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Quantifying teenagers' sleep patterns and sex differences in social jetlag using at-home sleep monitoring

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A B S T R A C T

Sleep plays an important role in the formative developmental processes occurring during the teenage years. At the same time, teenagers' changing bioregulatory mechanisms and psychosocial factors converge into the so-called social jetlag, a sleep timing misalignment between weekdays and weekends. The aim of this study was to quantify the course of day-to-day changes in sleep/wake patterns and sleep stage distributions, and the sex differences in social jetlag among teenagers. We observed the sleep of 156 teenagers (58.3% girls, 15–16 years) using a novel sleep monitor over the course of up to 10 consecutive days. 1323 nights of data were analyzed using multilevel modeling. On average, participants went to bed at 23:41, woke up at 07:48, slept for 7.7 h and had 85.5% sleep efficiency. Sleep stage distributions were in line with normative data. We found later sleep onset and offset, longer time in bed, sleep duration, and sleep onset latency ($p = .001$), greater proportion of light sleep and lower proportion of deep sleep, and poorer sleep efficiency (all $p < .001$) on weekend nights starting on Friday and Saturday. On Friday nights, girls had longer time awake after sleep onset ($p = .020$) than boys. On Friday and Saturday nights, girls fell asleep earlier ($p < .001$ and $p = .006$, respectively). On Saturday nights, girls had shorter sleep latency ($p = .024$), and better sleep efficiency ($p = .019$) than boys. In sum, teenagers' sleep patterns reflected healthy, albeit somewhat short sleep. There was convincing evidence of social jetlag, and girls exhibited less severe social jetlag than boys.

1. Introduction

Sleep plays an important role in the formative developmental changes of the brain, body, personality, emotional well-being, and intellect [1–3] occurring during adolescence. Concurrently, changes in the sleep/wake homeostatic process and circadian regulation, and psychosocial factors such as exposure to evening light from electronic devices, and early school start-times [4], converge together to the readily-observable adolescent evening shift in alertness and preference for later bedtimes [5]. These changes contribute to the "perfect storm of short, ill-timed, and inadequate sleep" [4,6], most markedly among teenagers (i.e., ages 14–17 years, as defined by Ref. [7]), ultimately resulting in chronically reduced sleep durations [8,9]. Sleep loss negatively affects school performances [10], mood and anxiety levels [11], highlighting the sensitivity of the developing brain to inadequate sleep.

In teenagers, sleep of optimal duration and quality is thought to support optimal maturation and brain development [12]. Compared with adults, for which many developmental and maturational processes are completed at ~25 years of age [13], teenagers need 1–2 h more sleep, i.e., between 8 and 10 h per night [7]. Sleep efficiency of ≥85% is considered to reflect good sleep quality [14]. However, a community study of 301 teenagers showed average sleep durations well below the recommendations, with only ~6 h 15 min of sleep per school night [15]. Moreover, merely 10% gained recommended sleep duration on school nights, but overall, sleep

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efficiency was within the normal range [15]. In contrast, other studies showed that teenagers obtained sleep durations close to the recommended levels [16], contributing to a lack of clarity around teenagers' sleep patterns.

In addition to adequate sleep duration and quality, normal sleep encompasses a specific internal structure. Sleep is comprised of three stages: light sleep, deep sleep, and rapid eye movement (REM) sleep [17]. Each sleep stage fulfils a distinct yet complementary role to the overall function of sleep [18]. Light sleep is involved in memory consolidation and sensory processing of external inputs [19], and makes up ~55% of the nighttime sleep period. Deep sleep has important functions in declarative memory consolidation [20], and endocrine, cardiovascular, and muscular recovery [21], and makes up ~20% of the sleep period. REM is implicated in procedural memory consolidation [20], creative problem solving [22], and emotional memory consolidation and processing [23], and makes up ~25% of all nightly sleep. However, insight into the habitual sleep stage distributions among teenagers is currently lacking.

The concurrent influence of adolescents' changing bioregulatory mechanisms and psychosocial factors on sleep are apparent in sleep timing misalignment between weekdays (i.e., school nights) vs. weekends, the so-called *social jetlag* [24]. It has been estimated that only ~10% of teenagers obtain a minimum of 8 h of sleep on weekday nights, while the percentage increases to ~40% on weekend nights [25]. Sleep is shorter, and bedtimes and risetimes are earlier on school nights, when compared to weekend nights [15,16,26,27]. However, despite an extension of sleep duration at the weekend, sleep quality seems to concurrently deteriorate [15]. Previous studies utilizing subjective sleep measurements indicate that girls may have more severe social jetlag than boys, and highlighted the incidence of sex differences in social jetlag across countries and latitudes (e.g., south and north of Europe, East Asia, North America) [28–32]. Given the sex discrepancy in subjectively vs. objectively quantified sleep patterns [33], it is of great interest to also study sex differences in social jetlag among teenagers using objective measurements of sleep. However, such studies are scarce, showing only that on weekends, girls sleep more [25], and go to sleep earlier [33] than boys. These studies pooled all weekend and weekday nights [25,33], obscuring a more detailed, day-to-day insight into sex differences in social jetlag. In addition, it is unclear whether social jetlag affects the teenagers' sleep stage distributions across several consecutive days including weekdays and weekends.

