and psychopathology are best represented by a linear relationship. Overall, this study does not provide evidence that higher durations of LPA and MVPA alone and regardless of the context relate to reduced symptoms of psychopathology in the general adolescent population. A more integrative approach considering the interdependency of multiple lifestyle factors, as well as the domain, context, and individual experience of PA may add value to the understanding of the PA-psychopathology relationship.

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Chapter 4 - Fitbit Charge 2-derived sleep duration, sleep quality, and symptoms of psychopathology in general population adolescents from the SIGMA cohort

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Abstract

Background: While subjective measures have demonstrated an association between sleep duration, sleep quality, and symptoms of psychopathology in adolescents, findings from more reliable, objective measures remain limited and inconsistent. In this study, we investigate if Fitbit Charge 2-derived sleep duration, non-compliance with sleep duration guidelines, and sleep quality are associated with symptoms of psychopathology in adolescents.

Methods: Adolescents (N= 558) aged 11-17 years from the SIGMA cohort wore the Fitbit Charge 2 measuring sleep duration and sleep quality during 4-6 days. Participants completed the Brief Symptom Inventory-53, assessing symptoms of general psychopathology, depression, anxiety, and psychoticism. Power analysis and non-linear model selection were conducted within a training subset (n=56). The optimal non-linear and linear models were fit to the remainder of the dataset (n=502).

Results: Sleep duration and non-compliance with sleep guidelines were not associated with symptoms of general psychopathology, depression, anxiety, and psychoticism in general population adolescents. Further, sleep quality was not associated with symptom levels of anxiety and psychoticism, but positive associations were found between sleep quality, depression, psychoticism, and general psychopathology symptoms.

Conclusions: Our non-significant findings converge with those of an increasing body of literature using objective measures of sleep that does not find significant associations between sleep duration, sleep quality and psychopathology symptoms. Overall, our results suggest that associations between sleep duration and psychopathology symptoms in previous studies may be a function of the subjective, self-report nature of the employed measures, and do not generalize to objectively collected sleep data.

1. Introduction

Adolescence is a vulnerable developmental period for the onset of psychopathology symptoms (Patton et al., 2014), and 50% of these mental health symptoms persist into early adulthood (Kessler et al., 2007). Two risk factors that may increase symptoms of psychopathology, are inadequate sleep duration and quality. Adequate sleep refers to age-specific sleep duration needs, while good sleep quality is characterized by continuous, uninterrupted sleep, and feelings of refreshment upon awakening (Kline, 2013).

Current literature suggests that adequate sleep duration and good quality sleep are essential for adolescents' mental and physical health (Cairns et al., 2014; Matricciani et al., 2019). Most guidelines, such as from the American Society of Sleep Medicine and the National Sleep Foundation, contend that younger adolescents between 11-13 years old should sleep 9-11 hours, and older adolescents between 14-17 years old should sleep between 8-10 hours per night, to maintain general health (Paruthi et al., 2016). Yet, the percentage of adolescents reaching the recommended sleep duration is low. Only about two thirds of the younger and older adolescents sleep the recommended duration of at least 8-9 hours per night on a school night depending on the adolescent's age, according to international studies (Delaruelle et al., 2019; Michaud & Chaput, 2016).

Previous longitudinal studies demonstrate that both very short and very long sleep durations than recommended by guidelines (i.e. 8-9 hrs per night) are associated with subsequent psychopathology symptoms (Morishima et al., 2020; Ojio et al., 2016). Sleeping shorter or longer than recommended by guidelines (i.e. 8-9 hrs per night) on a school night is associated with a higher risk of developing symptoms of depression and anxiety (Kaneita et al., 2007; Liu et al., 2020; Ojio et al., 2016). Overall, as findings show associations of both short and long sleep duration with psychopathology symptoms, a non-linear (U-shaped) relationship between sleep duration and psychopathology has been suggested (Liu et al.2020).

Furthermore, prospective studies provide stronger evidence for sleep duration predicting the development of psychopathology rather than vice versa, however few studies have investigated the potential longitudinal effects of depressive symptoms on sleep duration (Lovato & Gradisar, 2014). In contrast, the prospective relationships between lower sleep quality and more symptoms of depression and anxiety is considered bi-directional (Kaneita et al., 2009). Despite

the considerable number of studies on the topic, there is still uncertainty around the study's' conclusions. whether sleep relates to psychopathology. There is a great discrepancy between the literature mentioned above, which relies on self-report data, and recent studies applying objective i.e. non-self-report, measures to investigate the sleep – psychopathology relationship. In fact, the small number of objective data studies investigating the longitudinal association between sleep duration, symptoms of general psychopathology (Ranum et al., 2019) and depression (Slykerman et al., 2020), do not find evidence for a sleep duration – psychopathology relationship. Similarly, recent research found no association between Fitbit Charge 2-derived sleep quality and symptoms of psychoticism (Koopman-Verhoeff et al., 2019). Overall, these objective findings are meaningful, since they challenge the conclusions from previous literature, which is largely based on retrospective self-report.

Self-report data are considered less reliable, as they overestimate sleep duration by 30-60 minutes compared to actigraphy and polysomnography (Guedes et al., 2016; Matthews et al., 2018). Research devices (e.g. actigraphy and polysomnography) are the best tools for accurately measuring sleep, but one downside is that they are relatively expensive – thereby limiting the sample sizes for studies that use these methods. However, more cost-effective alternatives such as multi-sensor consumer devices measure sleep duration in adolescents with comparable accuracy to actigraphy (Lee et al., 2019; Menghini et al., 2021) and provide almost equally accurate sleep epochs, such as total sleep time (i.e. sensitivity (0.95-0.96) and specificity (0.58-0.69) when compared to polysomnography in adults (Haghayegh et al., 2019).

Whilst multi-sensor consumer devices cannot replace polysomnography, their cost-effectiveness facilitates collection of objective sleep data from larger samples. Previous literature has not only focused mainly on self-report measures, but was also limited to specific psychopathologies such as depression, anxiety, and psychoticism. In contrast, broader associations with general psychopathology symptoms remain unknown. This is particularly relevant in adolescence, when psychopathology is still developing and less differentiated than in adults (Hartmann et al., 2021). More research is necessary in order to better understand how sleep duration and quality relate to general psychopathology. Yet, since studies using objective measures are still limited, exploring the relationship of sleep duration and quality with symptoms of depression, anxiety, and psychoticism remains relevant as well.

Moreover, no previous study has investigated a non-linear relationship between sleep duration and psychopathology in objectively measures sleep despite both short and long sleep duration being associated with a risk for psychopathology symptoms (Morishima et al., 2020; Ojio et al., 2016).

In this study, we aim to investigate 1) if there is a non-linear association between Fitbit Charge 2-derived sleep duration and psychopathology, 2) if non-compliance with sleep duration guidelines is associated with more psychopathology symptoms, and 3) if there is a linear relationship between Fitbit Charge 2-derived sleep quality and psychopathology. Our confirmatory analyses investigated the associations of sleep and general psychopathology. We hypothesised that short and long sleep duration and poor-quality sleep are associated with more symptoms of general psychopathology. We also explored the relationship between non-compliance with sleep guidelines and general psychopathology symptoms[2]. We conducted further exploratory analyses to examine the associations of sleep duration, sleep quality, and non-compliance with sleep guidelines with depression, anxiety, and psychoticism symptoms.

2. Methods

2.1. Sample and recruitment

Data from Wave 1 of the SIGMA study, a large-scale, ongoing, accelerated longitudinal study of adolescent mental health in Flanders, Belgium, are used in this study. In total, 1913 adolescents were included in Wave 1 (age range 11-19 at enrolment). Full details of the methods, measures and sample have been described elsewhere (Kirtley et al., 2021). The participants of the SIGMA study were recruited as a general population sample via schools, with an opt-in consent procedure. Students at each school were invited to take part in the study, regardless of sociodemographic or psychological factors, e.g. known presence/absence of psychological disorder. The inclusion criteria were: (a) being a current student in the first (age 11-12), third (13-14) or fifth (age 15-16) year at a participating school; and (b) being able to read and write Dutch to an acceptable level. Ethical approval for this study was obtained from the UZ/KU Leuven Medical Ethics Committee (Ref: S6 1395).

[2]This analysis was described as confirmatory in an earlier version of the manuscript. However, following helpful suggestions from peer-reviewers, we changed our original, registered analytic plan for this analysis, and now therefore consider it to be exploratory.

2.2. Procedure

Self-reported symptoms of psychopathology were assessed via a tablet computer, in class groups at school. Following completion, students were instructed to wear a Fitbit Charge 2 device on their wrist, during 7 consecutive days and 24 hours per day. At night, the Fitbit Charge 2 automatically collects data on the participant's sleep duration and sleep quality. Participants were asked to remove the device whenever they would be in contact with water (e.g. when swimming, showering) since the device is not water resistant.

In addition to wearing the Fitbit device, participants were also prompted to answer ten brief questionnaires per day for six days via smartphone during 7:30 am to 22:30 pm as part of the experience sampling method (ESM) component of the larger study (Myin-Germeys et al., 2018). These ESM data were not used within the current study. To avoid conflict between the ESM questionnaires and participants' sleep schedules, we instructed them to follow their normal individual daily life rhythm, such as sleeping in during the weekend or going to bed early, even if this meant missing ESM questionnaires. We also arranged with the school's contact person that the measurement week was a usual week of participants' daily lives to ensure that the sleep variables would be representable. A usual week was defined as a week when the participants had classes at school every day, and no extra-curricular activities were planned (e.g. day out, internship). After the 7-day Fitbit wear period, they returned the material at their school. Participants received a 10-euro voucher for participation.

2.3. Measures

2.3.1. Symptoms of psychopathology

The Brief Symptom Inventory – 53 (BSI-53; Derogatis, 1993) was used to assess symptoms of psychopathology only once. It includes 10 different subscales on somatization, compulsiveness, social insecurity, depression, anxiety, aggression, phobia, paranoia, psychoticism, and additional items (e.g. suicidal thoughts, sleep quality). Example items are feeling unworthy, nervous, or distrustful to most people from the depression, anxiety, and psychosis subscales respectively. Participants were asked to report on all 53 items how much they had experienced them during the last week, including the day of assessment on a scale ranging from 0 ('not at all') to 4 ('very much').

They also had a response option 'I do not want to answer this question'.[3] We used the Global Severity Index (GSI), which is a mean score of all 53 items and also mean values of the subscales of depression, anxiety, and psychosis. One of the 53 items is on sleep quality. Due to the overlap with our predictor variable, this variable was excluded, and the BSI-GSI value was calculated based on 52 items.

The Dutch version of the BSI-53 is sufficiently valid and reliable (Beurs & Zitman, 2006). In the current study, overall reliability was good: McDonald's Omega ω = .97, as was the reliability of the subscales depression (ω = .90), anxiety (ω =.87), and psychoticism (ω = .75). GSI scores were calculated in accordance with the BSI-53 guidelines. Therefore, participants with BSI- 53 data containing more than 3 missing values in total or more than 1 missing value per subscale were excluded.

2.3.2. Sleep

We measured sleep duration and sleep quality with the consumer tracker device Fitbit Charge 2. Sleep duration is considered as the time spent asleep, and therefore automatically excludes periods in bed which had been recorded as being awake or restless during the tracked sleep time (Fitbit, 2021a). Sleep quality is assessed by a sleep quality score which is based on heart rate, the time spent awake or restless, and sleep stages. This score is based on a proprietary algorithm, meaning that information about the exact method used to calculate the sleep quality score is not publicly available. The score ranges from 0-100, with a higher score indicating a higher level of sleep quality. A sleep score of 90-100 is defined by Fitbit as 'excellent', 80-89 as 'good', 60-79 as 'fair', and a score below 60 as 'poor' (Fitbit, 2021c).

The screen of the device was disabled to prevent participants receiving feedback on their activity (which may influence their behaviour), but the distance (km) they covered daily was still displayed as this could not be turned off. To create average minutes of sleep duration and sleep quality, the sum of sleep minutes and the sum of the sleep quality score over the whole valid wear time period was divided by the number of valid measurement days.

[3] This option was introduced to all questionnaires at the request of schools (see Kirtley et al., 2021, for further information).

Following suggestions from peer-reviewers, to measure the effects of non-compliance with sleep duration guidelines, we created a non-compliance score capturing the individuals' deviation from their age-matched sleep guideline. This score was created by subtracting actual sleep duration per day from the recommended, age-matched sleep duration. Depending on the age group, recommended sleep duration values were 600 (11-13 years old) and 540 minutes (14-17-year olds), since these represent the mean value of recommended sleep duration of 9-11 hours, and 8-10 hours, for younger and older adolescents, respectively (Paruthi et al., 2016). A mean compliance score was calculated per individual, where the sum score was divided across all seven nights.

We used a threshold of at least ≥4 valid measurement days as an inclusion criterion in line with previous research (Migueles et al., 2017). A valid day was defined as having a measurement day with a sleep duration of ≥200 minutes and where sleep started after 9 pm. For more details regarding the data pre-processing steps and in- and exclusion criteria, please see **Appendix A**.

2.3.3. Covariates

Meta-analytic evidence suggests that adolescents' sleep duration decreases with older age (Galland et al., 2018), and that girls tend to sleep longer and have better sleep quality (Franco et al., 2020). Further, a cross-sectional study from Germany with comparable seasonal conditions shows that adolescents sleep less (~ 40 min) in summer as compared to winter, and that warm weather reduces sleep quality (Quante et al., 2019). Therefore, we included age (years), gender (male/female), and season (spring/summer/autumn/winter) as covariates into our analyses. Other relevant covariates such as socio-economic status (SES), parental education, and parental psychopathology, for example, were also collected within our study in parent questionnaires. However, since the response rate was very low (i.e. 20%), we did not include these additional covariates in our analyses. Bullying (van Geel et al., 2015), social support (de Grey et al., 2018), and childhood trauma (Brindle et al., 2018) have been shown to be related to both sleep and psychopathology, and were also assessed within the SIGMA study, but were not included within our analyses, since our main focus was to perform a basic model first given the lack of previous objective studies and their non-significant findings.

2.4. Open Science Practices

This study was post-registered on the Open Science Framework (see: https://osf.io/8v3m5/?view_only=b023aa5d3af948a6919a73cf2902254e). Post-registration is similar to a pre-registration, where a 'locked', un-editable plan for the research questions, hypotheses, and statistical analysis is created prior to data collection. In post-registration, however, the plan is created *after* data collection, but before having had access to the data and conducting the analyses, although parts of the data may have been used in previous analyses (Benning et al., 2019). In our post-registration, only the confirmatory analyses have been pre-defined, whereas exploratory analyses were not. Therefore, we refer also to 'registered, confirmatory' analyses, and 'non-registered, exploratory' analyses. To differentiate between confirmatory and exploratory analyses, we report and discuss our findings separately in the results and discussion section. Deviations from the post-registration are reported in **Appendix B**.

2.5. Statistical analysis

The aims of the statistical analysis were threefold. Given that we wanted to assess the non-linear relationship between sleep duration and psychopathology symptoms, we used a linear regression model including cubic regression splines, which enable us to investigate the non-linear relationship. Cubic regression splines have a high degree of freedom, and are therefore, able to catch the variability of slope flexibly. Also, they allow smooth interpolation of fixed points, called knots (Harrell, 2020). In this study, the use of cubic splines allows us to accurately determine the potential 'cut-off points' where sleep duration becomes (mal)adaptive.

To prepare for our analyses, we first assessed how many cubic spline knots provided the best fit. Second, after the best fitting model had been determined, we conducted a simulation-based power analysis to understand if our sample was sufficiently powered. To address these two aims, we conducted a few preparatory steps; (a) a data cleaning procedure according to the pre-defined in- and exclusion criteria; and subsequently, (b) a sample selection, where we drew a random stratified 10% subsample considering age and gender from the total, cleaned sample. After we imputed the missing data within this 10% training subsample, we first, compared various numbers of knots in cubic splines and determined which linear model including either 3, 4, or 5 knots for the cubic splines provided the best fit.

Second, after the model was specified, we used the 10% training subsample to conduct two separate simulation-based power analyses. Third, and finally, we estimated the models within the remaining dataset, the 90% testing dataset.

2.5.1. Preparatory steps

First, we applied the inclusion and exclusion criteria to the full dataset (N=1178). We performed this step before dividing our sample into training and testing samples, as we were aware of a high amount of missing sleep data (~58%) from a previous study (Hagemann et al., 2021). After having excluded participants (a) whose device did not record any data during the complete 8-day measurement period (N= 247), (b) were older than 17 years of age (N=26), and (c) had less than 4 days of valid data (N= 347), the total sample consisted of 558 participants. Within the cleaned sample, 32.9% of the observations within the variables sleep duration and sleep quality were missing. We used Little's Test for Missing Completely At Random (MCAR) (Little, 1988) within Stata Version 15.1 (StataCorp, 2017) to explore the pattern of the missing data in the sleep, psychopathology, and control variables. The results indicated that the missing values within the complete dataset including all variables were not MCAR (X^2= 121.49; df= 25; p≤ .001). In general, a recommended approach is then to perform a multilevel multiple imputation, as it may decrease the risk of bias as compared to listwise deletion if data is either missing at random or not missing at random (van Ginkel et al., 2020).

After the data cleaning steps, we divided our total sample into stratified subsamples, a 10% training (N=56) and a 90% (N=502) testing dataset. Then, we conducted multiple multilevel imputation for the sleep duration, sleep quality, and general psychopathology, depression, anxiety, and psychoticism variables within both subsamples, as this approach is currently recommended for multilevel data, where measurement days are nested within participants (van Ginkel et al., 2020). To conduct a multiple imputation for multilevel models, we used the 'mitml'-package (Grund et al., 2019) in R (R Core Team, 2019). We imputed data across 10 datasets, since a number between three to ten imputations has shown to yield sufficiently efficient and replicable estimates (Rubin, 1987; von Hippel, 2018).

Since multilevel imputation of level-2 variables (i.e. outcome variables) is restricted to one variable per multiple imputation (e.g. only general psychopathology) within the *mitml* package, we created three separate imputation datasets from the main imputed dataset with the imputed variable of general psychopathology when investigating the effects of depression, anxiety, and psychoticism.

2.5.2. Knot selection for cubic splines of sleep duration and non-compliance with the training subsample (n=56)

To assess the non-linear relationship between sleep duration, non-compliance, and psychopathology, we included cubic splines for the independent variables within the linear regression model included cubic splines. We determined across three models how many knots within the cubic splines for sleep duration and non-compliance would provide the best model fit: 3, 4, and 5 knots in R (R Core Team, 2019). Please see **Appendix C** for more details on the knot selection procedure.

2.5.3. Conducting a two-step simulation-based power analysis

Given that no comparable previous literature is available to estimate the distribution of sleep duration and sleep quality and also the estimated effect sizes for the relationships between the sleep variables and psychopathology are unknown, we applied a simulation-based approach (Lane & Hennes, 2018) for calculating the power for Hypothesis 1, Hypothesis 2, and Hypothesis 3 within the random 10% training subsample (n = 56). Please see **Appendix D** for more details on the simulation-based power analysis.

