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Adolescents' next-day perceptions of their sleep quality, quantity, sleepiness and sleepiness-related symptoms relative to actigraphy metrics

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ABSTRACT

Background: Next-day perceptions of sleep and related symptoms are frequently collected in research and clinical practice, but how they correlate with objective sleep measures in adolescents has received little attention.
Methods: Participants were aged 16–17 years and without a sleep disorder, anxiety or depression diagnosis. Seven-day wrist actigraphy was collected alongside daily survey ratings of sleep quality, sufficiency, morning and daytime sleepiness, and sleepiness-related mood and concentration. Within-person associations between daily actigraphic sleep metrics (6 variables representing quantity, quality and timing) and subjective ratings were estimated using mixed effects regression models with participant included as a random effect.
Results: The sample comprised 71 adolescents (49 % female, 51 % male). No actigraphy metrics linked to sleep sufficiency ratings. Sleep onset was the strongest correlate of sleep quality and morning sleepiness in the expected direction e.g. every 10 min later onset led to a −1.4 point (95 % CI: −2.1, −0.7) drop in the sleep quality score (5-point scale, higher worse), but significant relationships were only in females. While actigraphic sleep quantity metrics were linked to several ratings, all effect sizes were marginal. Sleep quality metrics in the overall sample were not correlated to any ratings. Unexpectedly, timing and quantity metrics linked to sleepiness-related mood ratings, but in the opposite direction hypothesized.
Conclusions: The lack of correlation between objective and subjective sleep quality add to the complexity of defining sleep quality accurately. Sleep onset timing, rarely explored in these types of studies emerged as an important correlate of sleep quality perception and other subjective ratings.

1. Introduction

Sleep during adolescence is influenced by a unique combination of hormonal, psychosocial, and environmental factors (e.g., social media, gaming, academic pressures) that emerge during this developmental stage [1]. This period is also characterised by increased independence, all of which combine to significantly impact behaviour including sleep patterns. During puberty, hormonal and circadian biological clock changes contribute to a slower build-up of homeostatic sleep pressure crucial for initiating sleep, along with a phase delay resulting in a preference for later sleep and wake times [2,3]. Bedtimes progressively shift later with each passing year [4], but rise times during the week are constrained by societal demands such as early school start times, restricting the amount of sleep adolescents obtain.

Sleep disturbances, often presenting as insomnia complaints, are also a common feature of adolescent's sleep patterns [5]. These disturbances include prolonged sleep latency, difficulty maintaining sleep, and early morning awakenings. Notably, insomnia complaints are particularly prevalent among adolescents with anxiety disorders [6]. Both insufficient and disturbed sleep can impact next-day functioning, with sleepiness being the hallmark symptom in adolescents [7]. Daily mood and concentration can also be adversely impacted, reflecting the well-established benefits of sleep in the neurobiological stabilisation of emotional regulation and cognitive performance [8].

Disruptions to sleep can influence how satisfied individuals are with the amount of sleep they get, captured through perceptions of sleep

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sufficiency [9]. Disruptions to sleep also link to perceptions of sleep quality. Although there is no universally agreed definition of sleep quality [10], the term is widely utilised in sleep health and sleep medicine with researchers using a wide range of tools and definitions [11]. It is assessed either through subjective self-reports or by measuring various quantitative sleep parameters, typically using polysomnography or actigraphy.

In 2017, the US-based National Sleep Foundation published recommendations for sleep quality metrics, informed by a panel of experts reaching consensus opinions about what constitutes good sleep quality in relation to good health outcomes, and vice versa for poor quality sleep [12]. They identified shorter sleep latencies, fewer awakenings, and reduced waking after sleep onset as key indicators of good sleep quality and developed age-appropriate recommendations for metrics related to these sleep variables. However, they also noted that the recommendations were based on limited scientific data, with particular challenges in defining what actually constitutes poor sleep quality. Most of the studies utilised were cross-sectional and focused on outcomes influenced by "usual" sleep patterns, not daily fluctuations that impact next-day performance, with a dearth of studies in the adolescent age group. Furthermore, the recommendations arose only from studies with quantitative measures of sleep quality and did not consider perception of sleep quality.

Subjective perceptions of sleep may in fact hold greater practical and clinical relevance than quantitative sleep metrics alone. For instance, it is well established that many adults with insomnia symptoms display sleep patterns similar to those of normal sleepers when assessed using objective measures [13,14], making it difficult to distinguish between the two groups based solely on these metrics. This highlights the need for a more comprehensive understanding of individuals' sleep experiences and identification of objective markers that accurately correspond with perceptions of an individual's sleep and sleep-related symptoms. Additionally, it is important to account for sex differences in studies of this nature, as females (both adolescents and adults) often perceive their sleep as worse than males [15,16], despite objective sleep measures typically indicating the opposite [17,18]. The underlying reasons for this potential discrepancy remain unclear, including the exact mechanisms by which biological sex and/or gender identity influence both sleep and perceptions of sleep [19].

The overall aim of this study was to investigate actigraph-derived sleep metric correlates of perceptions of sleep quality, sleep sufficiency and sleep-related symptoms (sleepiness, and mood and concentration due to sleepiness) over one week. We also aimed to explore gender differences in these correlations. We focused our study on a sample of adolescents with a narrow age range and excluded individuals diagnosed with sleep disorders and anxiety or depression to minimise the confounding effects of mental health issues on sleep. Importantly, we used within-person analyses to minimise variability in a study of this nature where all behaviors of interest are expected to fluctuate daily.