The present study aimed to extend our current understanding of teenagers' sleep/wake patterns and sleep stages, focusing on sex differences in the daily changes underpinning social jetlag. We observed the sleep of 156 Norwegian teenagers using a novel, unobtrusive sleep monitor validated for the assessment of sleep stages [34]. It was hypothesized that the sample would obtain sleep durations below the current recommendations [7], and that they would exhibit social jetlag. It was hypothesized that girls would have less severe social jetlag than boys.

2. Materials and methods

2.1. Participants

Participants were recruited from grades 8 and 9 in four Norwegian middle schools in the Trøndelag region. The school start times for these participants were 08:15. School principals were contacted by e-mail with information about the research project, relevant ethical issues, and the need for parental consent from all participants below the age of 16 years. Parents of the children attending these schools were contacted by the school with information about the study and the requirement for parental consent. Out of the potential 215 participants, parental consent was given for 156 teenagers, and all 156 (41.7% boys, 58.3% girls) participated in the study. This corresponds to a participation rate of 72.6%. Mean age of the sample was 15.2 years, with a standard deviation of 0.4 years (range 15–16 years). Norwegian Center for Research Data (NSD) approved the study (project ID 885271).

2.2. Procedure

Eight classes comprising of 30–35 students each participated in the data collection, which started in March 2020 and entailed day-to-day monitoring of sleep/wake patterns of each participant for 10 consecutive days. Due to a limited number of sleep monitors (35), data was collected for one class at a time. Thus, data collection lasted until November 2020.

Once all participants returned their signed parental consent forms, the participating classes were visited twice by the research team at their respective schools. At the first school visit, two or three team members described the research project and delivered the equipment for home sleep monitoring, SOMNOFY® (described below). A representative from the company behind SOMNOFY® also attended the first school visit. All devices were then handled by the participants themselves in their own homes. The sleep data was collected in the participants' own bedrooms, where SOMNOFY® is regarded to be non-intrusive to the sleeper. To secure data quality, participants were guided on how to activate and place their sleep monitors in their bedroom for optimal functionality. Participants were instructed to keep their sleep schedules as normal, unaffected by the sleep assessment. No information on the importance of sleep was given at this first visit to avoid behavior change. Participants were assigned a randomized code to allow the researchers to link their sleep monitor data to their personal data, obtained from a web-based demographic questionnaire. At the second visit, researchers collected the sleep monitors from the participants and conducted a presentation about sleep health.

2.3. Instruments

In addition to a demographic questionnaire measuring descriptive data (e.g., sex and age), a SOMNOFY® sleep monitor was used to detect sleep/wake patterns and sleep stages. The SOMNOFY® sleep monitor is a novel, fully unobtrusive tool for sleep assessment, utilizing an impulse radio ultra-wideband (IR-UWB) pulse radar and Doppler technology described in detail by Toften and colleagues [34]. Recently, a full validation of SOMNOFY® against polysomnography (PSG), the gold standard in clinical sleep measurement, has shown the contactless sleep monitor to be an adequate measure of sleep and wake, as well as sleep stages, in a healthy adult population [34]. Table 1 gives a short description of the sleep variables that were detected for the purposes of this study.

2.4. Data sample

The total number of nights in the study was 1859, excluding daytime sleep and naps. 436 nights were collected during a school lockdown due to the Covid-19 pandemic, and later excluded. A further 100 nights of data were removed based on a post-hoc review of data quality. Two independent reviewers removed nights of sleep fulfilling one or both of the following conditions: (1) more than 15 min of poor data quality affecting sleep scoring, due to blocked or non-optimal placement of the sensor, or (2) other periodic movements, due to pets, fans/ventilators, etc. Thus, 1323 nights of data were analyzed, indicating 93% compliance with the

Table 1
Sleep variables derived from the SOMNOFY® sleep monitor.