2.5.4. Estimation of the models in the testing subsample (n=502)

After selecting the number of knots within the training subsample and the imputation of the missing data, we estimated the model to assess our confirmatory hypotheses (1) on the non-linear association between sleep duration and general symptoms of psychopathology, and (2) the non-linear associations of sleep duration and symptoms of psychopathology, and 3) on the linear association between sleep quality and symptoms of psychopathology within the 90% testing subsample. Both linear models were estimated in R (R Core Team, 2019) with the *lm* and *rcs* functions using the rms package for the cubic splines (Harrell, 2020).

We used Rubin's rules for pooling effect estimates and standard errors across the imputed datasets (Rubin, 1987). The Wald test was calculated using the pooled regression coefficient and standard error. The degrees of freedom and the p-value for the pooled estimate were derived from the adjusted formula version to calculate the df (Van Buuren, 2018) using the MICE package in R (van Buuren & Groothuis-Oudshoorn, 2011).

3. Results

3.1. Characteristics of the training and testing subsample

Table 1 shows the means, standard deviations, and percentages for the variables gender, age, season, sleep duration, sleep quality, BSI-GSI for both the training and the testing subset with and without data imputation. One participant identified as 'other' when indicating gender. Within the subsequent analyses, we set this participant's gender to 'NA', since one participant would not provide enough information to estimate the effect of gender as a three-level factor variable.

Table 1 *Means, standard deviations, and percentages within the unimputed and imputed training (n=56) and testing subsample (n=502, across 10 imputed datasets)*

	Unimputed training subset (n=56)	Unimputed testing subset (n=502)	Imputed training subset (n=56 x 10)	Imputed testing subset (n=502 x 10)
Age (years)	13.09 (1.51)	13.13 (1.49)	13.09 (1.51)	13.13 (1.49)
Gender (% female)	64	64	64	64
Season: Winter (%)	43	36	43	36
Season: Spring (%)	45	49	45	49
Season: Autumn (%)	12	15	12	15
Sleep duration (minutes)	472.02 (47.03)	465.85 (54)	470.74 (35.79)	470.51 (36.28)
Non-compliance (minutes)	117.26 (51.00)	118.60 (44.00)	119.87 (41.47)	118.17 (36.69)
Sleep quality (0-100)	91.73 (2.16)	92.42 (2.34)	91.79 (1.77)	92.43 (1.93)
BSI-GSI	.83 (.72)	.84 (.62)	.83 (.72)	.84 (.62)
Depressiveness	.84 (.72)	.78 (.60)	.84 (.72)	.78 (.60)
Anxiety	.84 (.72)	.87 (.60)	.84 (.72)	.87 (.60)
Psychoticism	.72 (.72)	.64 (.60)	.72 (.72)	.64 (.60)

3.2. Knot selection of cubic splines in training subsample (n=56)

We estimated the non-linear effects of the variables sleep duration and non-compliance on general psychopathology within three different linear regression models. Age, gender, and season were included as control variables. In each model, the non-linear effects were implemented by adding cubic splines to the variables sleep duration and non-compliance. To determine how many splines would be needed for the variables sleep duration and non-compliance, the number of knots of the cubic splines differed (3, 4, and 5), while the rest of the model remained the same. Each of the three models with differing knots for the cubic splines was estimated across 10 imputed datasets. Then, we compared the AIC, BIC, and MSPE values in each of the three linear regression models across 10 imputed datasets.

Considering all values, the linear regression model including three cubic spline knots for sleep duration and non-compliance had the lowest AIC, BIC and MSPE values with one exception for the AIC values within the sixth imputed dataset. Standard errors of the MSPE values are reported in **Appendix G**. Overall, we concluded that the linear model with 3 cubic splines knots provided the best fit (**Table 2** and **Table 3**).

Table 2 *BIC and AIC values for three linear regression models estimating the non-linear effects of sleep duration and non-compliance on general psychopathology symptoms when including differing numbers of knots (3, 4, or 5) within cubic splines among ten imputed datasets in the training subsample (n=56)*

Dataset	1	2	3	4	5	6	7	8	9	10
BIC										
3 knots	148.98	162.31	149.83	161.04	148.53	148.55	156.55	165.10	155.95	145.64
4 knots	155.71	168.65	157.77	167.17	156.41	151.73	163.70	173.07	163.39	150.76
5 knots	162.76	174.90	162.34	170.81	164.23	156.76	171.33	176.08	170.87	156.60
AIC										
3 knots	128.72	142.06	129.58	140.78	128.28	128.29	136.30	144.86	135.70	125.38
4 knots	131.40	144.35	133.46	142.86	132.11	127.43	139.40	148.76	139.08	126.45
5 knots	134.40	146.54	133.99	142.46	135.88	128.40	142.97	147.74	142.51	128.24

Note: BIC = Bayesian Information Criterion; AIC = Akaike Information Criterion

Table 3 *Mean Squared Prediction Error (MSPE) values for three linear regression models estimating the non-linear effects of sleep duration and non-compliance on general psychopathology symptoms when including differing numbers of knots (3, 4, or 5) within cubic splines among ten imputed datasets in the training subsample (n=56)*

Dataset	1	2	3	4	5	6	7	8	9	10
MSPE										
3 knots	0.66	0.81	0.74	0.93	0.96	0.71	0.75	0.79	0.76	0.66
4 knots	115.81	40.20	37.89	141.86	59.57	225.45	35.59	206.62	228.28	104.63
5 knots	110.16	42.10	39.85	340.31	569.57	938.83	202.70	167.88	299.65	285.30

Note: MSPE = Mean Squared Prediction Error

3.3. Simulation-based power analyses

We estimated the power for two hypotheses using a simulation-based power analysis in a sample of N=502 using the selected linear model including 3 knots within the cubic regression splines. Our results indicated that a power of .19 would be estimated to reject Null Hypothesis 1 ("There is no non-linear association between sleep duration and symptoms of psychopathology"). Further, in order to reject Null Hypothesis 2 ("Complying with age-specific guidelines for sleep duration is associated with symptoms of psychopathology") a power of .99 was reached. Lastly, for Null-Hypothesis 3 ("There is no association between sleep quality and symptoms of psychopathology") the estimated power was >.99. Since we consider a power of .80 to be sufficient, we conclude that only H2 and H3 are adequately powered, while H1 is underpowered.

3.4. Sample characteristics

The main (i.e. testing) sample of N=502 was characterized by mainly younger adolescents with a mean age of 13 years old, and mostly girls (60%). The participants had on average a sleep duration of 8 hours per night, and a very good sleep quality (>90/100). They deviated from the recommended sleep durations by sleeping on average 2 hours less than the sleep guidelines suggests (117 minutes) – which relates to an adjusted deviation of 1 hour since subjective data overestimates sleep by including awakening at night in total sleep duration as opposed to objective data (Chaput et al., 2018).

Levels of general psychopathology were very mild, since only values from 2.5 and higher are considered to be clinically relevant (although not a diagnosis). Adolescents scored highest for depressive symptoms (.87), followed general psychopathology (.84), anxiety symptoms (.78), and psychosis symptoms (.64). Anxious symptoms included feeling tense, nervous, and restless; depressed symptoms comprised feelings of melancholy, loneliness, suicide, hopelessness and worthlessness, and psychotic symptoms covered thought of being controlled by others, feeling alone amongst others, doubting one's sanity (Derogatis, 1993).

3.5. Confirmatory analyses

3.5.1. Model fit values for non- linear associations between sleep duration, non-compliance, and symptoms of general psychopathology in the testing dataset (n=502)

In order to examine the non-linear association between sleep duration and general psychopathology, we conducted a confirmatory analysis using a linear regression model

including cubic regression splines with three knots for the variables sleep duration and non-compliance. The pooled results across the 10 imputed datasets can be found in **Table 4**. There were no significant associations between sleep duration, non-compliance with sleep guidelines, age, and symptoms of psychopathology. Girls had more symptoms of psychopathology when compared to boys. Season (spring and autumn) were not associated with more symptoms of psychopathology when compared to the season winter.

Table 4 *Results from a linear regression model estimating the non-linear effects of sleep duration and non-compliance with cubic splines including 3 knots on symptoms of general psychopathology (BSI-GSI-53) in the testing subsample (n=502)*

	Dependent variable		
Independent variables	BSI-GSI-53		
	β (SE)	b (SE)	p
Intercept	2.61 (2.44)	-	.29
Sleep duration	-.005 (.004)	-.30 (.23)	.20
Spline sleep duration with 3 knots	.004 (.003)	.25 (.20)	.21
Non-compliance	.001 (.003)	.07 (.21)	.75
Spline non-compliance with 3 knots	-.004 (.003)	-.22 (.19)	.26
Age	.04 (.04)	.10 (.11)	.35
Gender: girls	**.18 (.06)**	**.68 (1.35)**	**.004**
Season: spring	-.13 (.07)	-.21 (.11)	.06
Season: autumn	.02 (.09)	.04 (.16)	.80

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; SE= standard error

3.5.2. Model fit values for the linear associations between sleep quality and general symptoms of psychopathology

In order to assess the association between sleep quality and symptoms of general psychopathology, we conducted a confirmatory analysis using a linear regression model. The pooled results across the 10 imputed datasets can be found in **Table 5**. There were positive, significant associations between sleep quality, age, gender, and general symptoms of psychopathology. Girls had more symptoms of psychopathology when compared to boys. Season (spring and autumn) were not associated with more symptoms of psychopathology when compared to the season winter. Since we did not conduct measurements during the summer due to the students' break, no effects are reported for summer compared to winter.

Table 5 *Associations between sleep quality and psychopathology (BSI-GSI-53) estimated with a linear regression in the testing dataset (n=502)*

	Dependent variable		
Independent variables	BSI-GSI-53		
	β (SE)	b (SE)	p
Sleep quality	**.05 (.02)**	**.17 (.06)**	**.005**
Age	**.06 (.02)**	**.16 (.05)**	**.004**
Gender: girls	**.14 (.06)**	**.23 (.10)**	**.03**
Season: spring	-.13 (.07)	-.19 (.11)	.08
Season: autumn	.02 (.09)	.02 (.15)	.91

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; SE= standard error

3.6. Exploratory analyses

3.6.1. Model fit values for the associations between sleep duration and symptoms of depression, anxiety, and psychoticism in the testing dataset (n=502)

We conducted exploratory analyses using a linear regression model including cubic regression splines. The pooled results across the 10 imputed datasets can be found in **Table 6**. Sleep duration and non-compliance with sleep guidelines were unrelated to symptoms of depression, anxiety, and psychoticism. Girls had significantly more symptoms of depression, anxiety, and

psychoticism when compared to boys. During spring, adolescents reported significantly fewer symptoms of anxiety when compared to winter.

Table 6 *Results from a linear regression model estimating the non-linear effects of sleep duration and non-compliance with cubic splines including 3 knots on symptoms of depression, anxiety, and psychoticism from the BSI in the testing subsample (n=502)*

	Dependent variables					
Independent variables	Depression		Anxiety		Psychoticism	
	β (SE)	p	β (SE)	p	β (SE)	p
Intercept	2.67 (3.33)	.42	4.32 (2.71)	.11	1.04 (2.65)	.70
Sleep duration	-.008 (.005)	.15	-.008 (.004)	.08	-.003 (.004)	.51
Spline sleep duration with 3 knots	.007 (.004)	.08	-.0003 (.004)	.92	.003 (.004)	.43
Non-compliance	.004 (.005)	.36	-.004 (.003)	.23	.002 (.004)	.65
Splines non-compliance with 3 knots	-.007 (.004)	.09	-.004 (.003)	.20	-.003 (.004)	.44
Age	.08 (.06)	.18	-.005 (.05)	.91	.06 (.05)	.24
Gender: girls	.28 (.09)	**.003**	.17 (.07)	**.01**	.17 (.07)	**.01**
Season: spring	-.14 (.10)	.16	-.13 (.07)	.08	-.15 (.07)	**.04**
Season: autumn	.06 (.15)	.66	.05 (.10)	.63	.002 (.10)	.98

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; SE= standard error

3.6.2. Model fit values for the associations between sleep quality and symptoms of depression, anxiety, and psychoticism in the testing dataset (n=502)

We conducted exploratory analyses using a linear regression model. The pooled results across the 10 imputed datasets can be found in **Table 7**. We found positive, significant associations between sleep quality, depression, and psychoticism symptoms, whereas associations between sleep quality and anxiety symptoms were non-significant. Age was associated with more symptoms of depression and psychoticism. Girls had significantly more symptoms of

depression and anxiety when compared to boys. Adolescents did not report more symptoms of depression, anxiety, and psychoticism during spring and autumn when compared to winter.

Table 7 *Associations between sleep quality and symptoms of depression, anxiety, and psychoticism estimated with a linear regression in the testing dataset (n=502)*

	Dependent variables					
Independent variables	Depression		Anxiety		Psychoticism	
	β (SE)	p	β (SE)	p	β (SE)	p
Sleep quality	**.08 (.02)**	**<.001**	.02 (.02)	.32	**.05 (.02)**	**.01**
Age	**.10 (.03)**	**<.001**	.05 (.02)	.06	**.06 (.02)**	**.01**
Gender: girls	**.19 (.09)**	**.04**	**.16 (.07)**	**.02**	.12 (.07)	.07
Season: spring	-.11 (.09)	.30	-.13 (.07)	.07	-.13 (.07)	.07
Season: autumn	.07 (.14)	.62	.02 (.10)	.88	-.007 (.10)	.94

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; SE= standard error

4. Discussion

To the best of our knowledge, this is the first study investigating the associations of Fitbit Charge 2-derived sleep duration, sleep quality, and symptoms of general psychopathology in an adolescent general population sample. Our findings showed that Fitbit Charge 2-derived sleep duration and non-compliance with sleep guidelines were not significantly associated with general symptoms of psychopathology, whereas Fitbit Charge-2 derived sleep quality was significantly and positively related to symptoms of general psychopathology. Our exploratory analyses related to non-compliance and symptoms of depression, anxiety, and psychoticism showed that sleep duration and non-compliance with sleep guidelines were unrelated to symptoms of depression, anxiety, and psychoticism. Sleep quality was not associated with anxiety symptoms, but positively associated with symptoms of depression and psychoticism.

4.1. Confirmatory analyses – sleep and general psychopathology

4.1.1. Sleep duration, non-compliance with sleep guidelines, and general psychopathology.

Our non-significant results between sleep duration and general psychopathology are in contrast to previous significant findings from cross-sectional and longitudinal self-report studies suggesting adverse effects on mental health due to short sleep duration (Matamura et al., 2014) or parent-reported insufficient sleep (Hestetun et al., 2018). However, they are in line with results from the similarly-sized prospective Trondheim Early Secure Study, showing that accelerometery-measured short sleep duration at the age of 10 (n= 557) was not associated with emotional or behavioural disorders two years later (Ranum et al., 2019).

Similarly, also the prospective Auckland Birthweight Collaborative Study (n= 467) did not find any associations between objectively measured sleep at age 11 and depressive symptoms at age 16. (Slykerman et al., 2020). While keeping in mind that our power analysis suggests insufficient power to assess the sleep duration – psychopathology relationship (0.19), these and our findings add to an emerging picture that findings from objectively measured data do not align with those from self-report data studies. They challenge the previously established sleep duration – psychopathology relationship since objective sleep duration measures are considered to be more reliable in adolescents (Guedes et al., 2016) and individuals with psychopathology symptoms, hostility, and poor health (Matthews et al., 2018).

Alternatively, our non-significant findings may imply that other aspects of sleep duration, such as sleep duration variability and individual sleep duration needs are more relevant to psychopathology than general sleep duration. For example, objective data studies on within-person effects of sleep duration find that – when experiencing stressful life events - sleep duration variability relates to more anxiety symptoms in adolescents (Bustamante et al., 2020). These preliminary empirical findings suggest changes in sleep duration, rather than average sleep duration may be relevant for psychopathology symptoms. Increasing consensus suggests that sleep duration needs are variable across individuals, implying that recommendations from sleep guidelines may apply to most, but not to all individuals equally (Chaput et al., 2018). Therefore, an individualized approach assessing deviations from individual sleep duration needs may improve our understanding of the sleep duration – psychopathology relationship.

4.1.2. Sleep quality and general psychopathology symptoms.

Our counterintuitive, positive associations between sleep quality and general symptoms of psychopathology contradict previously reported negative associations between self-reported sleep quality and psychiatric symptoms (Hestetun et al., 2018). Given these inconsistent findings with previous literature, careful interpretation and consideration of the measure's limitations are warranted, yet remain constrained by the undisclosed algorithm of the Fitbit sleep quality score. This score consists of the components sleep duration (i.e. awakenings/time asleep), sleep quality (length of REM and deep sleep), and restoration (heartrate) (Fitbit, 2021c). Longer sleep durations, longer REM and deep sleep provide a higher score, whereas high sleeping heart rate lowers the score (Fitbit, 2021c).

However, firstly, sleep efficiency may not be adequately captured in the Fitbit sleep quality measure due to low sleep duration specificity (Haghayegh et al., 2019), which may have biased the sleep quality scores. Secondly, while sleep stage accuracy is low compared to polysomnography (Lee et al., 2019; Menghini et al., 2021), it is unclear what exact amount of REM sleep has been considered as healthy due to the undisclosed algorithm. Since extensive REM sleep has been linked with depression (Riemann et al., 2020), not accounting for this in the Fitbit's algorithm may have biased the Fitbit sleep quality score towards positive associations with psychopathology symptoms. Thirdly, the heart rate measure in the sleep quality score may have biased our findings, since arousal and low parasympathetic activity have been associated with depression (Kemp et al., 2010).

Despite the outlined limitations, opting for alternatives to measure sleep quality as suggested by reviewers was not possible in this study. Given the low accuracy to capture awakening periods and lack of valid data in the variables sleep onset latency and wake after sleep onset in our sample, we could not use sleep efficiency (the ratio between time in bed vs. time asleep), which is the gold standard measure for sleep quality (Ohayon et al., 2017), as an alternative measure. Additionally, controlling for the effects of heart rate was not possible as we did not use minute-level data within this study. Hopefully, reporting our findings may raise awareness of the device's limitations and lack of interpretability, particularly given the wide-spread and increasing use of Fitbit devices – currently 711 studies are registered - (ClinicalTrials.gov, 2021) in research .In light of the potentially even more crucial role of sleep quality in psychopathology development compared to sleep duration (Bin, 2016; Hestetun et al., 2018;

Muzni et al., 2021; Wainberg et al., 2021), more rigorous and transparent approaches to measuring sleep quality using commercially-available wearables need to be developed.

4.2. Exploratory analyses

4.2.1. Sleep duration, non-compliance with sleep guidelines, and symptoms of depression, anxiety, and psychoticism.

Similar to our confirmatory analyses, our non-significant findings of sleep duration, non-compliance with sleep duration guidelines, and symptoms of depression, anxiety, and psychoticism diverge from large-scale self-report studies, reporting associations between both short and long sleep duration and risk for symptoms of psychoticism (Morishima et al., 2020), depression, and anxiety (Ojio et al., 2016). However, they are in line with those from the Auckland Birthweight Collaborative Study (n=871; 50.5% girls), showing that accelerometery-derived sleep duration in 11-year olds was neither cross-sectionally nor longitudinally associated with depressive symptoms at the age of 16 (n= 491) (Slykerman et al., 2020).