2. Methods

2.1. Participants and procedures

Ethics approval for the study was granted by the University of Otago Human Ethics Committee (reference number 22/068). The study took place between May and November 2022 and participants were recruited via social media, community noticeboards and through school administration systems. Interested subjects were provided with an online link to study information, and if interested completed a screening questionnaire to ensure eligibility. Inclusion criteria included participants aged 16–17 years 11 months, currently living in New Zealand, and with access to a mobile phone/laptop with mobile data/Wi-Fi. Exclusion criteria were a current diagnosis of depression/anxiety, a diagnosed sleep disorder, or learning difficulties that would make it difficult to participate. Using the assumption that 100 observations is appropriate to estimate a correlation [20], and applying a design effect of 3.1 (within-person correlation of 0.7 and at least 4 nights of data per participant), 78 participants would be needed. To allow for some loss of data, the aim was to recruit 85 participants.

Eligible participants met with the researcher (CT) via Zoom for a detailed explanation of the study and procedures before providing written informed consent to enrol. Participants then completed the demographic and other key questionnaires outlined in section 2.2 and received the Actigraph (section 2.4.1) via return courier to wear for seven consecutive 24-h periods. Participants were instructed to complete the daily survey ratings (section 2.4.2) corresponding to their previous night's sleep. Questionnaire and daily survey data were collected and managed using REDCap (Research Electronic Data Capture) tools hosted at the University of Otago. REDCap is a secure, web-based software platform designed to support data capture for research studies [21,22]. Upon completion of the study, participants received a NZ$40 voucher as a token of appreciation for their participation.

2.2. ***Participant*** *demographic and other questionnaires*

Participants completed demographic, sleep, well-being, and anxiety/depression questionnaires to generate a detailed profile relevant to the study's focus.

Demographic information, height and weight. Demographic data were collected which included participants' home addresses, to enable data-matching to the New Zealand (NZ) Deprivation Index 2018 [23]. This index is a widely used area-level measure of relative socioeconomic deprivation in NZ, and is an index that combines nine census variables associated with eight dimensions of deprivation, such as income, employment and living condition. The index scores are categorized by deciles, with one representing the ten percent of areas with least deprivation, and ten representing the ten percent of areas with highest deprivation. Ethnicity questions allowed participants to report multiple ethnicities. Responses were then categorized using a prioritization system, with Māori (the Indigenous population of NZ) listed first, followed by Pacific, Asian, NZ European, and then other ethnicities. Additional questions asked about gender with responses items limited to "male", "female", "gender neutral", or "I'd rather not say". Height and weight were self-reported and used to calculate body mass index (BMI) and relevant z-scores from which weight status was defined, determined according to World Health Organization growth reference data [24].

Sleep Disturbance. Participants completed the Patient-Reported Outcomes Measurement Information System (PROMIS) Paediatric Sleep Disturbance short form (SF-8*)* for adolescents aged 13–17 years which asks about sleep quality and difficulties with getting to sleep or staying asleep over the last week [25]. Each of the eight items are rated on a Likert scale from one to five, with one indicating the least disturbed sleep and five indicating the most disturbed sleep. The ratings from all eight items were added to form a raw score ranging from 8 to 40. The scores were expressed as a *T*-score with a mean of 50 (standard deviation of 10) equivalent to the 50th percentile of the US general population it was developed amongst [25]. Cronbach's alpha in the current sample was 0.85 representing good internal consistency. The following *T*-score cut points were used to estimate the severity of sleep disturbance being $\leq$55 within normal range 56–59 mild, 60–65 moderate, and $\geq$66 severe [26].

Sleep -related Impairment. The short form (SF-8) PROMIS Pediatric Sleep-Related Impairment for adolescents aged 13–17 years was used to assesses perceptions of sleepiness and tiredness and reported impairments during the day as experienced over the previous week [25]. Each of the eight items are rated from one to five, with one indicating the least impaired sleep and five indicating the most impaired sleep and expressed as t-scores as described above for the Sleep Disturbance scale. *T*-score cut points are used to estimate the severity of sleep impairment with $<$54 indicating normal range, 55–58 mild, 59–64 moderate, and $>$65 severe [26]. Cronbach's alpha in the current sample was 0.91

suggesting excellent internal consistency.

Well-being. Participants completed the World Health Organization-Five Well-Being Index (WHO-5), a short self-reported measure of mental well-being over the previous two-week period using five positively worded items that reflect the presence or absence of well-being [27]. The raw score ranges from 0 to 25, 0 representing worst possible and 25 representing best possible well-being. A total score <13 can indicate poor well-being and a risk of depression. Cronbach's alpha in the current sample was 0.86 representing good internal consitency.

Anxiety and Depression. Information was collected using the Revised Child Anxiety and Depression Scale–Short Version (RCADS–25), a 25–item self–report measure for children and adolescents between 8 and 18 years of age [28] and is based on the DSM–IV criteria [29]. The scale has two subscales and an overall score. The two subscales comprise the 15-item Anxiety Total scale e.g. separation anxiety, social phobia, generalised anxiety disorder, panic disorder and obsessive–compulsive disorder (OCD) and the 10-item Depression Total scale. Item responses are on a 4–point scale with options: "Never", "Sometimes", "Often" and "Always" with higher scores indicative of higher levels of anxiety and depression symptoms. Scoring is based on *T*–scores, with an overall RCADS *T*–score <65 indicating normal, 65–69 borderline, and ≥70 clinical levels of symptoms of anxiety and depression. RCADS items in the current sample showed excellent internal consistency (Cronbach's alpha = 0.93).