4.2.2. Sleep quality and symptoms of depression, anxiety, and psychoticism.

Our positive, significant, and weak associations between sleep quality and depression do not align with findings from objectively measured (Hamann et al., 2019) and subjectively-assessed self-report data (Kaneita et al., 2009; Raniti et al., 2017). Similarly, the significant, positive, and weak associations between symptoms of psychoticism are in contrast with an accelerometery measured sleep quality and psychotic-like experiences study (N=814) (Koopman-Verhoeff et al., 2019). These inconsistent findings with previous literature require cautious interpretation due to the limitations of the Fitbit sleep score measure as elaborated above.

4.3. Strengths and limitations

Our study has several considerable strengths. First, we aimed to ensure maximal rigor by using open science practices (post-registration and open code) to increase the transparency and reproducibility of our work, conducting a simulation-based power analysis, and addressing missing data using multiple imputation methods for multilevel data in order to decrease the risk of bias (van Ginkel et al., 2020). Second, given the absence of a 'gold standard' for handling missing Fitbit data (Feehan et al., 2018), our method may be a starting point to help to increase the rigor of future research using Fitbit devices.

Our results also need to be interpreted in light of some limitations. First, the design of our study may have influenced participants' sleep routine despite our instructions to maintain their normal routine. Since participants responded also to early-morning or late-evening Experience Sampling questionnaires (data not used in the current study), some participants may have got up earlier in the weekend or stayed up later to answer the questionnaires. Second, as mentioned earlier in the discussion, the Fitbit sleep quality score has considerable limitations which decrease the interpretability of our findings. Future work may opt for an alternative, more transparent measure for more reliable interpretation of the sleep quality findings.

Third, the data within this study are cross-sectional. Therefore, causality of the relationship cannot be inferred. Forth, we did not empirically evaluate if the multiple multilevel imputation of the outcome variables depression, anxiety, psychoticism, and general psychopathology was warranted. When not imputed, sleep duration and non-compliance with sleep duration guidelines were associated with more symptoms of depression and anxiety in general population adolescents. Also, sleep quality was not associated with general psychopathology and psychoticism symptoms when these variables were not imputed (**Appendix F**). Although multiple imputation is theoretically and we followed a 2-step approach to evaluate the validity of imputation (**Appendix F**), future research needs to explore empirically the reliability and appropriateness of multiple imputation and listwise deletion within this type of data.

5. Conclusion

To conclude, our study does not provide evidence that Fitbit Charge 2-derived sleep duration and non-compliance with sleep guidelines are associated with symptoms of psychopathology in the general adolescent population. A more individualized approach, considering unique sleep duration needs and variability in day-to-day sleep durations may be alternative ways to improve our understanding of the objectively measured sleep duration – psychopathology relationship. Our findings suggesting an association between Fitbit Charge 2-derived better sleep quality and more symptoms of depression, psychoticism, and general psychopathology require cautious interpretation due to the proprietary Fitbit algorithm used to derive sleep quality values. Alternative, more transparent measures of sleep quality may increase the validity of future research.

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Chapter 5 - Coping and sleep quality in youth: An Experience Sampling study

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Abstract

Introduction: Sleep quality is closely linked with mental health. Two factors that influence sleep are coping style and locus of control, yet these have not been investigated in daily life. In this study, we examined associations between coping styles and sleep quality in daily life and the potential mediating effect of daily locus of control in a sample of youth, a group particularly vulnerable to developing psychopathology.

Methods: 379 youths from the TwinssCan study participated in an Experience Sampling study, assessing sleep quality as well as state locus of control over the most negative event from the previous day. Participants also completed the Utrecht Coping List, which assessed engagement, disengagement, and emotion-focused coping.

Results: Disengagement, 'passive reaction, and emotion-focused coping were associated with lower daily sleep quality. State locus of control did not mediate any effects of coping styles on quality of sleep.

Conclusions: Disengagement, 'passive reaction', and emotion-focused coping were associated with decreased sleep quality during several consecutive days, which may put youths at risk for developing future insomnia, and strain their mental well-being over time. Thus, there may be value in asking about coping when a young individual presents with sleep problems; however, impaired coping when sleeping poorly should also be considered.

1. Introduction

One in three youths experience decreased sleep quality (Li et al., 2020). Broadly, the term 'sleep quality' encompasses 'one's satisfaction with the sleep experience, integrating aspects of sleep initiation, sleep maintenance, sleep quantity, and refreshment upon awakening' (Kline, 2013, p.117). Poor sleep quality is associated with impaired daytime functioning including decreased daytime alertness, low school performance, and depressed mood (Short et al., 2013). Longitudinal research has shown that poor sleep quality can, directly or indirectly, be a catalyst for the development of poor mental health in adolescents (Kaneita et al., 2009). Promoting good quality sleep, including subjective sleep satisfaction, maintenance, refreshment, and adequate initiation (≤ 30 min) (Ohayon et al., 2017) during adolescence is therefore important for good adolescent health, well-being, and development.

Poor sleep quality, such as experiencing difficulty falling asleep and waking up frequently, are influenced by many factors, one of which is an individual's coping style (Kalmbach et al., 2018). Coping style is an individual's behavioural, emotional or cognitive response when being in a subjectively stressful situation (Ellen A. Skinner et al., 2003). Coping has been conceptualised *both* as a state or situational response to a specific stressor (Lazarus & Folkman, 1984), and as a trait or disposition (Carver & Scheier, 1994). State coping assumes that coping varies depending on contextual aspects, such as the personal resources of the individual and the appraised meaning of the stressor (Lazarus & Folkman, 1984). Trait coping assumes that individuals tend to apply certain coping styles consistently across situations (Carver & Scheier, 1994).

Empirical evidence suggests that individuals have internalized both a state and a trait component of coping, as equal variability between state and trait coping style use was found in within- and between person analyses (Roesch et al., 2010) applying the Experience Sampling Method (ESM; (Csikszentmihalyi & Larson, 1987; Myin-Germeys et al., 2018). This (partial) consistency in coping may be explained by, on the one hand, a certain balance between given demands within an individual's life, and stable resources of the individual, on the other (Roesch et al., 2010).

Coping models have structured an individual's stress response in terms of emotion- or problem-focus (Lazarus & Folkman, 1984), or the individual's possibility for adaption (i.e. accommodative coping (Skinner et al., 2003), among many others. Further higher-order

distinctions of coping strategies have been made, whereby the grouping into *engagement* and *disengagement* coping seems to be of greatest importance (Carver & Connor-Smith, 2010). *Engagement* coping styles include behavioural and cognitive efforts to engage with the stressor in an attempt to reduce it and minimize associated emotions. These include *active coping* (e.g. confidently working on solving the problem), *comforting thoughts coping* (e.g. putting things into perspective) and *seeking social support* (e.g. talking to a friend) (Dijkstra & Homan, 2016). *Disengagement* coping styles relate to diverting oneself from the stressor and avoiding related emotions, such as *palliative reaction* (e.g. seeking lively company when feeling worried), *avoidance* (e.g. waiting and seeing what happens), and *reacting passively* (e.g. letting oneself to be overcome by the problem) (Dijkstra & Homan, 2016). Another form of coping is *expressing emotions/anger* (e.g. showing one's frustration), which can be considered neither as engagement nor disengagement coping and should be viewed as a distinct form of coping (Dijkstra & Homan, 2016).

Along with coping, control also plays an important role in human behaviour. Locus of control is defined as a *trait* and the degree to which an individual cross-situationally attributes outcomes and events in their life to their own behaviour (internal locus), as opposed to external forces (external locus) (Rotter, 1954). While the definition of locus of control relates to the individual's *general* belief of control, previous studies on well-being have also conceptualized locus of control as situational or a *state* (Keeton et al., 2008; Ryon & Gleason, 2014). For consistency with previous literature, we also will apply the term *state* locus of control. We use this term synonymously with previously defined state control terms, such as control appraisal (Lazarus & Folkman, 1984) and self-efficacy (Bandura, 1977).

Control and coping are bi-directionally linked. According to coping theory (Lazarus & Folkman, 1984, p. 80) and Social Learning Theory (Bandura, 1977), an individual's state locus of control in a given situation influences the effectiveness and efforts of coping: If control is low, fewer coping efforts will be made, reinforcing a sense of low control. Emotion-focused coping is expected to lead to better outcomes in low control situations. If control is high, more coping efforts will be made. If these are successful, this mastery experience will in turn reinforce an individual's locus of control, and lead to better outcomes. However, the idea that the effectiveness of coping depends on the controllability of the stressor has received mixed empirical support, but studies find that - generally - active coping leads to better, and

disengagement and emotion-focused coping (i.e. venting emotions) to worse adjustment *regardless of controllability* of the situation (Stanisławski, 2019).

Vice versa, coping behaviour also influences state locus of control (Ellen A. Skinner & Zimmer-Gembeck, 2011). The way that an individual copes in real life builds the foundation of his or her locus of control, as it may become an experience of control itself (Ellen A. Skinner & Zimmer-Gembeck, 2011). As such, engagement coping increases feelings of competence (i.e. higher control), while disengagement coping may enhance perceptions of helplessness (i.e. lower control) (Ellen A. Skinner & Zimmer-Gembeck, 2011).

To date, the former relationship of locus of control affecting coping has been investigated more intensely in youth (Boals et al., 2011; Borecka-Biernat, 2020; Doron et al., 2009; Kurtović et al., 2018), whereas studies investigating the effects of coping on control are scarce and limited to the adult population (Dijkstra & Homan, 2016). Recent studies have investigated the relationship of coping with adolescent mental health. For example, disengagement coping styles have been associated with more negative mood (Santiago et al., 2017) and non-suicidal self-injury (Kiekens et al., 2015), whereas using more engagement coping buffered poverty-related stress on negative and positive mood (Santiago et al., 2017), and was unrelated to non-suicidal self-injury (Kiekens et al., 2015).

Also, in sleep, a role of coping has been suggested. The findings from existing literature on coping and sleep quality are limited; results are mixed, differ between subjective and objective measures and domain of sleep quality, and suggest a unidirectional association. 'Social support' coping was associated with better *subjective* sleep quality (van Schalkwijk et al., 2015), while 'problem-focused' coping was not (Matthews et al., 2016; Sadeh et al., 2004). When measured *objectively*, engagement coping is partially related to longer sleep duration (Matthews et al., 2016; Sadeh et al., 2004), delayed sleep, and daytime sleepiness (Matthews et al., 2016), but is not associated with sleep fragmentation (Matthews et al., 2016; Sadeh et al., 2004). In sum, 'social support' coping seems to relate to better sleep quality, whereas overall engagement coping only partially improves sleep (i.e. sleep duration).

Studies investigating the effects of *disengagement* coping found no statistically significant associations with overall *subjective* sleep quality (Matthews et al., 2016; Sadeh et al., 2004). In *objectively* measured sleep, *disengagement* coping was related to *objectively* measured shorter

sleep duration, fragmented sleep, delayed sleep, and daytime sleepiness in one study (Matthews et al., 2016), but not in another (Sadeh et al., 2004). *Emotion-focused* coping was associated with reduced *subjective* sleep quality and decreased *objective* sleep duration during periods of high stress only (Sadeh et al., 2004). Taken together, disengagement coping and emotion-focused coping seem to relate to poor-quality sleep in youth.

Overall, these previous studies suggest that the coping - sleep literature is in line with previous studies on coping and well-being in youth. However, associations between coping and *subjective* sleep quality are mostly non-significant. This may be because *overall* subjective sleep quality was assessed, and the subdomains of sleep quality were not considered. Studies also differed in the way in which coping strategies were grouped into coping styles and engagement or disengagement coping, since consensus on the structure of coping is lacking (Compas et al., 2017; Stanisławski, 2019).

To date, the exact nature of the relationship between coping and sleep is unclear. One potential pathway could be via hyperarousal and low control. When individuals apply disengagement coping - an important contributor to insomnia (Riemann et al., 2020) – empirical evidence suggests that perceptions of control are lowered (Ellen A. Skinner & Zimmer-Gembeck, 2011) and, consequently, hyperarousal increases (Liu et al., 2021). This process happens through a negative feedback loop, where unsuccessful coping increases helplessness and lowers control (Ellen A. Skinner & Zimmer-Gembeck, 2011). Lower control has been unidirectionally associated with poor sleep in adolescents (Alfano et al., 2009; DeAngelis et al., 2019), which relates to a heighted stress response (Liu et al., 2021) and is incompatible with sleep (Riemann et al., 2020). Consequently, poor sleep quality develops as a process involving hyperarousal and low control. This suggested relationship may apply regardless of situational controllability, since empirical evidence suggests that negative health outcomes relate to disengagement coping across situations (Stanisławski, 2019).

Currently, it also remains unclear whether effects of coping on sleep may be age-dependent. Youth undergo tremendous maturational development when transitioning to adulthood, involving cognitive, social, and affective changes, including coping (Zimmer-Gembeck & Skinner, 2011) and sleep (Park et al., 2019), which may extend at least until the mid-twenties. Over time, adolescents develop more coping capacities, moving from reliance on adults to self-

reliance when employing problem-solving coping, and learning to adjust their coping styles to be situationally appropriate. (Zimmer-Gembeck & Skinner, 2011). Further, adolescents' sleep duration and quality decrease as they become older (Park et al., 2019). Moreover, due to the hierarchical phasic development of the brain, with cognitive abilities maturing during adolescence (up to 19 years old), and cognitive-emotional capacity maturing within the twenties (Simmonds et al., 2014), younger youth (15-20 years old) and older youth (21-25 years old) may also differ with regard to coping and sleep. Yet, previous studies have overlooked age-specific effects of coping on sleep. To date, previous studies have looked at coping either within younger (mean age 15 years) (Matthews et al., 2016; van Schalkwijk et al., 2015) or older youth (mean age 24 years) (Faber & Schlarb, 2016; Sadeh et al., 2004) samples – yet studies looking at both age groups are lacking. Therefore, we conducted exploratory analyses within these two age groups as determined by their chronological age.

In the current study, we use pre-existing Experience Sampling Method data from a large study of adolescent twins, triplets, and their non-twin siblings. The experience sampling method (ESM; Csikszentmihalyi & Larson, 1987; Myin-Germeys et al., 2018) is a measurement technique that captures individuals' experiences of daily life at multiple time points, which leads to a more diverse and complete picture compared to retrospective, single time-point measurements, such as questionnaires (Hektner et al., 2007; Mehl & Conner, 2012) and is therefore ideally suited to capture the within-person fluctuations in control and sleep (Keeton et al., 2008; Ryon & Gleason, 2014).

We aim to test our suggested theoretical model of coping – control- sleep by investigating (1) how trait coping styles relate to sleep at the daily level in youth. Furthermore, we investigate (2) if state locus of control mediates the association between trait coping style and quality of sleep. First, we hypothesize that individuals with engagement coping styles will report higher sleep quality, whilst individuals using disengagement coping styles will report lower quality of sleep. Second, we hypothesize that the engagement coping and sleep quality relationship will be mediated by higher internal state locus of control, whilst the disengagement coping and sleep relationship will be mediated by a lower internal daily locus of control. Exploratory analyses will be conducted for age-dependent effects of coping on sleep. Upon reviewer request, we also estimated the direct and indirect effects of an alternative model, control – coping – sleep, in exploratory analyses.[i]

2. Methods

2.1 Participants

We used wave 1 data from TwinssCan, a longitudinal Twin Study of adolescent twins and their siblings, recruited from the East Flanders Prospective Twin Survey (Derom et al., 2019; Pries et al., 2019; www.twins.be). Data used in the current study were from a pre-existing dataset, in which baseline data were collected between 2010 and 2014 (Pries et al., 2019). Participants were recruited through a newsletter invitation aiming to better understand the role of aberrant salience, reward sensitivity, and stress sensitivity as indicators for psychotic and depressive lability. The study included structured interviews, neurocognition and experimental tasks, questionnaires, and data collected using ESM.

Inclusion criteria for TwinssCan were (1) being aged 15-35 years, (2) sufficient understanding and ability to verbally describe the study procedure and give informed consent (if below age 18, consent was given by caregiver), (3) ability to provide valid, reliable and complete data in the questionnaires, structured interviews, and experimental tasks. The only exclusion criterion was the presence of pervasive mental disorders as indicated by the caregiver. In our study, we used a youth subsample of the TwinssCan sample, namely, all participants aged 15-25 years. The study was approved by the Medical Ethics Review Committee at the KU Leuven University Hospital (Commissie Medische Ethiek van de Universitaire ziekenhuizen KU Leuven, Nr. B32220107766).

2.2. Measures

2.2.1 Experience Sampling Method (ESM): Daily locus of control and sleep quality

The ESM is a structured diary technique that assesses current experiences and contexts in everyday life (Hektner et al., 2007; Mehl & Conner, 2012; Myin-Germeys et al., 2018). To report their experiences, participants received an electronic personal diary assistant (PDA), called “Psy-Mate” (patented) which emitted a signal (“beep”) at random moments, ten times per day between 7:30 am and 10:30 pm, whereupon participants were presented with a short questionnaire during 6 consecutive days. Additionally, they received daily morning and evening questionnaires, which included prospective and retrospective questions about the current day, respectively. Daily locus of control and quality of sleep were assessed at the daily level using ESM.

In the morning questionnaire, participants were asked to rate the quality of their sleep on the previous night ("I slept well") on a 7-point Likert-type scale ranging from 1 (do not agree) to 7 (very much agree) in the morning. Using a single Likert item to assess the previous night's sleep quality has been considered the most appropriate and accepted way of measuring overall sleep quality, as it provides a distinction from single sleep parameters, such as sleep onset latency or awakenings at night (Kline, 2013; Krystal & Edinger, 2008).

Also, single items are a common way to assess behaviour and experiences in ESM research. In the evening, participants were asked to report the extent to which they had control over the most unpleasant event of the day ("How much control did you have over this event?") on a 7-point Likert-type scale ranging from 1 (very little) to 7 (a lot). Individuals were briefed about the measurement procedure beforehand and practiced the questionnaire in a demo version to familiarize themselves with the 1-7 Likert-type response format on daily locus of control and the sleep quality, and the -3 to +3 Likert-type response format about the pleasantness of the most negative event.

2.2.2. Coping-style

Individuals' general coping-style was assessed with the original Dutch version of the Utrecht Coping List (UCL; (Schreurs, Tellegen, & Willige, 1984). The UCL is a 47-item questionnaire, which measures seven different coping styles, which were all considered separately: active tackling, avoidance, comforting thoughts, expressing emotions, palliative reaction, passive reaction, and social support. Example items for each of the coping style subscales are: "working purposefully on a solution for the problem" (active tackling); "trying to avoid difficult situations" (avoidance); "thinking that worse things could also happen to you" (comforting thoughts); "showing that you are angry at the person who is responsible" (expressing emotions); "talking to friends and family about the problem" (social support); "feeling like you cannot do anything about the problem" (passive reaction); and "trying to feel better about the situation through drinking alcohol" (palliative reaction). Active tackling, comforting thoughts, and social support are considered engagement coping, whereas avoidance, palliative reaction, and passive reaction are considered disengagement coping.

Expressing emotion is seen as a separate coping style which fits neither engagement nor disengagement coping (Dijkstra & Homan, 2016). Responses are given on a four-point Likert-type scale from 1 (never) to 4 (very often), to indicate how often they generally use a specific

coping style when dealing with challenges in daily life. Per subscale, the raw scores were transformed into norm scores via a 5-point norm table, running from very low to very high. The number of items per scale differed: active tackling consisted of seven items, avoidance of eight items, comforting thoughts of five items, expressing emotions of three items, palliative reaction of eight items, passive reaction of eight items, and social support of six items. Mean values were calculated separately for each subscale. The UCL has been validated in both adolescents and adults (Sanderman & Ormel, 1992; Schaufeli & Van Dierendonck, 1992).

2.3. Inclusion and exclusion criteria

The full wave 1 sample consisted of 840 twins, triplets, and their siblings aged 15-35 years old. Participants completing less than 33% of the ESM measurements (i.e. 18 beeps) were excluded from the sample (N=790). We had no access to the full wave 1 sample and were therefore unable to account for these missing data due to incomplete beeps. Further exclusion criteria for this study were a) <15 years and > 25 years old (N=747), b) rating the most negative event of the day as positive (N=719), and c) completing ESM data beyond the 6-day ESM measurement period (N=718), to preserve data quality.

Rating the most negative event of the day was assessed as follows: "Think about the most negative event of the day. This event was: very unpleasant (-3) to very pleasant (+3)". Participants rating the most negative event of the day as positive (i.e., from +3 to +1) were excluded. Participants continuing with ESM beyond the protocol period were given extra time to complete ESM due to answering less than 30% of the questionnaires within the six-day period, and they may therefore generally differ from the rest of sample. Lastly, we excluded d) participants having less than 3 pairs of rated lagged state locus of control in the evening and subsequently rated sleep quality in the morning (N=386). The final sample of this study consisted of 386 participants aged 15-25 years old. Among 386 participants, 349 were twins (134 monozygotic), 11 were triplets, 25 were non-twin siblings, and 1 participant with unknown status.

2.4. Missing data exploration

After having applied our inclusion and exclusion criteria, our dataset consisted of 386 participants. In this sample, 1.3% of coping data, 19% of the lagged state locus control data, and 13% of the sleep quality data were missing. We explored patterns of missing data using Little's Test for Missing Completely At Random (MCAR) (Little, 1988) within Stata Version

15.1 (StataCorp, 2017). According to our results, the missing data within our sample were not missing completely at random (X^2 = 124.11; df = 69; p = < 0.001).

2.5. Statistical analysis

2.5.1 Path c: Total effects of coping on sleep (theoretical model) and effects of locus of control on sleep (alternative model)

In our theoretical model in path c, we investigated the effects of seven different trait coping styles on quality of sleep as measured daily with the ESM. The values of the coping subscales were divided by the number of items to create an average and were mean-centred using the grand mean. All coping styles, age, and gender were included in the same model. The data were hierarchically structured, with quality of sleep over six consecutive days (level 1) nested within individuals (level 2), nested within twin pairs (level 3). Linear mixed effect models (LMM), treating the twin-pair as a random effect with the subject nested within, enabled assessment of between-individual differences (intercepts).

The model was fit using the "lmerTest"-package (Kuznetsova et al., 2017) in RStudio version 3.6.2 (RStudio Team, 2015). Random effects were added for the coping styles, with coping style nested within the "individual", nested within "twin-pair". We accounted for multiple comparisons with a Bonferroni correction (Bonferroni, 1936), by adjusting the test for significant effects relative to the number of estimated models. Since we estimated paths a, b, and c, we divided our p-value of 0.05 by three (adjusted cut-off p-value = 0.017) when estimating the effects of coping on sleep and the indirect, mediated effects of locus of control in the coping-sleep relationship.

In the alternative model suggested by a reviewer, we investigated the effects of state locus of control on subjective sleep quality, which were both measured with the ESM. The values of the state locus control variable were person-mean centred. The model included also age and gender. As in the theoretical model, we accounted for the three levels of the data, and fit the model using the "lmerTest package (Kuznetsova et al., 2017) in RStudio version 3.6.2 (RStudio Team, 2015).

2.5.2. Path ab: The mediating role of state locus of control in the coping-sleep relationship (theoretical model) and the mediating role of coping in the control-sleep relationship

Within our theoretical model, we aimed to investigate the possible mediation of state locus of control in the coping sleep-relationship (**Fig. 1**). While coping was measured at baseline, state locus of control was measured at t, and quality of sleep was measured at t+1; therefore, state locus of control was lagged within individuals. As coping is a level 2 variable, we conducted a 2-1-1 mediation analysis. We used the analysis of the indirect effect, a more contemporary approach than the common four-step procedure (Baron & Kenny, 1986; James & Brett, 1984; Judd & Kenny, 1981). One test for the indirect effects, is to build confidence intervals (CIs) for mediated effects (MacKinnon, Fritz, Williams, & Lockwood, 2007). The mediated effect is the product of two regression coefficients, of path a and path b. The distribution-of-the-product method has the best statistical performance of existing methods for building CIs for the mediated effects (Tofighi & MacKinnon, 2011).

One single mediation model was tested for all coping styles together. Both path a and path b were assessed by separate linear mixed models (LMM) using the R package "lmerTest" (Kuznetsova et al., 2017). A random slope for daily locus of control, nested within individuals, was added. State locus of control was within-person centred. Gender and age were added as covariates. Significance was approximated by Wald based 95% confidence intervals around fixed effects. Random slopes were not assessed. Standardized indirect effects were estimated using R package "Rmediation" (Tofighi & MacKinnon, 2011). Confidence intervals (CI) were estimated by the product of confidence limits for indirect effects procedure (PRODCLIN; MacKinnon et al., 2007). We did not test for direct effects, or pathway c', within our mediation analysis, as traditional mediation analysis is not recommended in multilevel models (Bauer, Preacher, & Gil, 2006).

We accounted for multiple testing in the mediation analysis by increasing the 95% CI to 99.65%, which is equivalent to an adjusted p-value of 0.017 (3 models were tested), because the R package RMediation only provides confidence intervals but not p-values (Tofighi & MacKinnon, 2011). To account for developmental differences within our youth sample (15-25 years old), we conducted a sensitivity analysis for younger (15-20 years old) and older (21-25 years old) youth (see Supplement). In the alternative model, we aimed to explore the mediating role of coping in the state locus of control – sleep quality relationship. We used the same approach as for the theoretical model described above, the distribution-of-the-product-method

(Tofighi & MacKinnon, 2011), however with different paths a and b. In both paths, control and coping were person-mean centered.

2.5.3 Descriptive statistics

Pearson's correlations were calculated in Stata version 15 (StataCorp, 2017), means and standard deviations in RStudio version 3.6.3 (RStudio Team, 2015).

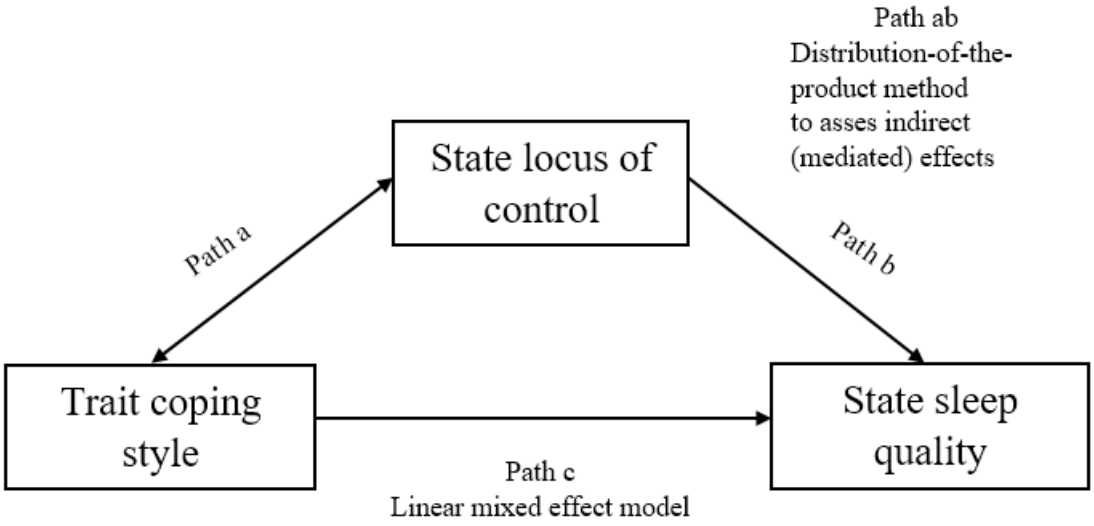

Fig. 1: *Conceptual model of the proposed bi-directional relationships between coping style, state locus of control, and quality of sleep. In our theoretical model, coping was measured at baseline, state locus of control during the ESM period each evening (at t), and quality of sleep during the ESM period each morning on the following day (t+1). A 2-1-1 mediation analysis was conducted.*
In our alternative model, the effects of state locus of control in the evening (at t) on trait coping and sleep quality the next day (at t+1) were assessed. A 1-2-1 mediation analysis was estimated.

3. Results

3.1 Sample

The mean age of the final sample (N=386) was 17.40 years old (SD = 2.46) and 38.26% were male. The average number of ESM days was 5.21 (.69), overall non-compliance was 14%. In the younger subsample (n=343; 15-20 years old), the mean age was 16.70 (SD = 1.47) and 39.88% were male. In the older subsample (n= 43; 21-25 years old), the mean age was 23.10 (SD = 1.24) and 27.91% were male. Our sample (N=386) including participants with at least 3 pairs of rated locus of control items in the evening and sleep quality items the following morning did not differ significantly from the sample with less than 3 pairs of locus of control and sleep (N=332) in terms of sleep quality, coping style, and state locus control. We provide an overview of the means, standard deviations, and zero-order correlations among study variables are reported in **Table 1**.

Table 1 *Descriptive statistics: Means, standard deviations, and correlations of all included variables (N=379)*

Measure		Mean	SD	Correlation						
				1	2	3	4	5	6	7
Coping styles										
	1. Active	2.47	.47	____						
	2. Comforting thoughts	2.47	.51	.47***	____					
	3. Social support	2.41	.63	.19***	.18***	____				
	4. Emotion-focused	2.27	.42	.09***	<.01	.26****	____			
	5. Passive reaction	1.71	.51	-.10***	-.05*	-.05*	.19***	____		
	6. Palliative reaction	2.27	.42	.18***	.32***	.22***	.27***	.19***	____	
	7. Avoidant	2.05	.42	.03	.21***	-.09***	-.01	.33***	.35***	____
Daily locus of control		3.26	1.83	-.02	.06*	-.01	-.05	-.01	.08***	.05
Sleep quality		5.19	1.83	.01***	.05*	-.04*	-.11***	-.19***	.03	-.01
	Number of ESM days	5.21	.69							
Control Variables	Age	17.40	2.46	.18***	.13***	.23**	-.01	-.03	.02	-.03
	Gender (% female)	61.74		-.17***	.08***	-.27***	-.03	.15***	.04	-.01

*Note: SD = standard deviation, ESM = Experience Sampling Method, * = p-value < 0.05, ** = p-value < 0.01, *** = p-value < 0.001*

3.2 Theoretical model: Associations between coping styles and quality of sleep

There were significant negative associations between emotion-focused coping, 'passive-reaction' coping, and sleep quality. Associations between active coping, comforting thoughts coping, social support coping, palliative reaction coping, and avoidant coping were non-significant. Older age was significantly related to lower sleep quality, while gender was unrelated to sleep quality. Within this model, and also the following ones, we estimated the models in the full sample (N=386), yet the output of the models showed only results for N=379, due to missingness within our data.

When we estimated the exploratory effects of overall engagement (i.e.; active, social support, and comforting thoughts coping) and disengagement coping (i.e.; passive reaction, palliative reaction, and avoidant coping) within one model, including the control variable age and gender, there was an overall significant negative association of disengagement coping with sleep quality, while there were no overall effects of engagement coping. The control variable age and gender were significant.

In our sensitivity analysis, we found that - compared to the findings in the overall sample - active coping was also associated with better sleep quality in the younger youth subsample, whereas disengagement coping was not. In the older youth subsample, more social support coping and engagement coping also related to better sleep quality, while emotion-focused coping and disengagement coping were no longer significantly related to sleep quality. See **Table 2** for full results and the **Supplement** for the sensitivity analysis.

Table 2 *Direct effects of coping – sleep (theoretical model) and control – sleep (alternative model) in N=379 using linear mixed effects models*

Independent variable	Dependent variable	Path c	β (SE)	95% CI	p
Theoretical model: Total effects of coping – sleep (path c)					
Coping	Quality of sleep				
Active			.26 (.12)	.02 - .50	**.03**
Comforting thoughts			-.08 (.11)	-.30 - .15	.50
Social support			-.01 (.09)	-.19 - .16	.87
Emotion-focused			-.22 (.09)	-.40 - -.04	**.01***
Passive reaction			-.50 (.11)	-.71 - -.29	**<.001***
Palliative reaction			.24 (.13)	-.02 - .50	.07
Avoidant			.05 (.13)	-.20 - .31	.68
Age			-.05 (.02)	-.09 - -.01	**.02**
Gender			-.15 (.11)	-.36 - .07	.18
Grouped coping style effects					
Engagement			.08 (.05)	-.006 - .17	.07
Disengagement			-.13 (.05)	-.23 - -.03	.009
Age			-.05 (.02)	-.09 - -.006	**.03**
Gender			-.27 (.10)	-.48 - -.07	**.02**
Alternative model: Total effects of state locus control – sleep (path c)					
Locus of control	Quality of sleep		-.005 (.02)	-.09 - -.01	**.01**
Age			-.04 (.02)	-.08 - -.0005	.05
Gender			-.27 (.11)	-.47 - -.06	**.01**

*Note: β = regression coefficient, SE = standard error, CI= confidence interval, in bold = p < 0.05; * = remains statistically significant after Bonferroni correction applied (adjusted cut-off p = 0.017)*

3.3 Theoretical model: Mediated (indirect) effects of coping on quality of sleep via state locus of control

3.3.1 Effects of coping style on state locus of control (Pathway a)

The results of the analysis of the relationship between coping and state locus of control can be found in **Table 3**. There were significant positive associations 'palliative reaction' and state locus of control after adjusting for the Bonferroni correction. There no significant associations between active coping, comforting thoughts coping, social support coping, emotion-focused coping, passive coping, avoidant coping, and state locus of control. Age and gender were not associated with state locus of control.

3.3.2 Effect of state locus of control on quality of sleep (Pathway b)

Full results for this analysis are given in **Table 3**. State locus of control was not significantly related with quality of sleep anymore after adjusting for multiple testing.

3.3.3 Indirect effects of coping on quality of sleep (Pathway ab)

There were no significant mediated effects of state locus of control between any coping style and quality of sleep. Likewise, within our sensitivity analysis, did not find any indirect effects of daily locus of control in the younger (15-20 years-old) and older (21-25 years-old) subsample. See **Table 5** for full results and the Supplement for the sensitivity analysis.

Table 3 *Estimates and confidence intervals for estimated pathways a and b using mixed effects linear models in the overall sample (N=379) for the theoretical model*

Theoretical model: Coping – locus of control - sleep					
Independent variable	Dependent variable	Path	Estimates		
Coping	State locus of control	path a	β (SE)	95% CI	p
Active			-.18 (.15)	-.47 – .11	.22
Comforting thoughts			.21 (.14)	-.06 – .48	.13
Social support			-.05 (.11)	-.26 – .16	.61
Emotion-focused			-.15 (.11)	-.36 – .06	.16
Passive reaction			-.10 (.13)	-.35 – .15	.44
Palliative reaction			**.40 (.16)**	**.08 – .07**	**.01***
Avoidant			.06 (.16)	-.25 – .37	.44
Age			-.02 (.03)	-.07 – .03	.39
Gender			.12 (.11)	-.14 – .38	.36
State locus of control	Quality of sleep	path b	-.02 (.13)	-.09 – -.006	**.04**

*Note: β = regression coefficient, SE = standard error, CI= confidence interval, in bold = p < 0.05, * = remained statistically significant after adjusted Bonferroni correction (p = 0.017)*

Table 4 *Estimates and confidence intervals for estimated pathways a and b using mixed effects linear models in the overall sample (N=379) for the alternative model*

Alternative model: Locus of control – coping - sleep					
Independent variable	Dependent variable	Path		Estimates	
State locus of control	Coping	path a	β (SE)	95% CI	p
	Active		-.004 (.02)	-.06 - .05	.83
	Comforting thoughts		**.05 (.02)**	**-.01 - .10**	**.03**
	Social support		-.01 (.03)	-.08 - .06	.60
	Emotion-focused		-.03 (.03)	-.10 - .04	.27
	Passive reaction		-.01 (.02)	-.07 - .05	.56
	Palliative reaction		**.05 (.02)**	**.001 - .01**	**.008**
	Avoidant		.03 (.02)	-.004 - .03	.12
	Age		-	-	
	Gender		-	-	
Coping	Quality of sleep	path b	β (SE)	95% CI	p
Active			**.31 (.13)**		**.01**
Comforting thoughts			-.09 (.12)		.45
Social support			-.05 (.09)		.55
Emotion-focused			-.18 (.09)		.03
Passive reaction			**-.50 (.09)**		**<.01**
Palliative reaction			.24 (.14)		.07
Avoidant			.04 (.14)		.76
Age			**-.06 (.02)**		**.009**
Gender			-.09 (.11)		.41

*Note: β = regression coefficient, SE = standard error, CI= confidence interval, in bold = p < 0.05, * = remained statistically significant after adjusted Bonferroni correction (p = 0.017)*

Table 5 *Mediated (indirect) effects of locus of control in the coping – sleep relationship (theoretical model) and mediated (indirect) effects of coping in the control – sleep relationship (alternative model) estimated for each coping style with 99%[1] bias – corrected CI using the distribution-of-the-product-method[2] (N= 379)*

	Theoretical model		**Alternative model**	
	Coping - control - sleep		**Control - coping - sleep**	
	Path ab		Path ab	
Coping	β (SE)	99% CI	β (SE)	99% CI
Active	.009 (.009)	-.01 – .04	-.001 (.071)	-.03 - .02
Comforting thoughts	-.01 (.009)	-.02 – .02	.001 (.004)	-.01 – .02
Social support	.002 (.001)	-.02 – .02	.002 (.003)	-.01 – .02
Emotion-focused	.007 (.007)	-.008 – .03	-.01 (.007)	-.03 – .004
Passive reaction	.005 (.007)	-.02 – .03	.007 (.01)	-.03 – .04
Palliative reaction	-.02 (.01)	-.06 – .006	.01 (.009)	-.007 – .05
Avoidant	-.002 (.009)	-.03 – .02	.001 (.005)	-.061– .02

Note: β = regression coefficient, SE = standard error, CI= confidence interval, in bold = $p < 0.05$; [1]The Bonferroni correction was applied by adjusting the CI to 99.15, which corresponds to an adjusted cut-off of 0.017 (0.05/ 3 models).[2]The distribution of the product of the coefficient CI was produced by RMediation. p-values are not reported for this method.

3.4. Testing an alternative model: The control – coping – sleep relationship

Upon a reviewer's request, we also estimated the effects of an alternative model with reversed directionality of the control and coping variable, i.e. the control – coping – sleep relationship. In our analyses, we explored both the direct effects of control on sleep, and also the mediated effects of coping in the control-sleep relationship. We found that low locus of control was associated with lower sleep quality (path c) (**Table 2**). Trait coping did not mediate the control – sleep relationship (**Table 3** and **5**).