2.3. Daily measures

2.3.1. Actigraphy

Participants wore an Actigraph wGT3X-BT (ActiGraph, Pensacola FL, USA) wearable devices on their non-dominant wrist for 7 continuous days and nights. Actigraphs were initialised in 15-sec epochs and data were processed using a count-scaled algorithm integrated into the script developed in MATLAB (MathWorks, Natick, MA, USA). The algorithm and its development is explained in greater detail elsewhere [30] and has been validated in children aged 8–16 years with this device [31]. The script identifies sleep offset as the final minute of a 15-min continuous sleep segment followed by 5 min of wakefulness, and defines sleep onset as the commencement of 15 consecutive minutes of sleep following 5 min of wakefulness. Data processing was performed using either automated or manual mode (for individuals with widely variable sleep patterns) to enable calculations of night-by-night standard sleep metrics defined below within the domains of sleep timing, quantity and quality. For descriptive purposes only, seven-day averages for each sleep metric were weighted according to the number of week and weekend days.

- **Timing:** Sleep Onset, clock time of first consecutive minutes scored as evening sleep; Sleep Offset, clock time of first consecutive minutes scored as morning wake.
- **Quantity:** Sleep Period Time (SPT), the elapsed time between sleep onset and sleep offset; Total Sleep Time (TST), represents actual sleep amount and is calculated as SPT minus Wake after Sleep Onset (WASO).
- **Quality:** WASO, number of minutes scored as awake between sleep onset and offset; Number of awakenings >5 min (between sleep onset and offset); Sleep Efficiency, the percent of time asleep between sleep onset and offset and thus excludes sleep latency.

2.3.2. Daily survey ratings

Participants were asked to complete six daily rating scales for seven consecutive days, starting the day after they began wearing the wearable device. Questions for the six items were self-styled and brief as described below. Links to the daily surveys were sent to the participant's mobile phone using the MultiTxt function set up to automatically send a text message at 6 p.m. A reminder text was automatically sent at 9 p.m. to anyone who hadn't completed their survey by that point.

Sleep quality and sufficiency. Sleep quality was assessed with the question "How was the quality of your sleep last night?" rated on a 5-point Likert-type scale, with anchors of 0 = "very bad" to 4 = "very good". For sleep sufficiency, the following question was asked: "Do you feel you had enough sleep? rated on a Likert-type scale, with anchors of 0 = "No, not nearly enough" to 4 = "Far more than I needed".

Sleepiness and sleepiness-related symptoms. Daily sleepiness ratings were assessed in relation to morning and daytime sleep with the following questions: "I still felt sleepy when I woke up" and "I felt sleepy most of the day" rated on 4 point Likert-type scales, with anchors of 0 = "Not at all" to 3 = "A lot". Using the same response scales, questions for sleepiness related symptoms of concentration and mood respectively asked: "I had a hard time concentrating today because I was sleepy" and "I was in a bad mood today because I was sleepy".

2.4. Statistical analyses

All statistical analyses were performed in Stata 18.5 (StataCorp, Texas). Descriptive statistics were calculated to describe the characteristics of participants and provide summaries of all measures. As this is a repeated measures study, within-person standard deviation (SD) of sleep metrics were also reported to indicate within-person variability. Associations between sleep metrics and next-day measures were estimated using mixed effects regression models, with data in long-form by day. The next-day measure was the outcome variable, the actigraphic sleep metric was the exposure variable, and participant was included as a random effect. Mean differences, 95 % confidence intervals (CI) and p-values were calculated. P-values are not reported in the tables to focus on effect sizes, but statistically significant results ($p < 0.05$) are indicated. Standardised mean differences were also calculated using pooled SD to allow for comparison and assessment of effect sizes. Relative effect sizes were interpreted based on *Cohen's d = 0.20, 0.50, and 0.80 for small, large and medium respectively*. Results were stratified by gender to examine if relationships looked to be moderated by gender, but formal assessment of an interaction with a p-value was not undertaken as this was an exploratory analysis. Residuals of regression models were plotted and visually assessed for homoskedasticity and normality.

3. Results

One hundred and forty-six adolescents completed the screening survey, 24 (16.4 %) of whom were ineligible, with a further 31 (21.2 %) not responding to researcher follow-up. While 85 participants (58.2 % recruitment rate) initially enrolled in the study, 71 participants completed all measures with dropouts relating to actigraph malfunction or non-return. Compliance to actigraphy wear was excellent, returning a median of 7 consecutive nights (range 5–7) with just 3 participants wearing the device for 5 nights. Adherence to survey completion was also excellent with 68 out of 71 participants responding with survey ratings over the required 7 consecutive days, with a further 3 over 6 consecutive days. The total number of days available for most analyses was 469 of a possible 497 days (94 %).

3.1. Participant characteristics

As shown in Table 1, the mean ± SD age of the 71 participants was 16.9 ± 0.6 years, 49.3 % were female with all participants responding to the gender question as either male or female. Participants were predominantly NZ European, with 12.7 % identifying as Māori. Over half of the sample resided in areas of low deprivation whilst less than one tenth were from areas of high deprivation. Most were secondary school students (97 %) with the remaining 3 % unemployed. From the questionnaires, most participants returned scores reflecting good well-being, with 25.4 % (n = 18) returning scores reflecting poor well-being (Supplementary Table 1). A prior diagnosis of depression or anxiety were exclusion criteria with 5.7 % and 11.4 % of enrolled participants

Table 1
Participant characteristics (n = 71).