3.5. Comparing model fit

Following a reviewer's suggestion, we also compared the model fit between our theoretical model (coping – control – sleep), and an alternative model (control – coping – sleep). Our exploratory analyses based on the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) indicated that the alternative model had a better model fit when comparing the effects of control on sleep (AIC: 4604.25; BIC 4640.94) to the effects of coping on sleep (AIC: 5590.47; BIC: 5661.15) in the theoretical model.

4. Discussion

The current study is, to the best of our knowledge, the first investigation which explores the coping-sleep relationship in a youth sample over the age span of 15-25 years and the potential underlying psychological mechanisms in this relationship. Overall, our results show that disengagement, 'passive reaction', and emotion-focused coping measured at baseline were negatively associated with subjective quality of sleep, as measured in daily life in youth. However, we found no significant associations between other coping styles and sleep quality. Additionally, locus of control over the most negative event in daily life did not mediate any coping style - sleep relationship.

The results from our sensitivity analysis investigating the coping – sleep relationship by age group showed that active coping was also associated with better sleep quality in the younger youth subsample, whereas disengagement coping was not – in contrast to the overall sample. In the older youth subsample, we found that social support coping and engagement coping additionally related to better sleep quality, while emotion-focused coping and disengagement coping were not related to sleep quality anymore.

In line with our hypothesis, our findings indicate that those youth who habitually apply more disengagement and 'passive reaction' coping when experiencing stress, also experience worse sleep quality than youth who use this type of coping strategy less. Youth who feel unable to address their stressors may find that their sleep suffers, however, reduced sleep quality may also be impacting youth's ability to address problems. These findings are novel as no previous study has found a relationship of disengagement coping with *subjective* sleep quality in youth (Faber & Schlarb, 2016; Matthews et al., 2016; Sadeh et al., 2004), whereas a relationship with *objective* quality sleep (i.e. sleep fragmentation and sleep onset delay) was found before (Matthews et al., 2016). *Subjective* sleep quality in particular is associated with psychosocial stress and negative affect as opposed to objective sleep quality measures (Jackowska et al., 2011). Youth scoring high on poor sleep quality when using more passive reaction coping could therefore also experience distress and negative affect.

Our exploratory analyses revealed that emotion-focused coping was associated with poor quality sleep. These findings support previously reported poor sleep quality in youth applying more emotion-focused coping during stressful periods (Sadeh et al., 2004) and suggest that the associations are also present during in non-stressful periods. The associations between emotion-focused coping and sleep quality may be bi-directional. For example, empirical work has shown that people with insomnia apply more emotion-focused coping - potentially due to sleep-related decreases in emotional information processing, energy, and alertness - which has been shown to negatively affect emotions (Kahn et al., 2013), and may, consequently, increase emotion-focused coping (Morin et al., 2003).

As we have measured quality sleep repeatedly over 3-5 nights per week, our results highlight that disengagement coping, 'passive reaction', and emotion-focused coping relate to poor sleep quality during a prolonged period of time. Whilst an occasional night with poor sleep quality may be unpleasant, youth experiencing poor quality sleep during at least three days of the week when using more disengagement, 'passive reaction', and emotion-focused coping may be concerning, as having sleep problems for at least three days a week partially classifies for acute insomnia (American Psychiatric Association, 2013), which may reach a threshold for treatment. Further, if sleep problems persist for months, they may enhance symptoms of psychopathology over time (Kaneita et al., 2009). Therefore, we believe that there may be value in asking about coping when youth present with sleep problems, and clinicians should also be alert that youth reporting poor sleep quality may also experience impaired coping.

Clinically, these findings suggest that in order to improve sleep quality, efforts and attention should be directed at reducing youths' disengagement, 'passive reaction', and emotion-focused coping behaviour. As coping is a developmental process which youth expand their coping capacities and deployment, coping behaviours during adolescence partially lay the foundation for future adult coping practices (Jenzer et al., 2019; Wingo et al., 2015). Consequently, decreasing disengagement, 'passive reaction', and emotion-focused coping early on may offer an opportunity to positively impact youths' sleep quality, which could translate into better sleep later in life.

Our non-significant mediation analysis findings may suggest that the relationships between disengagement, 'passive reaction', emotion-focused coping, and sleep are not explained by locus of control in daily life, contrary to our hypothesis. Alternatively, underlying mechanisms other than locus of control may explain the coping - sleep relationship. These may include pre-sleep arousal for example, which has shown to mediate the stress-sleep relationship in youth (Maskevich et al., 2020). Pre-sleep arousal, including physiological arousal (i.e. elevated heart rate, cortisol, and sympathetic nervous system) (Andreassi, 2010), has been widely linked with sleep disturbances, yet researchers have not fully understood the pathways between arousal and sleep yet (Kahn et al., 2013). Early work has suggested that heightened cognitive (Kales et al., 1976) and emotional (Perlis et al., 1997) arousal may lead to physiological arousal compromising sleep. Since individuals high in passive reaction coping tend to become highly cognitively involved with the stressor (Yeh et al., 2015), and individuals high in emotion-focused coping are prone to physiological arousal due to venting their emotions (Zantinge et al., 2017), these responses may be related also to heightened physiological pre-sleep arousal, leading to sleep problems. Next to these approaches, also a genetic vulnerability for physiological and emotional hyperarousal has been suggested, which may lead to sleep disturbances (Kahn et al., 2013; Riemann et al., 2010).

Contrary to our hypothesis, our overall grouped results of engagement coping and sleep quality were non-significant. While the absence of evidence does not imply evidence of absence, these findings may mean that that youth generally applying more engagement coping when facing stressful events do not experience better sleep quality. Interestingly, these findings are in contrast to previous research finding positive (van Schalkwijk et al., 2015) associations, but are consistent with two other studies demonstrating non-significant effects of coping on subjective sleep quality (Matthews et al., 2016; Sadeh et al., 2004). Potentially, the effects of coping on

sleep are mixed, because problem-focused coping can sometimes be in conflict with getting good quality sleep due to a higher mental workload (Jansen et al., 2020). Also, as suggested by Dijkstra and Homan (2016), social support may only occasionally result in receiving successful social support, since it is dependent on others. Given that our results do not support a relationship between engagement coping and sleep quality in youth, it may be more relevant to focus on reducing disengagement, 'passive reaction', and emotion-focused coping instead of on increasing the use of engagement coping to improve youths' quality of sleep.

In our sensitivity analyses, we found that particularly in older youth, different associations between coping and sleep occurred: The significant associations between social support coping and engagement coping, and non-significant associations between emotion-focused coping and disengagement coping suggest a simultaneous shift from less to more effective coping strategies with increasing age. As suggested by Zimmer-Gembeck and Skinner (2011), coping deployment and capacities develop from using more engagement coping styles with increasing age, whereas disengagement coping styles remain stable. This is in line with our findings, as 'passive reaction' coping remained significantly associated with poor sleep quality. However, the older youth subsample was small (n=43), suggesting that these initial findings need replication.

Notably, comparing our results to other studies is particularly challenging, since the methodology from the small amount of previous research varies considerably in several aspects, which limits our ability to conclude whether particular elements of the methodology may have driven the differences in results. As such, the methods employed in previous research differ from those used in our study in terms of *context* (high stress vs. low stress) (Sadeh et al., 2004), *measurement frequency* (single vs. multiple timepoints) (Faber & Schlarb, 2016; van Schalkwijk et al., 2015) and *operationalization*, such as the way in which coping items were grouped into coping strategies (Faber & Schlarb, 2016; Matthews et al., 2016; Sadeh et al., 2004; van Schalkwijk et al., 2015). As a result, the high methodological variation across previous studies limits the comparability and overall interpretation of the existing coping and sleep literature.

Finally, the results from the alternative model suggested by reviewers show that lower control relates to poor-quality sleep in youth, which is in line with previous literature in adolescents (Alfano et al., 2009; DeAngelis et al., 2019). These effects were not mediated by any trait

coping strategy. As suggested earlier, alternative explanations for the relationship may include hyperarousal. Our results may suggest that adolescents having an external locus of control over the most negative events in daily life sleep poorly as compared to adolescents having an internal locus of control over the most negative event in daily life – and may imply that decreasing external locus of control in daily life could improve sleep quality in youth.

4.1. Strengths, limitations, and future directions

Our study has a number of strengths. First, to the best of our knowledge, this study is the first to investigate how coping in youth relates to quality of sleep and locus of control at a daily level, by using ESM. This methodological approach allows behaviours and experiences to be captured as they occur outside of the laboratory, instead of measuring individuals' self-reflection upon their usual behaviour (Myin-Germeys et al., 2018). Additionally, this method overcomes some of the problems of recall bias and allows us to investigate day-to-day variability and associations (Myin-Germeys et al., 2018), which increases the overall validity of the measured variables as compared to single timepoint measures. Second, our study also benefited from a relatively large sample size (n= 379), which is not typical of many youth ESM studies. Moreover, our study included both younger and older youth, allowing us to investigate the coping-sleep relationship over a wider age range, whereas previous studies have looked at either younger (Matthews et al., 2016; van Schalkwijk et al., 2015) or older youth (Faber & Schlarb, 2016; Sadeh et al., 2004). Last, but not least, the results of our study may have clinical and practical implications. There may be value in exploring coping strategies when youth present with decreased sleep quality, and in asking about impaired coping, when youth report sleeping poorly.

Yet, there are also some limitations to be considered. First, the study is cross-sectional with respect to measuring the association between trait coping and daily measures of sleep. Therefore, further work would benefit from assessing both coping and sleep prospectively and preferably using intensive longitudinal methods, e.g. ESM. Second, coping style was measured once at baseline as a trait, while coping strategies may vary depending on the daily-life context and controllability of the stressor (Troy et al., 2013). For example, evidence in adults using Experience Sampling data suggests that state and trait variables of coping predict subsequent negative affect differently, such that at the *state* level, emotional coping predicted negative affect, whereas at the *trait* coping level, only avoidance coping predicted negative affect

(Roesch et al., 2010). Potentially, state coping also relates sleep differently than trait coping, yet no previous study has investigated this yet.

Third, we did not consider the potential influence of psychopathology symptoms, which may be associated with both coping style (Compas et al., 2017) and sleep quality (Gest et al., 2019). Fourth, whilst a single item question on sleep quality is generally accepted to assess sleep quality (Krystal & Edinger, 2008) and common to use in ESM studies, given the need to minimise participant burden, it remains vague. A single item does not provide a nuanced picture regarding which specific facet of sleep quality is compromised, and there may be individual differences in the specific aspect of sleep quality that drives the quality evaluation (e.g. awakenings, sleep onset latency). Additionally, the combined use of subjective and objective measures as provided in some previous studies (Matthews et al., 2016; Sadeh et al., 2004) may be informative. Future studies should attempt to combine ESM measures with further objective instruments to increase interpretability of results and comparability with other studies.

Fifth, our criterion to include only participants with at least three pairs of evening and morning data on 'locus of control' led to the inclusion of 386 participants out of 750 participants. However, we found that those who completed less than three pairs of evening and morning data did not differ from those had at least three pairs of beeps regarding coping style, sleep, or psychopathology symptoms.

Besides addressing our current study limitations, future studies may investigate how youth may reduce disengagement, 'passive reaction', and emotion-focused coping as these coping styles may sustain feelings of distress and poor sleep quality. Since the underlying mechanisms remain poorly understood, alternative pathways between coping and sleep (e.g. pre-sleep arousal) could be explored, as they will improve our understanding of how coping styles may affect quality of sleep in youth.

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Chapter 6 - General discussion

The main three goals of this PhD project were:

- (1) To investigate if a cross-sectional relationship exists between objectively measured light, moderate-vigorous physical activity, and general psychopathology symptoms; and what kind of model (e.g. linear or non-linear) would best represent the nature of the objectively measured physical activity-general psychopathology relationship.

- (2) To explore if there is a cross-sectional non-linear association between Fitbit Charge 2-derived sleep duration, sleep quality, and symptoms of psychopathology, and whether not complying with sleep duration recommendations is associated with more symptoms of psychopathology.

- (3) To disentangle whether trait coping styles relate cross-sectionally to sleep quality in youth, and if this potential relationship is mediated by locus of control (i.e. one's attribution of control over events to own behaviour or external circumstances).

In the first part of the discussion, I will summarise the main findings. Next, in part two, I consider the findings within the behavioural epidemiological framework, discuss the meaning of the findings, and suggest future directions for research. In part three, the general limitations of this PhD research project will be discussed. Lastly, in part four, I draw some final conclusions.

1. Key findings

(1) The first aim of this PhD project was to examine if the significant associations between *subjectively* measured physical activity and psychopathology reported in previous studies could be replicated using objective measures. Our findings in chapter 3, regarding the physical activity-psychopathology relationship, showed that the selected linear model did not indicate a significant association between objectively measured light physical activity, moderate-vigorous physical activity, and symptoms of depression, anxiety, psychoticism, and general psychopathology.

(2) Similarly, the second aim was to investigate if the significant associations of subjectively measured sleep duration, sleep quality, and psychopathology symptoms found in the previous literature could be replicated when using objective measures. In chapter 4, we report results showing that we did not find evidence that objectively measured sleep duration and non-compliance with sleep guidelines were associated with symptoms of psychopathology. Counterintuitively, we found that Fitbit Charge 2-derived sleep quality was positively associated with symptoms of depression, psychoticism, and general psychopathology symptoms. The non-significant findings in objective lifestyle data and psychopathology are in line with previous accelerometery data studies (Kandola et al., 2020; Slykerman et al., 2019; Toseeb et al., 2014; Wiles et al., 2012; Ranum et al., 2019; Koopman-Verhoeff et al., 2019), but in contrast with previous self-report data studies (Kaneita et al., 2007, 2009; Korczak et al., 2017; Liu et al., 2020; McMahon et al., 2017; Morishima et al., 2020; Ojio et al., 2016; Schuch et al., 2018, 2019).

(3) Lastly, we aimed to understand which factors relate to decreased quality sleep in adolescents. Our results in chapter 5 showed that 'passive reaction' and 'emotion-focused' coping styles were associated with decreased subjective sleep quality, whereas other coping styles were not. When we assessed the effects of grouped coping styles, we found that disengagement coping (i.e. avoidant coping, passive reaction coping, and palliative reaction coping) was associated with lower quality sleep. Further, locus of control did not mediate any coping – sleep quality relationship. These findings are in line with previous research suggesting that reducing disengagement coping may be more relevant to improving sleep quality than increasing engagement coping (Matthews et al., 2016).

2. Reflections and advancing knowledge

In the introduction, we have situated this PhD project within the first three processes of the behavioural epidemiological framework (Sallis et al., 2000). These include (1) establishing a link between lifestyle and psychopathology; (2) developing methods to measure lifestyle; and (3) identifying factors that influence/ relate to lifestyle. The behavioural epidemiological framework aims to outline the five necessary processes for investigating the relationship between health-related behaviours and health outcomes, so that these insights inform intervention and implementation in practice (Sallis et al., 2000). Theoretically, there is a sequential order between the processes, where process 1 is followed by process 2, for example. In research *practice*, however, non-linear pathways are also possible. For example, interventions for improving sleep quality, sleep duration, and physical activity levels may be developed, although there is a lack of evidence on the correlates of physical activity and sleep. Or, the development of new methods of measuring lifestyle may stimulate the investigation of health-related behaviours and health outcomes, despite established research on the topic. In the following sections, we place our findings within the behavioural epidemiological framework and suggest how future work could build on this research.

2.1. What do these non-significant findings between lifestyle and psychopathology symptoms in general populations adolescents mean?

In chapters 3 and 4, we estimated the associations between differing levels of physical activity and sleep levels, and symptoms of psychopathology – which were non-significant at the group-level. These findings can be situated within the first and second process of the behavioural epidemiological framework: (1) 'establishing a link between lifestyle and psychopathology' and (2) 'developing methods to measure lifestyle'. While the absence of evidence for an association does not imply that a relationship does not exist, it is possible that lifestyle may not be as relevant and impactful for *early* adolescent mental health and psychopathology development in the general population, as we have previously assumed based on subjective self-report data. In terms of the behavioural epidemiological framework, which aims to establish a relationship between lifestyle and psychopathology - as a risk factor for, inherent part, or consequence of psychopathology - our non-significant findings do not support any of these assumptions in general population adolescents. Based on the lack of support for a relationship, lifestyle may not be the promising target for early intervention and prevention that it appeared to be, based on subjective data.

Our non-significant findings at the group-level may imply that other factors are more important to adolescent mental health. For example, small, negative effects of low physical activity levels and inadequate sleep duration on psychopathology may be buffered by social support, which has been consistently linked with mental health (Colman et al., 2014; Scardera et al., 2020). Vice versa, positive effects of lifestyle on mental health may be diminished due to risk factors such as bullying (Lereya et al., 2015; Sharpe et al., 2021) or traumatic experiences (McKay et al., 2021; ten Have et al., 2019).

Alternatively, our non-significant findings at the group-level may imply that an adolescent's affective response to physical activity, and vice versa, is *individual* instead (i.e., happens at the within-person-level). For example, effects of lifestyle on acute, momentary affect states may occur when an individual deviates from his or her typical physical activity level mean instead of deviating from the group-level mean. Vice versa, negative affect states may represent in some individuals a driving force to become active whereas there are an additional burden in others (Cushing et al., 2018; Koch et al., 2020). Since momentary negative affect states may be a preceding subthreshold symptom in developing psychopathology in adolescence (Hartmann et al., 2021; McGorry et al., 2018), studying the early associations between physical activity and momentary affect is relevant.

Further, *individual characteristics*, such as physical activity expectations (Herring et al., 2022), self-determination (Owen et al., 2014), social support, self-efficacy, and perceived control (Cushing et al., 2018), but also consider different *physical activity characteristics*, such as leisure-time physical activity (White et al., 2017), incidental physical activity, exercise, and (non-) competitive sports may be important, as these seem to be relevant in the momentary physical activity – affect relationship (Koch et al., 2020; Szabo et al., 2020).

Similarly, in sleep studies, our non-significant findings at the group-level may indicate that effects of lifestyle are *individual*, and may not be observable at the group-level within the general adolescent population, potentially due to individual differences in sleep sensitivity to stress (i.e. sleep reactivity) (Kalmbach et al., 2018). For example, within-person variability in objectively measured sleep duration was associated with more symptoms of anxiety in adolescents, whereas between-person analyses did not reveal an association between sleep duration and anxiety symptoms and depression (Bustamante et al., 2020). Future research in longitudinal study designs may build on these preliminary findings.