Characteristics	
Age, mean (SD) years	16.9 (0.6)
Gender, n (%)	
Male	36 (50.7)
Female	35 (49.3)
Ethnicity[a], n (%)	
NZ European & other	58 (81.7)
Māori	9 (12.7)
Asian	4 (5.6)
Area-level deprivation[b], n (%)	
Low (NZ Dep 1–3)	39 (54.9)
Medium (NZ Dep 4–7)	26 (36.6)
High (NZ Dep 8–10)	6 (8.5)
BMI z-score[c], mean (SD)	0.48 (1.02)
Weight status[c], n (%)	
Normal weight	50 (71.4)
Overweight	13 (18.6)
Obese	7 (10.0)

[a] Participants could identify with more than one ethnicity and was then prioritized into one group by the following priority order: Māori, Pacific, Asian, New Zealand European & other.
[b] Area-level deprivation determined using home address which was data-matched to NZ Deprivation Index 2018 deciles.
[c] Weight status determined using BMI z-scores using WHO growth standards, with BMI z-score>1 & ≤2 being overweight and BMI z-score >2 being obese. One participant was missing BMI z-score data.

Table 2
Within-person mean scores for daily survey ratings for the whole sample and by gender.

Subjective rating	Score range	Full sample (n = 71)	Males (n = 36)	Females (n = 35)
		Mean (SD)	Mean (SD)	Mean (SD)
Sleep quality[a]	1 to 5	3.3 (0.6)	3.3 (0.6)	3.3 (0.6)
Sleep sufficiency[a]	1 to 5	2.5 (0.6)	2.5 (0.6)	2.5 (0.6)
Morning sleepiness[b]	1 to 4	1.8 (0.7)	1.6 (0.7)	2.0 (0.8)
Daytime sleepiness[b]	1 to 4	2.6 (0.7)	2.5 (0.7)	2.6 (0.7)
Sleepiness-related concentration[b]	1 to 4	2.0 (0.5)	1.8 (0.5)	2.2 (0.5)
Sleepiness-related mood[b]	1 to 4	2.1 (0.6)	2.0 (1.0)	2.1 (0.6)

[a] Higher score is better.
[b] Higher score is poorer.

returned RCADS scores in the borderline and clinical range respectively. A small proportion enrolled (4.2 %) reported severe sleep disturbance, with a slightly higher percentage (12.7 %) rating their sleep impairment as severe.

3.2. Daily survey ratings

Table 2 presents a summary of the within-person means for the 6 daily survey ratings. Mean scores are given for the total sample and stratified by gender. Scores generally indicated good sleep quality, few difficulties with sleepiness-related concentration and mood, moderate sleep sufficiency, and greater daytime sleepiness compared with morning sleepiness. Notable gender differences were only evident for concentration, whereby females reported more difficulties concentrating due to sleepiness compared to males.

3.3. Actigraphy

Table 3 provides summary descriptives for actigraphy variables collected over the 7 days and stratified by gender. The mean number of hours between sleep onset and offset (i.e. SPT) was 7.9 h, with a total sleep time (TST) of 7.33 h yielding a sleep efficiency of 92.8 %. The mean WASO was 34 min with a waking frequency per night close to 1. There were no significant differences in any of the sleep metrics by gender. Approximately one quarter of the 469 nights of sleep were recorded in the "not recommended" range for sleep duration, i.e. < 7 h using SPT, the closest variable to sleep duration used in guidelines [32], and for WASO (>50 min) [12] (Supplementary Table 4). Nights with waking frequencies (>2) and sleep efficiencies (<75 %) outside of the recommended ranges [12] were fewer (5.8 and 9 % respectively). When analysed by the number of participants with mean values in the "not recommended range", this was highest for WASO (n = 19, 26.8 %), with only 9, 1, and 6 participants falling into the "not recommended range" categories for SPT, sleep efficiency and waking frequency respectively. The actigraphy-derived sleep metrics were within the expected range, with all sleep quantity and timing metrics within ±30 min of the pooled mean estimates of normative values for 15–18 year olds as indicated from meta-analyses [33].

3.4. Associations between actigraphy sleep variables and daily survey ratings

3.4.1. Sleep quality and sufficiency

Table 4 presents the regression model outcomes and effects sizes summaries are presented visually in Fig. 1. Adolescents who went to sleep later reported significantly lower sleep quality, with every 10 min of later sleep onset being associated with a −1.4 point (95 % CI: −2.1, −0.7) difference in sleep quality ratings ($p < 0.001$), indicative of a very large effect size of −1.5. However, this was only apparent in females (Supplementary Table 5). Each 1 h longer SPT and TST was also related to significantly better sleep quality ratings but the effect sizes were marginal. In the full sample, daily actigraphic sleep quality metrics were not related to daily self-reported sleep quality, but actigraphic sleep efficiency showed a small effect size in females only. No actigraphy variable was linked to how sufficient adolescent's rated their sleep.

Table 3
Actigraphy-derived sleep variables over 7 days (n = 71 participants).

Sleep variables (7-day[a] actigraphy)	Mean (SD)[b]	Within-person SD, mean (SD)	Males, mean (SD)[b] (n = 36)	Female, mean (SD)[b] (n = 35)
Sleep Timing				
Sleep onset, hh:min PM	11:33 (68 min)	47 (25) min	11:41 (70 min)	11:26 (65 min)
Sleep offset, hh:min AM	7:27 (52 min)	51 (23) min	7:24 (51 min)	7:30 (52 min)
Sleep Quantity				
Sleep Period Time (SPT), hours	7.90 (52 min)	63 (30) min	7.7 (50 min)	8.1 (52 min)
Total Sleep Time (TST), hours	7.33 (55 min)	65 (31) min	7.1 (54 min)	7.5 (55 min)
Sleep Quality				
Number of wakings	0.97 (0.67)	0.79 (0.37)	1.05 (0.74)	0.90 (0.59)
WASO, min	34 (30)	33 (23)	35 (32)	33 (28)
Sleep efficiency, %	92.8 (6.2)	6.9 (4.5)	92.6 (6.6)	93.1 (5.8)

[a] n = 46 (64.8 %) had 7 nights; n = 22 (31.0 %) had 6 nights; and n = 3 (4.2 %) had 5 nights.
[b] Mean (SD) of within-person means reported.

Table 4
Associations between actigraphic sleep variables and next-day subjective ratings of sleep quality and sleep sufficiency (n = 71 participants, n = 469 nights).

	Sleep quality		Sleep sufficiency	
	Mean difference (95 % CI)[a] in score[b]	Standardised mean difference (95 % CI)[a]	Mean difference (95 % CI)[a] in score[c]	Standardised mean difference (95 % CI)[a]
Actigraphy measures				
Sleep timing				
Sleep onset, for 10 min later	**−1.4 (-2.1, -0.7)**	**−1.5 (-2.3, -0.8)**	−0.1 (−0.9, 0.6)	−0.1 (−0.9, 0.6)
Sleep offset, for 10 min later	0.7 (−0.1, 1.5)	0.8 (−0.1, 1.6)	0.0 (−0.9, 0.8)	0.0 (−0.9, 0.8)
Sleep quantity				
Sleep period time, for 1 h longer	**0.2 (0.1, 0.2)**	**0.2 (0.1, 0.2)**	0.0 (−0.1, 0.1)	0.0 (−0.1, 0.1)
Total sleep time, for 1 h longer	**0.1 (0.1, 0.2)**	**0.2 (0.1, 0.2)**	0.0 (−0.1, 0.1)	0.0 (−0.1, 0.1)
Sleep quality				
Awakenings, for 1 extra waking	0.0 (−0.1, 0.1)	0.0 (−0.1, 0.1)	0.0 (−0.1, 0.1)	0.0 (−0.1, 0.1)
WASO, for nights ≥15 min awake	0.0 (−0.2, 0.1)	0.0 (−0.2, 0.2)	0.0 (−0.2, 0.2)	0.0 (−0.2, 0.2)
Sleep efficiency, for nights <90 %	−0.1 (−0.3, 0.1)	−0.1 (−0.3, 0.1)	0.0 (−0.2, 0.2)	0.0 (−0.2, 0.2)

[a] Mean differences (95 % CI) were estimated from a mixed effects regression model with participant as a random effect adjusted for weekend days, and estimates are reported for a difference in actigraphy measure by the amount indicated. Results are reported to a precision of 1 decimal place, as more than this would indicate a level of unrealistic precision. Estimates with $p < 0.05$ are in bold.

[b] Sleep quality and sleep sufficiency scored on a scale from 1 to 5, with higher scores indicating better sleep quality or sleep sufficiency. Standardised results reported in units of pooled SD.

While the timing of sleep offset was not related to sleep quality in the full sample, males with later sleep offset reported better sleep quality [1.9 (95 % CI: 0.7, 3.1)].

3.4.2. Daytime sleepiness and sleepiness-related symptoms

Sleepiness. Regression model outcomes are shown in Supplementary Table 2 and Fig. 1 presents a visual summary of the effect sizes. Later sleep onset was associated with next-day perceptions of morning but not daytime sleepiness, such that every 10 min of later sleep onset resulted in a 0.8 point (95 % CI: 0.1, 1.5) worse rating for morning sleepiness ($p = 0.031$) with a large effect size (0.8) mainly attributed to females (Supplementary Table 5). By contrast, how much sleep adolescents received (TST) and their sleep period time was linked to daytime sleepiness ($p = 0.024$ and 0.028 respectively) in the expected directions but with small effect sizes (−0.1), suggesting no meaningful relationships.

Sleepiness-related concentration and mood. Regression model outcomes are shown in Supplementary Table 3 and Fig. 1 presents a visual summary of the effect sizes. In the full sample, sleep onset was not associated with ratings for "a hard time concentrating because of sleepiness". However, when analyses were stratified by gender, a pattern emerged, indicating that later sleep onset in females was linked to poorer concentration with a large effect size [1.2 (95 % CI: 0.2, 2.3)] (Supplementary Table 5). One hour longer TST was associated ($p = 0.027$) with better ratings for sleepiness-related concentration but only in females (Supplementary Table 5) and the effect sizes were very small.