At a methodological level, our findings may, firstly, imply that higher sampled studies may be necessary to estimate the probably small associations between objectively measured lifestyle and psychopathology. Among the very limited number of other objective studies, small, but significant effects between total objective physical activity, and light physical activity have been found in high-sampled (i.e., N=> 3000) cross-sectional analyses (Kandola et al., 2020; Wiles et al., 2012). Secondly, the variability of person-level lifestyle data may have been too low to pick up an association. As elaborated in chapter 3, a potential threshold for light physical activity may be around ~320 min of light physical activity (Kandola et al., 2020), yet the majority (i.e. 75%) of the average values in our study were lower (~250 min/day). However, the relationship remained non-significant after conducting a post-hoc sensitivity analysis in participants with higher average light physical activity values (N= 332; mean 360.28, SD 25.98), potentially due to lacking power. Similarly, associations between sleep duration and psychopathology may have not occurred in our sample due to lack of sleep duration variability. Significant associations of sleep duration and mental health may occur when reaching a threshold of on average 5-7 hours per night (Matamura et al., 2014, Ojio et al, 2016, Liu et al., 2020, Morishima et al., 2020), which may be adjusted to 4-6 hours per night when compared to objective sleep data to due inclusions of awakenings in subjective data (Chaput et al., 2018). However, this lower threshold of 4-6 hours average sleep duration has not been reached in our (mean 7.84) and previous objective data studies (Ranum et al., 2019, Slykerman et al., 2019), so that the lack of participants with short sleep durations could potentially explain the non-significant associations. The associations in a post-hoc sensitivity analysis in adolescents (N=43) having slept ≤ 6 hours remained non-significant, yet the analysis may have been underpowered, which requires further exploration in future research.

Overall, our non-significant findings, coupled with those from previous studies of lifestyle in general population adolescents, may suggest that lifestyle instead plays a more prominent role after the onset of psychopathology.

2.2. Lifestyle and psychopathology - What causes what?

In chapter 3 and 4, our lifestyle and psychopathology data from Wave 1 of the SIGMA study is cross-sectional. Therefore, results based on these data contribute very little to answering the question of directionality in the relationship between lifestyle and psychopathology symptoms. In chapters 3 and 4, our statistical models included lifestyle as an independent variable and psychopathology symptoms as a dependent variable – however, due to the cross-sectional

nature of the data, this approach does not imply directional interpretation of the results. Statistically, it would have been possible to estimate models in which psychopathology symptoms were an independent variable and lifestyle was a dependent variable – but even if the results had differed, they would not have contributed to the directionality question. In order to gain more insights on the directionality of this relationship, we would need longitudinal data, i.e. from multiple different time points.

We applied this cross-sectional design in chapters 3 and 4 because it allowed us to investigate many relevant, yet unexplored, questions for the field: The nature of the relationship (i.e. linear or non-linear), the unique effects of light physical activity, sleep phase-based quality of sleep, and a broad spectrum of psychopathology symptoms within a general population sample in early adolescence. We had also aimed to explore the moderating role of sedentary behaviour in the physical activity - psychopathology relationship, yet we omitted this research question due to high amounts of missingness.

Since the Fitbit Charge 2 data is longitudinal data measured over seven consecutive data, and we have collected data on affect and mood states within the same measurement period, investigating the prospective within-person effects between sleep, physical activity and ESM would have been a possible and a very interesting option in this research topic, which we had considered in the provisional doctoral plan of the PhD thesis. However, we did not apply this design for several reasons. First, practically, the process of extracting and linking minute-level Fitbit Charge 2 and ESM data, was too time-intensive for this PhD project. Second, based on our pilot data, we assumed high amounts of missing data, which might have increased in combination with the (incomplete) ESM data.

Consequently, the group-level comparison as applied in our study likely allowed us to include a larger sample than a prospective, within-person analysis approach applying ESM data. Third, and finally, at the time-point we were opting for the cross-sectional design in chapters 3 and 4, we assumed that a longitudinal analysis of the data would be possible with SIGMA Wave 2 data. However, due to the start of the COVID-19 pandemic in March 2020, data collection for the second wave was postponed.

2.3 Do objective and subjective concepts of lifestyle differ?

Within the literature, we find similar, non-significant results for cross-sectional objective lifestyle data studies and psychopathology for physical activity (Kandola et al., 2020; Slykerman et al., 2020; Wiles et al., 2012), sleep duration (Ranum et al., 2019; Slykerman et al., 2020), and sleep quality (Koopman-Verhoeff et al., 2019). However, we see that these findings do not replicate earlier, subjective data research (Kaneita et al., 2007, 2009; Korczak et al., 2017; Liu et al., 2020; McMahon et al., 2017; Morishima et al., 2020; Ojio et al., 2016; Schuch et al., 2018, 2019), suggesting that more physical activity, adequate sleep duration, and good quality sleep relate to fewer symptoms of psychopathology. These consistently diverging findings between subjective and objective findings suggest that questionnaires and multi-sensor devices measure different concepts of physical activity and sleep.

Epidemiological studies assessing physical activity via self-report questionnaires have the advantage that they capture the domains of physical activity, such as leisure-time, transport, household, and work-related physical activity (Korczak et al., 2017; McMahon et al., 2017). Assessing domains of physical activity is relevant because preliminary evidence suggests that leisure-time physical activity is associated with fewer symptoms of psychopathology (White et al., 2017). In contrast, physical activity during transport, and physical education classes is not associated with fewer symptoms of psychopathology (White et al., 2017). Objective measures of physical activity, in contrast, do not differentiate between domains of physical activity, but include an unknown mixture of various physical activity domains, which may eventually 'blur' the associations of physical activity and psychopathology. Consequently, differences in associations between subjective and objective data and psychopathology may occur due to (not) accounting for physical activity domains.

On the downside, questionnaires are less likely to capture incidental physical activity than objective measures (Castillo-Retamal & Hinckson, 2011), which is why unstructured light physical activity occurring within daily life (e.g. short walks, household chores) in particular is underreported when compared to objectively measured physical activity (Sullivan et al., 2012). However, capturing incidental versus structured physical activity is relevant because recent evidence suggests that incidental and exercise-related activity are differentially related to adolescents' mood when measured with objective measures and the Experience Sampling Method (ESM) (Koch et al., 2020).

Next to domain of physical activity, the context in which physical activity takes place may also influence mood and well-being. For example, being outdoors (Coon et al., 2011) or being in the company of others (Eime et al., 2013; VanKim & Nelson, 2013) has been suggested to have particularly positive effects on mood, whereas competitive sport environments may have negative effects on mood (Koch et al., 2020). Therefore, the context of physical activity may be an additional important aspect related to mental health, yet has so far mainly been investigated in subjective, but less in the context of objective data.

Similarly - although this has so far received little attention - considering the difference in conceptualization of subjective and objective sleep is relevant. On the upside, epidemiological studies using questionnaires have been able to study the prolonged periods of sleep (e.g. for a month) (Liu et al., 2020; Morishima et al., 2020; Ojio et al., 2016), whereas objective studies usually include a 7-day period (Ranum et al., 2019; Slykerman et al., 2020). Identifying the overall sleep patterns of sleep duration is more relevant for long-term health than just a brief snapshot in time (Chaput et al., 2018).

Studies using sleep quality questionnaires, such as the Pittsburgh Sleep Quality Index (PSQI) (Kaneita et al., 2009), measure a variety of sleep quality dimensions, such as subjective sleep quality, sleep latency, sleep duration, sleep efficiency, sleep disturbances, sleep medication, and daytime sleepiness. However, previous objective studies on sleep quality have focused only on a single dimension of sleep quality, such as sleep efficiency, for example, the time asleep whilst being in bed (Koopman-Verhoeff et al., 2019). Likewise, in chapter 4, the measured concepts of sleep quality were different from questionnaire-assessed sleep quality, including dimensions such as sleep stages, awakening, and heart rate. Overall, given these inherent differences in defining the content of specific sleep concepts, the diverging findings may not be very surprising after all.

Understanding what aspects of lifestyle may be measured in either subjective or objective lifestyle, and how they might relate differently to psychopathology, is relevant for future research and clinical interpretation. Novel ways of investigating lifestyle both objectively and subjectively will be elaborated in more detail in a later section.

2.4. Is it really about lifestyle – or is it just the subjective perception?

The current literature investigating subjectively measured lifestyle and psychopathology suggests that lifestyle is an important predictor of psychopathology symptoms. Yet, in the light of the current findings of this PhD thesis, which does not support this idea, we may need to carefully reconsider this relationship. It essentially boils down to the question: Is it really lifestyle that is related to psychopathology, or is it just the subjective perception of it?

Previous work comparing subjective and objective measures of sleep, and investigating factors in explaining the differences between the two, suggests that subjectively measured underestimation of sleep efficiency and overestimation of sleep problems were driven by psychosocial factors and affect, whereas objective measures were not (Jackowska et al., 2011). Therefore, the authors conclude that these aspects are important moderators that should be considered when making any conclusions about the sleep – health relationship. In the same vein, Matthews and colleagues (2018) found that subjective sleep duration is over- or underestimated to a greater extent in people reporting hostility, poor subjective health, and depressive symptoms as compared to healthy controls. Surprisingly, similar studies investigating psychosocial moderators in the physical activity – psychopathology relationship seem to be lacking.

The general difference between perception and actual observation at predicting health and well-being is well-acknowledged. Overall, findings from previous studies suggest that subjective measures are better predictors for self-reported health outcomes than objective ones (McLean et al., 2018). Consequently, this implies that subjective estimates of lifestyle could be important targets for prevention and intervention – in terms of identifying adolescents at risk. However, the non-significant objective associations between lifestyle and psychopathology would not provide support for intervention and prevention initiatives targeting lifestyle to address mental health problems in general population adolescents.

In the light of the potentially moderating aspects in the lifestyle-psychopathology relationship, it seems to be even more important for future work to consider a combined approach of objective and subjective measures which we will elaborate upon in a later section as it allows accounting for psychosocial factors and affect in the lifestyle-psychopathology relationship.

2.5. Practical implications: How to reduce emotion-focused coping and disengagement coping?

Lastly, our work in chapter 5, investigating if coping relates to subjective sleep quality and the potentially mediating role of locus of control, was situated in process (3) 'identifying factors that influence/ relate to lifestyle' of the behavioural epidemiological framework. We found that 'passive reaction', emotion-focused coping, and disengagement coping were related to poor sleep quality. 'Passive reaction' coping includes behaviours such as rumination about the past, isolating oneself from others, and using calming substances, but also feeling unable to do anything about the stressor, having a negative outlook on the situation, and being taken in by the difficult situation. Emotion-focused coping includes behaviours such as showing and expressing one's anger. Disengagement coping is a grouped variable including 'passive reaction' coping (e.g., being taken in by the problem), 'palliative reaction' coping (e.g. seeking distraction, using substances for tension reduction), and avoidant coping (e.g. avoiding difficult situations).

Our findings support previous negative associations of disengagement coping with objective sleep quality (Matthews et al., 2016), whereas they are in contrast with findings from the same study, where they did not find any significant associations between disengagement coping and subjectively measured sleep quality (Matthews et al., 2016). This is surprising since previous work has used a very similar methodology (i.e. daily sleep logs) and sample (i.e. young adolescents) as in our study (Matthews et al., 2016). Overall, the significant associations between disengagement coping, emotion-focused coping, and sleep quality, but non-significant findings for engagement coping and sleep findings could imply that those adolescents experiencing poor sleep quality may particularly benefit from employing 'passive reaction' coping less, instead of using engagement coping styles more, as other studies on well-being suggest (Dijkstra & Homan, 2016; Freire et al., 2016). However, since our findings are cross-sectional, future research on the long-term effects of disengagement coping, emotion-focused coping, and passive reaction coping may be relevant before building on processes such as (4) 'evaluating interventions to change lifestyle'.

Based on our findings, interventions to improve quality of sleep in youth might include efforts to enhance emotion-regulation, relaxation, and cognitive disengagement when feeling stressed. Short-term distraction can be a useful strategy to take the edge off a stressful situation if it includes the intention of returning to unpleasant emotions (Gratz & Tull, 2011; Linehan, 1993;

Wolgast & Lundh, 2017). Importantly, adaptive distraction as a coping strategy includes the willingness of experiential emotions exposure, which can increase well-being, whereas distraction without such an accepting attitude would be maladaptive for well-being (Wolgast & Lundh, 2017). Overall, constructive distraction could be a short-term effective emotion-regulation strategy to also improve sleep quality in those youth prone to using emotion-focused coping, passive-reaction coping, and general disengagement coping. Once stress-related tension has reduced, youth may feel capable to address the stressor or related emotions.

While this work has focused on the relationship between trait coping and sleep, coping behaviour also includes state components (Roesch et al., 2010). Empirical evidence suggests that state and trait coping relate differently to affect (Roesch et al., 2010), which may also be true for sleep quality. While investigating trait coping answers the question of what an individual generally does when stressed, state coping looks at the fine-grained situational responses under stress, when considering characteristics of the stressor and situational aspects (Roesch et al., 2010). So far, state coping and sleep have not been investigated in youth, but certainly would provide valuable insights into the momentary processes between coping, locus of control, and sleep.

2.6. Moving beyond current measurement limitations

Currently, research on lifestyle and psychopathology seems to stand at a cross-road. The evidence on objectively measured and subjectively-rated lifestyle and psychopathology clearly differs, yet the factors that contribute to these different findings need still to be unravelled. We have suggested many aspects that may contribute to the differences in conceptualization of subjective and objective measurement: (1) The domain and context of physical activity, (2) the assessed dimensions of the sleep quality construct, and (3) the length of the sleep duration period (i.e. a week vs. a month). We also discussed an alternative perspective of the lifestyle-psychopathology relationship: Exploring within-person effects between lifestyle and psychopathology. This aspect may be important particularly in early adolescence, when symptoms are still variable and subtle across individuals (Van Os, 2013).

In order to investigate these unanswered, yet important questions, an alternative novel study design that combines subjective and objective measures may be necessary. For example, participants might wear the multi-sensory device on their wrist to capture lifestyle objectively, and in parallel answer questions on their context, domain, and experience of physical activity

and sleep by means of the ESM. This combined approach, that also was applied in the SIGMA study, would combine the best of both worlds - the accuracy of objective measurement and additional information around lifestyle, such as domain and context of physical activity, subjective experiences of sleep, and comparable length of sleep duration assessment. Unfortunately, this approach was not feasible within this PhD

project, as elaborated above (see section, 2.2. for more details). Additionally, this approach would allow us to investigate within-person effects between lifestyle and psychopathology symptoms over time due to the repeated measurement. Eventually, this approach would allow us to advance knowledge in areas that have received relatively little attention, such as investigating dynamic, momentary associations between objectively measured physical activity, sleep, and momentary affect in general population adolescents.

Conceptionally, the field of lifestyle psychiatry tends to treat movement behaviours such as sleep, physical activity, and sedentary behaviour as equally determined by one's own will. However, we may also need to acknowledge that physical activity and sedentary behaviour have a more 'volitional' quality, whereas sleep duration and sleep quality are less under one own control, even when someone 'tries to sleep'. Many daytime behaviours influence sleep, such as coping and stress management (Faber & Schlarb, 2016; Matthews et al., 2016; Sadeh et al., 2004; van Schalkwijk et al., 2015), physical activity (Kelley & Kelley, 2017; Lang et al., 2013; Štefan et al., 2018; Yoong et al., 2016), diet (Boozari et al., 2021), and screen time (B. Carter et al., 2016; Lemola et al., 2015), so that sleep can also be considered as an outcome of other behaviours. Future research may study the effects of these behaviour in more depth and how these influence sleep related behaviours such as winding down before bedtime, time spent in bed, and sleep duration, subsequently.

3. General limitations and future directions

This PhD project has a few general limitations. First, our SIGMA sample may not have been fully representative of the adolescent population in Flanders, which limits the generalizability of our findings. If we compare the educational levels in our study from year 1, 3, and 5 to the general Flemish secondary school population 2018-2019, the SIGMA sample is comparable in school years 1 and 3, whereas in year 5, the general secondary education level (i.e. 'ASO') was underrepresented by 7%, the technical secondary education (i.e. 'TSO') was overrepresented

by 21%, and the vocational secondary education (i.e. 'BSO') was overrepresented by 9%, while the arts secondary education (i.e. 'KSO') was representative. If we look at the overall distribution of the school years in the SIGMA study, 55% of the sample were 1st years, whereas 23% were 2nd, and 22% 3rd years, respectively. However, first years were intentionally oversampled to maximise longitudinal follow-up across the target age range for the study.

Likewise, since only 75% of the participants indicated whether they identified themselves with a Belgian or non-Belgian culture - because this question was only included later in the study - it is unclear how ethnically diverse the sample was compared to the general Flemish population. In those participants who responded, 37% of the participants identified with a non-Belgian culture (Kirtley et al., 2021), which is roughly comparable to 34.4% in the general population (Kind en Gezin, 2019).

Second, the SIGMA (chapter 3 and 4) and TwinssCan (chapter 5) data are cross-sectional and therefore cannot contribute to the question of directionality. Future longitudinal studies may focus on the effects of psychopathology on lifestyle, in particular, since this relationship is currently understudied. Likewise, studies on the longitudinal effects of coping and sleep are missing to provide insights on the directionality. Understanding the longitudinal relationship better may offer opportunities for early prevention and intervention.

Third, the complexity of the relationship between lifestyle factors and psychopathology may have been simplified within this study. Although lifestyle factors may have a unique effect on psychopathology, which is worth exploring, they are also considered to be inter-related (Falck et al., 2021; Tremblay et al., 2016). Future studies may consider interactions in objective lifestyle data with regards to psychopathology (Sampasa-Kanyinga et al., 2020). Similarly, when studying the associations between coping and sleep quality, considering interactions between sleep quality and sleep duration may account for potential interactions (Chaput et al., 2018; Hestetun et al., 2018).

Fourth, we have not explored the potentially confounding role of social factors, such as social support (Colman et al., 2014; Scardera et al., 2020), bullying (Lereya et al., 2015; Sharpe et al., 2021), and childhood trauma (McKay et al., 2021; ten Have et al., 2019), which have shown to be linked to psychopathology, and sleep, in particular (Brindle et al., 2018; de Grey et al., 2018;

van Geel et al., 2015). Future studies may consider these social factors when investigating the lifestyle-psychopathology relationship.

Fifth, in both chapter 3 and 4, we have imputed the outcome variables of psychopathology based on a general recommendation (van Ginkel et al., 2020). This decision has affected our findings, since our results within the imputed dataset differ from those in the non-imputed dataset (see chapter 4). Despite the general recommendation to impute missing data within outcome variables, further empirical research is necessary to determine if multiple imputation or listwise deletion is most appropriate for these types of data.

4. Conclusion

This doctoral research project investigated the objectively measured lifestyle – psychopathology relationship in general population adolescents and explored coping as a behavioural correlate of sleep quality, as measured within ESM data. We found that objective lifestyle factors were unrelated to general psychopathology symptoms, depression, anxiety, and psychoticism, which is in contrast to self-report data studies suggesting predictive effects of lifestyle on psychopathology. Overall, these diverging findings may suggest that objective and subjective lifestyle measures cover different concepts. As an approach for future longitudinal research, we suggested a study design combining subjective and objective measures, whilst taking interactions between lifestyle, domain, and context factors into account. This approach would allow us to disentangle the unique role of measurement type, characteristics of lifestyle, and psycho-social factors influence in lifestyle-psychopathology relationship.

Lastly, we saw that 'passive reaction', emotion-focused and disengagement coping related to lower sleep quality and suggested how these results may inform future intervention studies and research. For example, interventions may include short-termed distraction and acceptance-based elements from Acceptance and Commitment Therapy to downregulate intense emotions during peaks of stress.

This PhD research project showed that the field of lifestyle research currently stands at an interesting cross-road. If future research continues to address the remaining, challenging issues regarding measurement methodology, these novel approaches may contribute to new insights in the lifestyle - psychopathology relationship.

Appendices

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Supplementary materials

Chapter 3

Supplement 1: Deviations from the post-registration

1. Change of sleep duration criteria

We made a change to the criteria for inclusion of the sleep criteria. In the post-registration, we stated that having less than 120 minutes sleep duration before 9pm would lead to an exclusion of the measurement day. Subsequently, we extended the sleep duration to up to 200 minutes. We extended the period because using the 120 minutes criterium would have included several periods of data points in the range between 120-200 minutes, which were unlikely to be real sleep.

2. Dropping of the variable 'weekday' as a covariate in the analyses

In our analyses, we looked at average values of PA, which provides only one score per participant as it was also planned within our post-registration. However, we falsely included 'weekday' as a covariate, since it is not possible to account for the influence of working days/ weekend days if we look at average PA, and thus, dropped the variable from the model.

3. Adding the variable 'season' as an interaction effect in the model

In order to understand season-dependent effects of PA and psychopathology, it needs to be added as an interaction effect in the model, not as a covariate, as was specified in our post-registration.

4. Power analysis

The power analysis in the pre-registration was falsely based on a logistic regression. We conducted a sensitivity power analysis based on a linear regression model instead.

5. Associations between sedentary behaviour and psychopathology and the moderating role of sedentary behaviour

Since a high percentage of the variable 'sedentary behaviour' was missing (~60%), we could not estimate the associations between sedentary behaviour and psychopathology or the interaction effects of sedentary behaviour.

6. Additional analyses

We conducted additional analyses, such as (a) a sensitivity analysis within a dataset including at least 4 valid days, and (b) exploratory analyses estimating the effects of depression, anxiety, and psychoticism on LPA and MVPA.

7. Additional model selection methods

In our post-registration, we had stated that in case that AIC and BIC would contradict each other, we would opt for the BIC values. However, upon further reading, we realised that in our study this approach was incorrect. Since the results from the AIC and BIC estimation did not favour a model, we also use k-fold cross-validation for additional model selection information.

Supplement 2: Data pre-processing steps

To determine the expected amount of usable data and to test analysis code, we had access to a small pilot sample (n=54). Using this pilot sample, we also defined criteria for missing data and non-wear time. Defining non-wear time is essential for inclusion and exclusion of accelerometery data. In general, non-wear time in accelerometery has been determined in numerous ways (e.g. threshold for signal in acceleration; heart rate detection). Previous studies using the Fitbit Charge 2 (FC2) device have used heart rate data as a proxy of wear time contact (Collins, Yang, Trentadue, Gong, & Losina, 2019). However, in this study, heart rate data were not available. Therefore, alternative proxies for non-wear time are needed and presented below.

'Defining' missing PA and data exclusion in physical activity variables

As non-wear time as a separate variable was unavailable, we used the variable of interest, PA, to decide if the PA variables represented non-wear time. Our dataset consisted of daily summaries of the variables of interest. Since wear of the device seemed unlikely when all PA variables (LPA, MPA, VPA) recorded zero simultaneously for a complete day, we labelled these days as 'missing data'. Regarding data exclusion, the following criteria were applied. First, measurement days on which a minimum threshold of daily LPA of 60 minutes per day was not reached was excluded. This threshold was set based on minimum PA duration required for basic activities such as self-care (eating, bathroom use). In doing so, we avoided including measurement days on which the device was worn for only a few hours/minutes per day, which would be insufficiently representative of PA over a full day. At the same time, this conservative approach allows for data from inactive participants wearing the device over the whole day to be included in the dataset. Second, we excluded measurement days from participants who were

not able to wear the device long enough due to scheduling within our study. As such, we excluded participants' day 1 data if they started wearing the Fitbit device later than 12pm Assuming that the majority of adolescents within the sample were going to bed later than 8pm, this cut-off allowed the participants to wear the device for at least 8 hours. Third, if all measurable variables of the Fitbit device, LPA, MPA, VPA, steps, and sleep, were missing over all 7 measurement days within one participant, the participant was excluded.

'Defining' missing sedentary behaviour

We determined that whenever sleep data were missing (=zero), sedentary behaviour was also considered as missing data. We chose this approach, as we observed within the pilot dataset that sedentary behaviour minutes seem to be constructed by subtracting both sleep data and active minutes from the value 1440 (total number of minutes within a 24h day). As such, a default value of 1440 was provided whenever PA and sleep duration were recorded as zero.

Data exclusion of sedentary behaviour

We excluded sedentary behaviour, whenever the sleep duration was below 200 minutes and started between 1pm and 9pm, since these brief periods unlikely recorded night time sleep.

Supplement 3: Sensitivity analysis

As current literature suggests including at least 4 valid days of accelerometery data in the dataset (Migueles et al., 2017), and our dataset consists of at least 3 valid days, we conducted a sensitivity analysis on a sample which included at least 4 valid days (n=434).

Associations between light and moderate-vigorous physical activity and symptoms of general psychopathology, depression, anxiety, and psychoticism

We conducted a sensitivity analysis using a linear regression model. The pooled results across the 10 imputed datasets can be found in **Table 1** and **Table 2**. There are no significant associations between LPA and MVPA with symptoms of general psychopathology (**Table 1**), depression, anxiety, and psychoticism (**Table 2**).

Table 1 *Associations between light (LPA) and moderate-vigorous physical activity (MVPA) and general psychopathology (GSI-BSI-53) estimated with a linear regression (n=434)*

	Dependent variable	
Independent variables	GSI-BSI	
	β (SE)	p
LPA	-.0002 (.0006)	.76
MVPA	-.0005 (.0009)	.58
Age	**.05 (.02)**	**.008**
Gender	**.28 (.06)**	**<.0001**
Season	.05 (.03)	.07

Note: in bold = alpha < 0.05; β= unstandardized regression coefficient; SE= standard error

Table 2 *Associations between light (LPA) and moderate-vigorous physical activity (MVPA) and depression, anxiety, and psychoticism estimated with a linear regression (n=434)*

	Dependent variables					
Independent variables	Depression		Anxiety		Psychoticism	
	β (SE)	p	β (SE)	p	β (SE)	p
LPA	-.0006 (.0009)	.51	.0003 (.0007)	.66	-.0003 (.0008)	.69
MVPA	-.0002 (.001)	.85	-.0009 (.0009)	.25	-.0002 (.001)	.82
Age	**.07 (.02)**	**.003**	.02 (.02)	.36	.02 (.02)	.07
Gender	**.31 (.08)**	**<.001**	**.26 (.06)**	**<.001**	**.24 (.06)**	**<.001**
Season	.05 (.04)	.22	.05 (.03)	.09	.05 (.03)	.06

Note: in bold = alpha < 0.05; β= unstandardized regression coefficient; SE= standard error

Supplement 4: Power analysis

Within the power analysis, we changed the linear regression function from *gls* to *lm,* as it estimates the model using least squares (Pinheiro et al., 2019). The *lm* function has very similar model assumptions as the *gls* function, as it also assumes that the errors are distributed independently.

Supplement 5: Standardized values of the main analyses

To allow comparability with previous studies, we provide the standardized values for the outcome variables depression, anxiety, and psychoticism in the testing subsample (n=464) in **Table 3**.

Table 3 *Associations between light (LPA) and moderate-vigorous physical activity (MVPA) and depression, anxiety, and psychoticism estimated with a linear regression (n=464)*

Independent variables	Dependent variables					
	Depression		Anxiety		Psychoticism	
	b (SE)	p	b (SE)	p	b (SE)	p
LPA	-.0003 (.0009)	.74	.0002 (.0005)	.70	-.0001 (.0004)	.77
MVPA	-.0009 (.0013)	.51	-.0003 (.0007)	.23	.0002 (.0007)	.71
Age	-.11 (.02)	<.001	.03 (.02)	.15	.05 (.02)	.03
Gender	-	-	-	-	-	-
Season	-	-	.05 (.03)	.09	.06 (.03)	.06

Note: in bold = alpha < 0.05; b= standardized regression coefficient; SE= standard error

Chapter 4

Appendix A: Inclusion and exclusion criteria

Our dataset consisted of daily summaries of the variables sleep duration and sleep quality. Common proxies of non-wear time at night (e.g. heart rate, accelerometer count) were not available. Alternatively, we decided that when both sleep duration and sleep quality were simultaneously recorded as 'zero' within the same measurement day, they were labelled as missing. These missing values may have occurred either due to non-wear of the device at night, or due to syncing too late. In that case, the existing data gets erased to provide storage for collecting more recent data. The device cannot store data for longer than 7-9 days and if that period is exceeded, the data collected on day 1 and 2 (sleep and active minutes) will be converted to zero values, in order to store data on the measurement days 9, 10, 11, and so on. This process was confirmed by a Fitbit customer service assistant.

Data exclusion

From our in-lab pilot testing, we also concluded that if the device was briefly removed during the day for at least one hour (due to showering or other reasons) then replaced, *but not worn during the night of the same day*, the device would incorrectly log this period of non-wear time as 'sleep' time. To avoid that short periods of 'sleep' occurred in our data, we excluded these brief 'sleep' periods using the following criterion: Any sleep time that was recorded before 9pm and with a duration of 200 minutes. Additionally, this decision was made since we wanted to assess the effects of night-time sleep. Also, if during all 8 measurement days, sleep duration and sleep quality were recorded as zero, all data from this participant were excluded from the analysis. Lastly, as this study investigates sleep in 11-17-year-olds, any participants older than 17 (N=26) were excluded from the analysis.

Appendix B: Deviations from the post-registration

1. Change from gam model to linear model

As we aimed to impute the missing values of sleep duration, we were not able to estimate generalized additive models using the gam function of the mgcv package, as this package does not support the use of multilevel multiple imputed datasets. Thus, we changed the model to a mixed effects linear model using cubic splines to account for the non-linear effects. As the ICCs of the linear mixed effects model were zero, we simplified the model and did not take the different clusters for school into account anymore.

2. Additional, exploratory analyses for the subscales depression, anxiety, and psychoticism

Since previous studies have mainly investigated the effects of sleep duration and quality on depression, anxiety, and psychoticism, we conducted exploratory analyse for these subscales.

3. Model validation

In our post-registration, we stated that we would check models met the assumption of independence. However, it was not possible for us to pool the imputed results within a plot, so we dropped this and evaluated the assumption of homogeneity only (**Appendix F**).

4. Imputation of the BSI data

We had stated in our post-registration that imputation would not be feasible, since 60% of the sleep data was missing. However, after we had excluded participants with less than 4 valid days, the 32% missingness of sleep duration and sleep quality seemed a justifiable amount of missingness to impute. Furthermore, based upon further reading after our post-registration, we decided that imputation of the BSI-GSI and BSI subscale variables depression, anxiety, and psychoticism is in general a better and more robust approach than listwise deletion (van Ginkel et al., 2020). We report the findings of the non-imputed BSI and Fitbit variables in the **Appendix F**.

5. Additional model selection methods

In our post-registration, we stated that if AIC and BIC contradicted each other, we would opt for the BIC values. However, upon further reading, we realised that this approach was incorrect. As the results from the AIC and BIC estimation did not favour a model, we also used the MSPE value calculated via k-fold cross-validation for additional model selection information.

6. Change of statistical analysis for estimating the effects of non-adherence with sleep guidelines on psychopathology symptoms

Following suggestions from peer-reviewers, we changed our original analysis plan as outlined in our post-registration, which was to analyse the effects of non-compliance with sleep guidelines on psychopathology symptoms by estimating interaction effects between age group and sleep duration. Instead, we created a non-compliance score which considers the age-matched sleep duration recommendations and implemented this variable into our model (please see the methods section for more details). Given the post-hoc change to our analysis plan for this hypothesis, we subsequently considered this analysis as exploratory. The interaction effects

between age group and sleep duration were removed. For transparency, however, we report the results from our initial original, planned statistical analysis, including the interaction effects between age group and sleep duration in **Appendix H**.

7. Change in terminology

As pointed out within our manuscript and by reviewers, Fitbit Charge 2 data currently has several limitations, such as lack of transparency - because of the proprietary nature of the algorithm - and accuracy. Since these limitations do not completely generalize to other objective measures of sleep, we have changed our terminology from 'objectively measured sleep duration / sleep quality' to "Fitbit Charge 2-derived sleep duration and quality" within the full draft, including the title.

Appendix C: Knot selection for cubic splines of sleep duration and non-compliance with the training subsample (n=56)

To determine how many knots would best represent the non-linear nature of the data when using cubic splines, we compared the model fit across three different models using 3, 4, and 5 knots in R (R Core Team, 2019). Each of the three linear regression models estimated the non-linear effects of sleep duration and non-compliance on symptoms of psychopathology through adding cubic splines with either 3, 4, or 5 knots to the predictor variables. For each of models including each either 3, 4, or 5 knots, we computed the Bayesian information Criterion (BIC), Akaike information criterion (AIC) values, and the mean squared prediction error (MSPE) across the 10 imputed datasets. The MSPE represents the expected differences between the predicted and observed values of a function which can be used for k-fold cross-validation (Hastie et al., 2008). In this approach, the sample is divided into different subsets (k) which are used to estimate the model for each fold. During this procedure, in each fold the k^{th} subset is kept aside for model validation, allowing the subsets to be cross-validated against each other. Afterwards, the computed MSPE values are averaged across the folds (Hastie et al., 2008). In this study, we used 10-fold cross-validation in each imputed dataset to compute the MSPE value, which was later pooled across all imputed datasets (Hastie et al., 2008). The best fit of the model was determined using a combined approach considering the lowest AIC, BIC, and MSPE value across all imputed datasets (Hagemann et al., 2021).

Appendix D: Conducting a simulation-based power analysis

The simulation-based power analyses (Lane & Hennes, 2018) was used to calculate the power for H1, H2, and H3 within the random 10% training subsample (n = 56). First, two separate linear regressions as outlined below were run in order to get the required effect sizes and model parameters. Second, these model parameters and effect sizes were used as input for 1000 Monte Carlo simulations, which sample size was set to n= 502, which is equal to the size of the testing dataset. Of these simulations, the proportion of simulations where the null hypothesis – the effect size of interest being significantly different from zero – was rejected at p <.05 was taken as the power. We considered power exceeding .80 to be sufficient.

Appendix E: Model validation

In line with our post-registration, we checked for homogeneity by plotting the fitted values against the residuals in both models. In the first model, estimating the non-linear effects of sleep duration and non-compliance with sleep guidelines on symptoms of general psychopathology (see **Fig.1**). Similarly, we checked our second model estimating the linear associations between sleep quality and symptoms of general psychopathology (see **Fig. 2**). Both plots show that the residuals are shrunk towards the lower values which may indicate that the assumption of homogeneity is violated. In future work, a larger training subsample may be needed for conducting model selection.

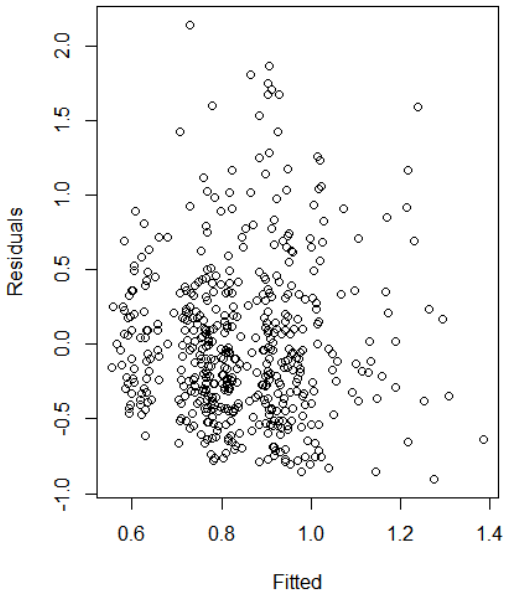

Fig. 1 *Fitted values against residuals for non- linear associations between sleep duration, non-compliance, and symptoms of general psychopathology in the testing dataset (n=502)*

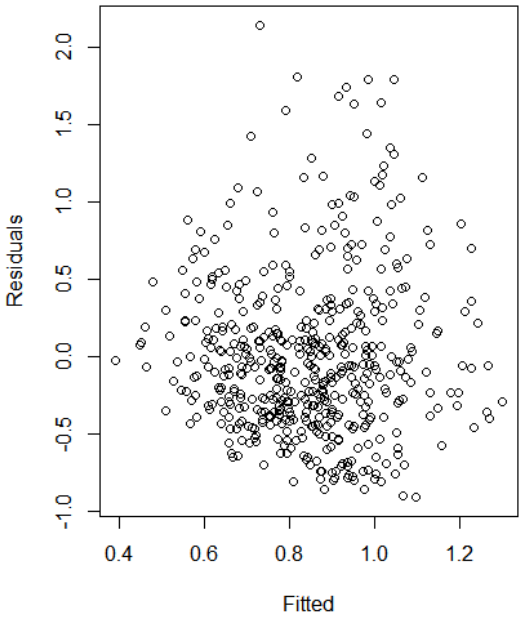

Fig. 2 *Fitted values against residuals for linear associations between sleep quality and symptoms of general psychopathology in the testing dataset (n=502)*

Appendix F: Results from non-imputed outcome variables

For transparency, we report the results of our original post-registered model here in which we did not impute the variables BSI GSI, depression, anxiety, and psychoticism (**Tables 1-4**): As opposed to models estimated using the fully imputed datasets, models using data where outcome variables (BSI GSI, depression, anxiety, and psychoticism symptoms) had not been imputed did not show a statistically significant association between sleep quality, general psychopathology symptoms, and psychoticism symptoms (**Table 2, Table 4**). In contrast, the associations between non-compliance with sleep guidelines, sleep duration, depression, and anxiety symptoms were significant when models were estimated using data in which the mean depression and anxiety symptoms variables were not imputed (**Table 3**). However, these associations were not significant in models in which the depression and anxiety symptoms were imputed.

In order to evaluate if the imputation of the BSI variable can be considered reliable, we followed the suggestions of van Ginkel (2020) to first check the imputed BSI values from anomalies (i.e. extreme minimum and maximum values) or patterns as observed in a histogram – and to compare the imputed and non-imputed BSI values. Our exploration of the imputed values compared to non-imputed BSI values indicated that means, minimum, and maximum values

did not differ between the imputed and non-imputed values (see **Table 5**) and that the histograms of the imputed and non-imputed BSI variable were comparable (see **Fig. 3** and **4**).

Second, van Ginkel (2020) suggests to conduct a MCAR test on the non-imputed dataset, since a violation of the MCAR assumption might explain the differences in results between imputed and non-imputed values. Because our non-imputed data were not MCAR as indicated by Little's MCAR test (X^2= 121.49; df= 25; p≤ .001), our differing findings may be explained by the violation of the MCAR assumption (van Ginkel et al., 2020). Although van Ginkel et al. (2020) state that when no anomalies can be detected in the imputed data, and the dataset is likely not MCAR, the imputation model can be trusted, we conclude that further empirical research needs to be conducted to determine whether listwise deletion or multiple imputation are more appropriate for this type of data.