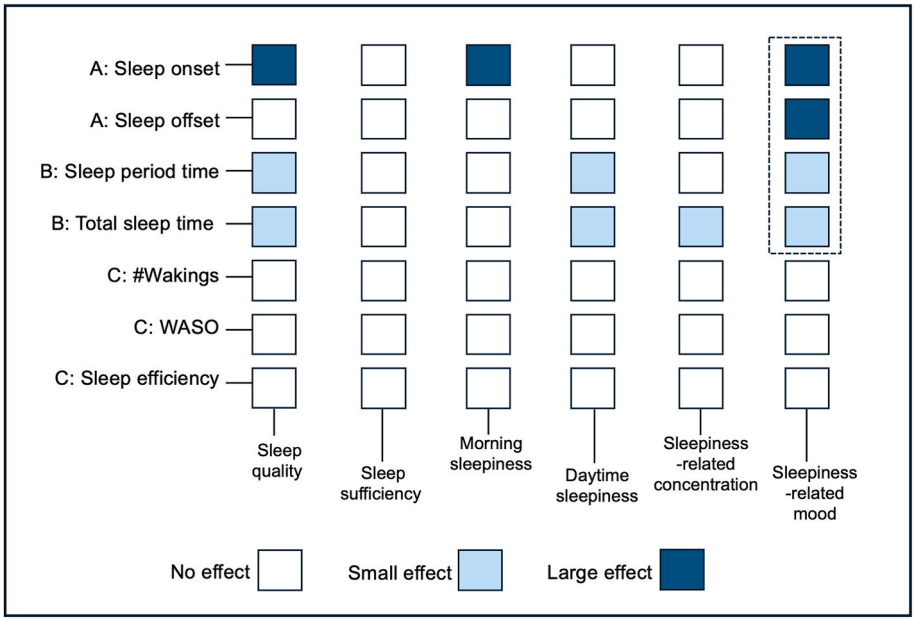

Fig. 1. Summary of magnitude of effect sizes found in the regression models exploring the relationships between actigraphy-derived sleep variables (x-axis) and subjective ratings (y-axis). The 6 sleep variables are defined within metrics of A: sleep timing, B: sleep quantity and C: sleep quality. All significant effects are in the expected directions e.g. later sleep onset and shorter sleep linked to worse sleep quality or more morning or daytime sleepiness, except those outlined in the dashed rectangle where the opposite effects were found.

Metrics of objectively-measured sleep quality were not related to sleepiness-related concentration or mood.

Adolescents who went to sleep later reported better sleepiness-related mood, with every 10-min delay in sleep onset associated with a −0.7-point reduction in ratings (95 % CI: −1.3, −0.0) i.e. reflecting better sleepiness-related mood ratings. Interestingly, a later sleep offset was associated with worse sleepiness-related mood (every 10-min delay in sleep offset was linked to a 0.8-point increase in mood ratings [95 % CI: 0.1, 1.5]). Effect sizes were large. No significant differences by gender were found for sleep onset but the significant associations with sleep offset were driven by male ratings (Supplementary Table 5). Sleep quantity metrics (SPT and TST) were also significant ($p = 0.001$ and < 0.001) and surprisingly in the direction of more sleep linked to poorer sleepiness-related mood ratings, but all effect sizes were small.

4. Discussion

This study aimed to investigate how actigraphy-derived sleep variables relate to next-day subjective assessments of quality, sufficiency, sleepiness, and symptoms of mood and concentration related to sleepiness in adolescents. Where associations were present, they primarily involved sleep timing (particularly sleep onset) and sleep quantity metrics, although the effect sizes for those were marginal. Surprisingly, actigraphy-defined sleep quality metrics [12] were linked to very few subjective ratings including perceived sleep quality and ratings of sleep sufficiency. None of the 6 actigraphy-derived sleep variables in fact were related to ratings of sleep sufficiency. The participants were older adolescents aged 16–17 years with typical 7-day actigraphy sleep metrics for their age [33], predominantly New Zealand European with good wellbeing and a small proportion with anxiety/depression scores in the borderline to clinical range.

The development of objective correlates of perceptions of sleep quality is challenging as sleep quality likely means different things amongst individuals [34], with age-related differences further complicating the picture [35]. As far as we are aware, no studies have been conducted in this area with the adolescent age group and only one in children utilising one night of both PSG and actigraphy [36]. In the current adolescent-focused study, we found that sleep onset timing had the strongest association with subjective sleep quality i.e. later onset linked to poorer ratings for sleep quality, and later offset (males only), longer TST and SPT marginally linked to better ratings. The association with sleep onset, primarily observed in females and offset only observed in males, suggests a potential difference in focus. Females may be more concerned with falling asleep on time and have been shown to prefer earlier bedtimes [37], whereas males might prioritise the opportunity to sleep in when evaluating their sleep quality.

Sleep efficiency was the only actigraphic sleep quality metric that linked with sleep quality ratings, however only in females. The discrepancy between male and female objective and subjective sleep findings is well-documented; while healthy women across various age groups have better sleep quality than men measured objectively, they report more sleep problems, including poorer sleep quality [19]. In the prior child study (aged 7–11 years) [36] only WASO was found to be associated with next-day subjective sleep quality ratings in a curvilinear reverse j-shaped pattern with sleep quality ratings showing a steady decline (worse ratings) from 0 to 30 min of WASO, beyond which there was little effect. No other actigraphic sleep quality or quantity variables were related, although the researchers did not explore sleep timing.

One of the most comprehensive studies in this area is an in-home single night PSG study in over 1500 older adults using machine learning algorithms to determine variable selection and the ordering of variables [38]. Sleep efficiency emerged as the strongest correlate of subjective sleep quality (determined through perceptions of depth and restfulness) and TST (sleep quantity metric) and sleep stage transitions were also significantly related to sleep quality in the expected directions [38]. Surprisingly, the amount of slow-wave sleep, which is linked to the restorative function of sleep, was not determined to be associated with subjective sleep quality. The closest variables to sleep onset and offset, i.e., lights out and lights on, were included in their models, but were not found to be predictors of sleep quality within this single night study. The same research group also reported that WASO was an important correlate of sleep quality across middle to late adulthood, alongside sleep efficiency, whereas our study in adolescents found only actigraphic sleep efficiency was linked to sleep quality ratings [35]. In combination, these findings support the notion that there are no consistent self-report measures that align with objective sleep quality metrics [39].

No actigraphic sleep metrics correlated with subjective ratings of sleep sufficiency in our study, despite the cohort reporting a high prevalence of dissatisfaction with the amount of sleep they were getting; 50 % of nights were rated as having “not nearly enough” or “not quite enough” sleep with 52 % of the participants experiencing at least one night classified as “not nearly enough” sleep. The absence of any associations could be due to several factors: the homogeneous nature of our sample, teens’ limited awareness of their optimal sleep needs, or the possibility that the single question does not serve as an adequate standalone tool for capturing sleep perceptions in community samples. More commonly it is used in fatigue-related research where it has been shown to be useful in differentiating shift workers from day workers [40], and recognised as an important tool in relation to long work hours linked to workplace injury [41].

Objective sleep timing variables played a significant role in relation to subjective sleepiness. Later sleep onset across the full sample was linked to morning sleepiness, though differential analyses revealed this relationship was only significant in females. Sleep quantity metrics (both SPT and TST), on the other hand, were linked to daytime sleepiness (albeit with small effect sizes), but again with a female preponderance (TST only). A possible explanation is that these findings are symptomatic of adolescent females having a stronger need for sleep compared to males, with a preference for earlier bedtimes and a longer sleep duration [37], borne out in objective measurements of sleep [17]. Beyond biological differences, female adolescents may tend to sleep earlier because they generally engage less in electronic devices [42] and interactive technology like videogaming [43] that can not only displace sleep time [44] but also enhance arousal when intense [45]. Although in this study, we found no significant within-person differences in sleep onset, the differences were in the direction of earlier sleep onset in females compared to males and with a non-significant trend evident towards a longer SPT in females ($p = 0.08$).

Questions about daytime perceptions of concentration and mood were asked specifically in relation to sleepiness acknowledging that adolescents, regardless of their sleep patterns, experience daily fluctuations in mood and concentration typical of this stage of development. We found that later sleep onset was only linked to poorer sleepiness-related concentration in females, with a large effect size, whereas longer TST was associated with better sleepiness-related concentration in females but the effect sizes were only marginal. It is acknowledged, however, that this single question about concentration related to sleepiness is very broad and therefore the findings must be interpreted with caution. Nevertheless, they highlight the importance of adequate sleep timing in sleep health messaging for adolescents to optimise daytime functioning. The reasons for the gender difference may be, as suggested above, symptomatic of females’ preference for earlier sleep onset and longer sleep with a potentially higher sleep need. Future research incorporating laboratory-based concentration tasks conducted on a daily basis in relation to sleep may be able to confirm this, but time of day for such tasks would be important to take into account given concentration can fluctuate throughout the day, regardless of the prior sleep.

Unexpectedly, we found that both later sleep onset and offset were associated with ratings in the direction of better and worse sleepiness-related mood respectively with sleep offset driven by male ratings. Less robust findings for TST were also in the same unexpected direction,

whereby shorter sleep predicted better mood ratings. We purposely asked about mood in relation to sleepiness, which, as far as we are aware other studies in this field have not; the rationale being to highlight the known connection between sleep issues and mood, critical for understanding sleep-related emotional regulation. Asking only about general mood would provide a broader understanding of emotional well-being but limit our ability to attribute it to a single factor such as sleep. In addition, with the wording of our single question item, we do not know if the ratings when improved reflect a positive mood, or merely an absence of negative mood.

We acknowledge that our sleep-specific mood question limits comparisons across different studies that assess general mood, but nevertheless it's important to point out that there are other studies that support the general concept that better sleep may not always translate to better mood the following day [46]. For example, a similar study design testing whether actigraphy-derived sleep variables would predict next day mood in 49 undergraduate students in Japan (average age 19.4 years) found that more sleep (TST) resulted in reduced positive affect (worse mood status) [47]. Another study combining mood ratings at multiple times across the day (8 times/day) with actigraphy variables in 32 patients with a schizophrenia spectrum disorder, found worse next-day negative affect (worse mood status) and/or psychotic symptoms after nights with higher sleep continuity [48]. Whilst the finding was not explained, they did raise the valid point that although the popular view is "the more sleep the better" there are many examples in the literature where more sleep may actually be maladaptive, when looking over short time frames. Indeed, the Japanese study surmised that their unexpected result could reflect a hangover from oversleeping [47], typically seen at weekends that has been associated with mood problems in adolescents potentially linked to circadian misalignment [49]. Noteworthy was our finding that it was only in males that later sleep offset was linked to worse symptoms of sleepiness-related mood (i.e. later morning sleep-in, worse sleepiness-related mood rating). Male adolescents have been reported to have more social jetlag (a misalignment of biological and social time) when sleep is measured objectively [50]. However, due to the absence of explanatory variables in the current study, such as more detailed and frequent assessments of daytime mood, stress levels, chronotype and timing of the circadian biological clock, we cannot confidently determine the mechanisms underlying the observed gender differences. This could be explored in future research.