Table 1 *Associations between sleep duration and psychopathology (GSI-BSI) estimated with a linear regression when the BSI variable was not imputed (n=502)*

	Dependent variable		
Independent variables	GSI-BSI		
	β (SE)	b (SE)	p
Intercept	3.37 (2.41)	-.10 (.16)	.52
Sleep duration	-.007 (.003)	-.41 (.22)	.07
Spline sleep duration 3 knots	.006 (.003)	.33 (.18)	.07
Non-compliance	.001 (.003)	.08 (.20)	.70
Spline non-compliance 3 knots	-.004 (.003)	-.28 (.19)	.14
Age	.05 (.04)	.12 (.10)	.26
Gender: girls	**.21 (.06)**	**.35 (.12)**	**.001**
Season: spring	**-.16 (.07)**	**-.27 (.11)**	**.02**
Season: autumn	-.003 (.10)	-.003 (.16)	.99

Note: in bold = p < 0.05; β= unstandardized regression coefficient; SE= standard error

Table 2 *Associations between sleep quality and psychopathology (GSI-BSI) estimated with a linear regression when the BSI variable was not imputed (n=502)*

	Dependent variable		
Independent variables	GSI-BSI		
	β (SE)	b (SE)	p
Sleep quality	.03 (.02)	10 (.06)	.09
Age	**.07 (.02)**	**.19 (.05)**	**.0002**
Gender: girls	**.18 (.06)**	**.30 (.11)**	**.004**
Season: spring	**-.15 (.07)**	**-.26 (.11)-.26 (.11)**	**.03**
Season: autumn	-.008 (.09)	-.01 (.15)	.92

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; SE= standard error

Table 3 *Associations between sleep duration and symptoms of depression, anxiety, and psychoticism estimated with three linear regression models when the outcome variables were not imputed (n=502)*

	Dependent variables					
Independent variables	Depression		Anxiety		Psychoticism	
	β (SE)	p	β (SE)	p	β (SE)	p
Intercept	2.99 (3.36)	.37	5.35 (2.70)	.05	1.71 (2.68)	.52
Sleep duration	-.010 (.006)	.08	-.009 (.004)	**.03**	-.004 (.003)	.29
Spline sleep duration 3 knots	.01 (.005)	**.03**	.007 (.004)	.08	.004 (.004)	.22
Non-compliance	.007 (.005)	.17	-.0007 (.003)	.17	.002 (.003)	.52
Spline non-compliance 3 knots	-.009 (.004)	**.03**	-.005(.003)	.17	-.004 (.003)	.23
Age	.12 (.06)	**.04**	.0001 (.05)	.99	.06 (.05)	.16
Gender: girls	.29 (.09)	**≤.001**	.20 (.07)	**.005**	.19 (.07)	**.007**
Season: spring	-.18 (.09)	.06	-.17 (.08)	**.03**	-.19 (.07)	**.01**
Season: autumn	.005 (.13)	.97	.05 (.11)	.66	-.03 (.11)	.77

Note: in bold = p < 0.05; β= unstandardized regression coefficient; SE= standard error

Table 4 *Associations between sleep quality and symptoms of depression, anxiety, and psychoticism estimated with three linear regression models when the subscales were not imputed (n=502)*

	Dependent variables					
Independent variables	Depression		Anxiety		Psychoticism	
	β (SE)	p	β (SE)	p	β (SE)	p
Sleep quality	.06 (.03)	.02	.007 (.02)	.74	.03 (.02)	.14
Age	.12 (.03)	**<.001**	.05 (.02)	**.02**	.07 (.02)	**.001**
Gender: girls	.23 (.09)	**.006**	.20 (.07)	**.004**	.16 (.07)	**.02**
Season: spring	-.16 (.09)	.09	-.17 (.08)	**.03**	-.18 (.08)	**.02**
Season: autumn	.003 (.13)	.91	.01 (.10)	.90	-.03 (.10)	.76

Note: in bold = p < 0.05; β= unstandardized regression coefficient; SE= standard error

Table 5 *Descriptive statistics of the BSI outcome variable when the variable is imputed and non-imputed in the testing subsample (N=502)*

	BSI variable	
Descriptive statistics	imputed	Non-imputed
Mean	0.84	.84
Minimum	-0.74	0
Maximum	2.90	2.87

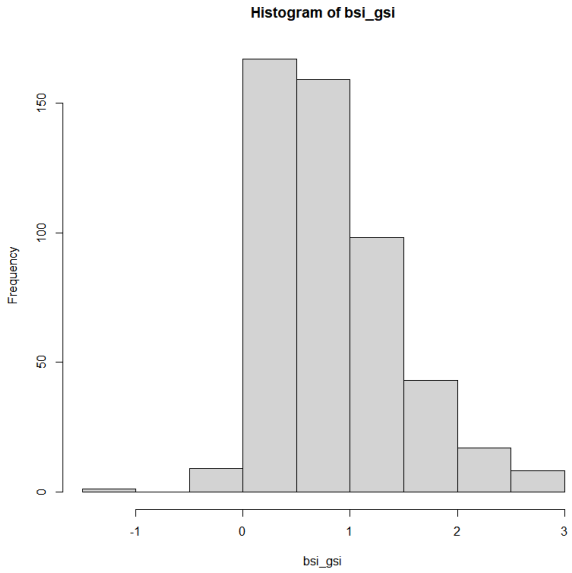

Fig. 3 *Histogram of the imputed BSI-GSI-53 variable in the testing subsample (N = 502)*

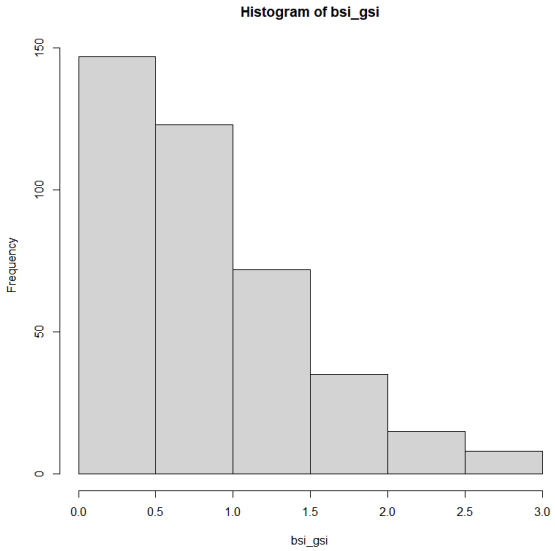

Fig. 4 *Histogram of the non-imputed BSI-GSI-53 variable in the testing subsample (N = 502)*

Appendix G

Table 6 *Standard error values of the Mean Squared Prediction Error (MSPE) values for three linear regression models estimating the non-linear effects of sleep duration and non-compliance on general psychopathology symptoms when including differing numbers of knots (3,4, or 5) within cubic splines among ten imputed datasets in the training subsample (n=56)*

Dataset	1	2	3	4	5	6	7	8	9	10
MSPE SE										
3 knots	0.26	0.39	0.32	0.39	0.57	0.32	0.35	0.41	0.32	0.30
4 knots	79.95	35.74	42.33	189.45	69.27	139.02	31.71	391.00	155.40	73.78
5 knots	116.08	2.56	39.32	353.72	835.83	1117.62	334.70	123.20	426.03	445.73

Note: MSPE = Mean Squared Prediction Error; SE =standard error

Appendix H: Original, post-registered statistical analysis of the effects of non-compliance with sleep guidelines and psychopathology

Following reviewers' comments that the operationalization of our research question "Does non-compliance with sleep guidelines relate to psychopathology symptoms?" (H2) may not be correct, we deviated from our previously planned statistical analysis, which included interaction effects between age groups and sleep duration to estimate non-compliance. We agreed with the reviewers that this approach did not capture a deviation from the sleep guidelines, but rather estimated the effects of sleep duration in different age groups instead. For transparency, we report the findings of our original, post-registered analysis here, including the interaction effects of age group and sleep duration on psychopathology symptoms in **Table 7** and **Table 8** below. The modified analysis is reported in the manuscript.

Table 7 *Results from a linear regression model estimating the non-linear effects of sleep duration and non-compliance with cubic splines including 3 knots on symptoms of symptoms general psychopathology (BSI-GSI-53) in the testing subsample (n=502).*

	Dependent variable		
Independent variables	BSI- GSI (53)		
	β (SE)	b (SE)	p
Intercept	.65 (1.20)	-	.59
Sleep duration	.0002 (.003)	.01 (.15)	.95
Spline sleep duration with 3 knots	-.0004 (.003)	.02 (.18)	.90
Sleep duration x age group	-.005 (.006)	-.31 (.32)	.35
Spline sleep duration with 3 knots x age group	.003 (.008)	.17 (.46)	.71
Age group: 14-17-year-olds	2.65 (2.37)	.31 (.33)	.30
Gender: girls	**.18 (.06)**	**.31 (.07)**	**.002**
Season: spring	-.12 (.07)	**-.20 (.06)**	.07
Season: autumn	.04 (.09)	.07 (.10)	.64

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; b = standardized regression coefficient, SE= standard error

Table 8 *Results from a linear regression model estimating the non-linear effects of sleep duration and non-compliance with cubic splines including 3 knots on symptoms of symptoms of depression, anxiety, and psychoticism in the testing subsample (n=502)*

	Dependent variables					
Independent variables	Depression		Anxiety		Psychoticism	
	β (SE)	p	β (SE)	P	β (SE)	p
Intercept	.30 (1.54)	.84	.84 (1.41)	.56	.66 (1.32)	.62
Sleep duration	.0003 (.003)	.85	-.0002 (.003)	.95	-.0002 (.003)	.94
Spline sleep duration with 3 knots	.0001 (.004)	.97	.001 (.004)	.72	.0006 (.003)	.84
Sleep duration x age group	-.008 (.01)	.49	-.005 (.01)	.64	-.001 (.009)	.91
Spline sleep duration with 3 knots x age group	-.008 (.07)	.90	.005 (.06)	.94	-.01 (.06)	.85
Age group: 14-17-year-olds	3.94 (4.76)	.42	2.42 (4.35)	.58	.86(2.27)	.71
Gender: girls	.27 (.08)	.001	.17 (.07)	.01	.17 (.07)	.01
Season: spring	-.13 (.09)	.15	-.13 (.07)	.07	-.14 (.07)	.05
Season: autumn	.08 (.13)	.57	.05 (.10)	.62	.01 (.10)	.86

Note: in bold = $p < 0.05$; β= unstandardized regression coefficient; SE= standard error

Chapter 5

Sensitivity analysis

The full TwinssCan sample included individuals aged 15-35 and the current study included a subsample of participants who were classed as "youths", i.e. aged 15-25 years old (Sawyer et al., 2018). To determine if there are age-specific associations between younger (15-20 years old) and older youth (21-25 years old), within the sample, we conducted a sensitivity analysis, where our youth sample was split into two groups: 15-20-year-olds and 21-25-year-olds.

For the younger youth subsample, (n = 336 individuals in 229 twin pairs), we found that active coping (b = .83, SE = .28, p = .006) was associated with better sleep quality, whereas 'passive reaction' coping (b = -.41, SE = .35, p = ≤.001) and emotion-focused coping were negatively associated with poor quality of sleep (b = -.23, SE = .09, p = .014). State locus of control did not mediate any coping- sleep quality relationship in the younger youth subsample.

In older youth subsample (n=43 individuals in 31 twin pairs), more social support coping (b = -.06, SE = .01, p = .02) and engagement coping (b= .47, SE= .15, p = .004) related to better sleep quality, while 'passive reaction' coping (b= -1.03, SE= .35, p= .02, p = .006) related to worse sleep quality. State locus of control did not mediate any coping- sleep quality relationship in the older youth subsample.

Scientific acknowledgements

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Personal Contribution

The work within this PhD project is the result of several contributors. Noëmi Hagemann supervised and coordinated the implementation, data collection, data extraction, and data management of the Fitbit Charge 2 with support of the SIGMA team and master students from the Physiotherapy and Rehabilitation Sciences. For all empirical studies, she performed the analyses and prepared the manuscript with support from GL. The contribution of the co-authors is listed below per chapter. Professor Davy Vancampfort, Dr. Olivia Kirtley, and Professor Myin-Germeys provided senior supervision and mentorship during the writing of the manuscripts.

Chapter 3

NH collected and analysed the data. NH and DV conceived the study. RA, KH, AH, and AL supported the data collection. GL and MW supported the data analysis and data-pre-processing. All co-authors contributed to the writing with review and editing. DV, OJK, and IMG provided supervision to NH.

Chapter 4

NH collected and analysed the data. NH and DV conceived the study. RA, KH, AH, and AL supported the data collection. GL and MW supported the data analysis and data pre-processing. All co-authors contributed to the writing with review and editing. DV, OJK, and IMG provided supervision to NH.

Chapter 5

NH and OJK conceived the study. JD, CD, SG, MDH, NJ, CML, BR, ET, JvO, RvW, and MW collected the data and designed the study. GL and OJK supported the data analysis. All co-authors contributed to the writing with review and editing. DV, OJK, and IMG provided supervision to NH.

Conflict of Interest Statement

The co-authors and doctoral candidate have no conflicts of interest to disclose.

About the Author

Noëmi Hagemann grew up in Osnabrück, Germany. After a sabbatical year, working on the maternity ward of the Franziskus Hospital Osnabrück and various organic farms in New South Wales and Queensland, Australia, she completed a 3-year apprenticeship to become a licensed physiotherapist at the Professor-Grewe Schule, Osnabrück. During this time, she worked on a case report on breathing exercises in patients after heart surgery, which later won a prize at the Verband Leitender Lehrkräfte (VLL). In 2013, she started her scientific education with a bachelor program *Physiotherapy* at Marburg University and the University of Applied Sciences, Fulda. During this time, she continued to work in ambulatory care with patients with musculoskeletal and neurological disorders, volunteered as a student representative at the occupational union "Physio Deutschland", received a full scholarship from the Bischöfliche Studienförderung Cusanuswerk, and worked during a 6-week internship at Ludwig-Maximilian University (LMU), Munich on a project on falls prevention in patients with Parkinson's disease. This research stay resulted in her first publication.

After receiving her Bachelor degree, she continued to deepen her clinical expertise during a 2-year full-time position as a clinical physiotherapist in ambulatory care at Praxis Achenbach, Marburg, where she completed advanced training in lymphatic drainage and Manual Therapy. During her work, Noëmi developed a strong interest in the body-mind connection, which led her to move to Leuven, Belgium, where she followed the international 2-year master program *Physiotherapy and Rehabilitation Sciences* at KU Leuven, to specialize as a physiotherapist within the field of mental health care. During this period, she wrote her master thesis on framing techniques and motivational processes of physical activity in elderly people, and graduated magna cum laude in 2017. After having developed an increased interest in the mental-health related effects of physical activity, she joined the SIGMA study on adolescent mental health at the Center of Contextual Psychiatry (CCP) at KU Leuven, to work on a 4-year PhD project to investigate early relationships between lifestyle and psychopathology in the general adolescent population.

List of publications

All publications indicated with * below are included as chapters of this doctoral thesis.

Achterhof, R., Kirtley, O., Schneider, M., **Hagemann, N.**, Hermans, K.S F M., Hiekkaranta, A. P., Lecei, A., Decoster, J., Derom, C., de Hert, M., Guloksuz, S., Jacobs, N., Menne-Lothmann, C., Rutten, B., Thiery, E., van Os, J., van Winkel, R., Wichers, M., & Myin-Germeys, I. (2020). *General psychopathology and its social correlates in the daily lives of youth*. *August*, 1–23. https://doi.org/10.31234/OSF.IO/95AFU

Achterhof, Robin, Kirtley, O. J., Schneider, M., Lafit, G., **Hagemann, N**., Hermans, K. S. F. M., Hiekkaranta, A. P., Lecei, A., & Myin-Germeys, I. (2021). Daily-Life Social Experiences as a Potential Mediator of the Relationship Between Parenting and Psychopathology in Adolescence. *Frontiers in Psychiatry*, *12*, 1279. https://doi.org/10.3389/fpsyt.2021.697127

***Hagemann, N**., Kirtley, O. J., Lafit, G., Wampers, M., Achterhof, R., Hermans, K. S. F. M., Hiekkaranta, A. P., Lecei, A., Myin-Germeys, I., & Vancampfort, D. (2021). Objectively measured physical activity and symptoms of psychopathology in general population adolescents from the SIGMA cohort. *Mental Health and Physical Activity*, *21*, 100416. https://doi.org/10.1016/j.mhpa.2021.100416

Hermans, K. S. F. M., Kirtley, O. J., Kasanova, Z., Achterhof, R., **Hagemann, N**., Hiekkaranta, A. P., Lecei, A., Zapata-Fonseca, L., Lafit, G., Fossion, R., Froese, T., & Myin-Germeys, I. (2021). Capacity for social contingency detection continues to develop across adolescence. *Social Development*. https://doi.org/10.1111/sode.12567

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Pre-prints:

Achterhof, Robin, Kirtley, O., Schneider, M., Lafit, G., & ... (2021). *Interrelationships Between Parenting Styles, Daily-life Social Experiences and Psychopathology in Adolescence*. PsyArXiv. https://doi.org/10.31234/OSF.IO/BCZDG

Achterhof, Robin, Myin-Germeys, I., Bamps, E., **Hagemann, N**., Hermans, K., Hiekkaranta, A. P., Janssens, J., Lecei, A., Lafit, G., & Kirtley, O. (2021). *COVID-19-related changes in adolescents' daily-life social interactions and psychopathology symptoms*. https://doi.org/10.31234/OSF.IO/5NFP2

***Hagemann, N.**, Kirtley, O. J., Lafit, G., Wampers, M., Achterhof, R., Hermans, K. S. F. M., Hiekkaranta, A. P., Lecei, A., Vancampfort, D., & Myin-Germeys, I. (2021). *Fitbit Charge 2 - derived sleep duration, sleep quality, and symptoms of psychopathology in general population adolescents from the SIGMA cohort*. https://doi.org/10.31234/osf.io/yx2eb

Hermans, K. S. F. M., Kirtley, O. J., Kasanova, Z., Achterhof, R., **Hagemann, N**., Hiekkaranta, A. P., Lecei, A., Zapata-Fonseca, L., Lafit, G., Fossion, R., & Froese, T. (2021). *Ecological and convergent validity of experimentally and dynamically assessed social capacity using the Perceptual Crossing Experiment in adolescence*. https://doi.org/10.31234/osf.io/jrzbw

Kirtley, O. J., Achterhof, R., **Hagemann, N**., Hermans, K. S. F. M. Hiekkaranta, A. P., Lecei, A., Boets, B., Henquet, C., Kasanova, Z., Schneider, M., Reiningshaus, U., Viechtbauer, W., & Myin-Germeys, I. (2021). *Initial cohort characteristics and protocol for SIGMA: An accelerated longitudinal study of environmental factors, inter- and intrapersonal processes, and mental health in adolescence.* https://doi.org/10.31234/osf.io/jp2fk

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About the cover

This picture shows mountaineering practices at L'Aiguille du Midi in France, taken by photographer Danouck van Kan. The mountaineers are guided by a skilled leader to get over the crest.

I believe this picture represents adolescence very well. Similarly, in adolescence, getting through that phase can be a slippery slope to pass. Just as the mountaineers, adolescents are confronted with mental, physical, and emotional challenges and benefit from essential social skills and support from others to get through adolescence safely and healthily.