The strengths and limitations of our research require discussion. The study results should be interpreted with consideration for the study sample, which is primarily New Zealand European 16–17 year olds without diagnoses of a sleep disorder, anxiety or depression. However, a limitation of the RCADS-25 for anxiety and depression is that it is based on DSM-IV diagnostic criteria [29] rather than the current DSM-5 TR [51]. It includes items related to OCD, which are no longer core symptoms of anxiety disorders under DSM-5 TR. Additionally, DSM-IV does not specifically assess suicidal ideation, now recognised as a critical symptom in the assessment of adolescent depression. We excluded individuals diagnosed with anxiety or depression given the well-known bidirectional relationship between mental health and sleep issues, alongside the evidence that anxiety can bias reports of sleep perception in youth [52], however these factors limit the applicability of results to adolescents experiencing these conditions. Our sample was not particularly diverse, which might limit extrapolation to other groups. In addition, the narrow age range provided the advantage of limiting variability in sleep, emotional, and cognitive development, which undergo significant changes across adolescence, but also means our findings may not be generalisable to other adolescent age groups. Strengths were notable in the high compliance of actigraphy wear and in daily survey responses. While actigraphy provides several benefits, particularly for 7-day measures and large-scale studies, its limitation lies in producing estimates of sleep metrics only (unlike gold standard PSG), and WASO remains a challenging variable to measure accurately [53]. Importantly, we used a within-person analysis approach which reduces confounding effects, increases power to estimate effects, and specifically examines how sleep affects next-day perceptions. However with the aim to model within-person fluctuations, not average variability, the approach limited our ability to assess the impact of regularity of sleep timing or duration requiring summary measures of habitual sleep over at least five nights for sleep onset [54] and more than seven for total sleep time [55].

A further limitation of our study is that we did not use sleep diaries to reduce participant burden, and therefore have no measure of sleep onset latency which is considered a sleep quality metric [12]. However, sleep onset latency is a very arbitrary measure [39] reliant on accurate participant input. Notably, devices do not routinely output sleep continuity metrics e.g. the longest or length of sleep periods overnight, relevant for assumptions about the integrity of sleep architecture critical for daily functioning. Actigraphy also cannot detect subtle autonomic arousals that may play a key role in disrupting the restorative aspects of sleep [56] that in turn could influence subjective ratings. Another consideration is that the time of day could have influenced the subjective ratings of morning sleepiness particularly, with the 6pm questioning potentially introducing recall bias. Our aim, however, was to additionally capture daytime symptoms without overburdening participants with more than one survey per day. Mood and concentration are well known to fluctuate across the day, but anchoring the questions specifically to sleepiness, may have minimised this. Without knowing how specifically participants answered these questions in relation to sleepiness, we suggest future studies ask about both sleep-related and general mood and concentration influences to facilitate an understanding of the relationships. Finally, when analysing next-day perceptions of sleep and daytime symptoms, we cannot disregard the influence of the prior day's experiences and behaviours in shaping that night's sleep.

5. Conclusions

The current within-person study design sheds new light on associations between actigraphic sleep variables and next day perceptions of sleep (quality and amount) and sleep-related symptoms (sleepiness, sleepiness-related mood and concentration) for adolescents. Findings highlighted that sleep onset time was the strongest associated variable across models for sleep quality and morning sleepiness, with marginal effects from TST for sleep quality, although both variables played out counter to hypotheses for sleepiness-related mood. Only one actigraphic sleep quality metric of the three explored was implicated in sleep quality ratings (sleep efficiency but only in females) supporting the view that there are no clear self-report measures that align with the objective sleep quality metrics, and vice versa [39]. None of the 6 actigraphy variables under study influenced adolescents' perceptions of the amount of sleep they received. Whilst each variable has some degree of overlap with one or more other variables, assessing them individually allowed us to tease out the most relevant, with important male-female differences emerging within several of the associations. As far as we are aware, sleep timing is rarely considered in studies designed to understand the objective correlates of next-day perceptions of sleep and related outcomes and we recommend this in future research, as well as ensuring consideration of sex differences. The counter-intuitive finding with sleepiness-related mood is certainly worthy of further investigation given some other studies asking about mood in general have reported similar effects, the reasons for which remain elusive, but do challenge the notion that more sleep and/or better sleep timing is better for all immediate sleep-related outcomes specifically as it concerns adolescents.

CRediT authorship contribution statement

Cameron Tang: Conceptualization, Methodology, Investigation, Project administration, Writing – original draft. **Kim Meredith-Jones:** Conceptualization, Methodology, Supervision, Software, Writing – review & editing, Resources. **Jillian Haszard:** Formal analysis, Writing –

review & editing. **T. Leigh Signal:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Shay-Ruby Wickham:** Writing – review & editing. **Diane Muller:** Writing – review & editing. **Rachael Taylor:** Writing – review & editing, Resources. **Barbara Galland:** Writing – original draft, Writing – review & editing, Conceptualization, Methodology, Visualization, Supervision, Funding acquisition.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare the following financial interests which may be considered as a potential competing interest. Jillian J Haszard was compensated for statistical services but had no role in the funding decision for that service or study design. Beyond that declared interest, there are no conflicts of interest to disclose regarding this study.

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Glossary

PROMIS, Patient-Reported Outcomes Measurement Information System; RCADS, Revised Child Anxiety and Depression Scale; TST, Total Sleep Time; SPT, Sleep Period Time; WASO, Wake After Sleep Onset; WHO-5: World Health Organization-Five Well-Being Index.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sleep.2025.106605.

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