Sleep variable	Unit	Description
Sleep onset	hh:mm	Timepoint of sleep start
Sleep offset	hh:mm	Timepoint of wake-up
Time in bed	h	The time spent in bed, including before sleep onset and after sleep offset
Sleep onset latency	h	The time it takes for the participant to fall asleep, from the intention to sleep (e.g., lights off) to sleep onset
Total sleep time	h	Total sleep time obtained from sleep onset to time at wake-up
Light sleep	h / %	Total amount of time in the light stages of sleep (stage N1 and N2) / Proportion of light sleep in relation to total sleep time
Deep sleep	h / %	Total amount of time in deep sleep (stage N3) / Proportion of deep sleep in relation to total sleep time
Rapid eye movement (REM) sleep	h / %	Total amount of time in REM sleep / Proportion of REM sleep in relation to total sleep time
Sleep onset REM	h	Time it takes to enter the first REM sleep stage
Wake after sleep onset	h	Time awake after sleep onset and before final awakening
Sleep efficiency	%	The percentage of time from sleep onset to wake-up time that was spent asleep
Respiration rate in non-REM sleep	N	The number of respiratory ventilations in 1 min

data collection. For 135 of the 156 participants, seven or more nights of data were available. Due to rigorous exclusion criteria, the remaining dataset exhibited high data quality.

2.5. Statistical analyses

The collected sleep data created a clustered data structure, in which up to 10 repeated measurements of sleep data were clustered within the 156 individual participants. To allow for the dependence inherent to clustered data structures and to correct for potential type I errors and biased parameter estimates in the statistical analyses, multi-level modeling was utilized. In the multi-level analyses, the repeated measurements (level 1) of sleep were clustered within the individuals (level 2). All statistical analyses were carried out in R, using the 'lme4' package [35].

Data was analyzed using random intercept models, using sex (0 = boys, 1 = girls) and night of the week (1 = night starting on Monday [intercept], 2 = night starting on Tuesday …, 7 = night starting on Sunday), and the interaction between the two, to predict each dependent sleep variable (see Table 1), respectively. All random intercept models were clustered on individual (random effect), and all used Maximum Likelihood Estimation. Results of the multilevel models are first presented for the main effects of day of the week on sleep variables, controlled for sex. Interaction effects are presented thereafter. Results of the main effects of sex on sleep variables, controlled for day of the week, are presented in the appendix. Results are presented as estimated effect ± standard error, followed by p-values. The alpha level was set at $p < .05$ for all models. Effect sizes were estimated using marginal (i.e., effects explained by fixed factors) and conditional Cohen's f^2 (i.e., effects explained by the full model). $f^2 \geq 0.02$ indicated a small effect, $f^2 \geq 0.15$ a medium effect, and $f^2 \geq 0.35$ a large effect [36].

3. Results

3.1. Average sleep patterns

On average, participants went to bed at 23:41 and woke up at 07:48. Sleep duration averaged at 7.7 h and sleep efficiency at 85.8%. 34.6% of the participants gained, on average, the recommended sleep duration of minimum 8 h of sleep, and 60.3% exhibited sleep efficiency signaling good sleep quality (≥85%). Descriptive statistics for the sleep variables are shown in Fig. 1.

Averaging the sleep on weekday nights, participants went to bed at 23:25 and woke up at 07:19. Sleep duration averaged at 7.5 h and sleep efficiency at 86.1%. 28.8% of the sample gained minimum 8 h of sleep, and 64.7% of the sample exhibited sleep efficiency of 85% or more. Averaging the sleep on weekend nights, participants went to bed at 00:43 and woke up at 09:34. Sleep duration averaged at 8.4 h and sleep efficiency at 84.4%. 59.6% of the sample gained minimum 8 h of sleep, and 50% of the sample exhibited sleep efficiency of 85% or more.

3.2. Day-to-day insight into social jetlag

Multi-level analyses, adjusted for the effects of sex, showed main effects of day of the week for **sleep onset**, with participants falling asleep later on Friday (01:35 ± 00:08 hh:mm, $p < .001$), Saturday (01:51 ± 00:08 hh:mm, $p < .001$), and Sunday nights (00:21 ± 00:08 hh:mm, $p = .008$); **sleep offset**, with participants waking up later on nights beginning on Thursday (i.e., Friday morning, 00:19 ± 00:08 hh:mm, $p = .004$), Friday (i.e., Saturday morning, 02:44 ± 00:08 hh:mm, $p < .001$), Saturday (i.e., Sunday morning, 02:29 ± 00:10 hh:mm, $p < .001$), and Sunday (i.e., Monday morning, 00:18 ± 00:09 hh:mm, $p = .014$); **time in bed**, with longer durations in bed on Friday (1.50 ± 0.19 h, $p < .001$) and Saturday (1.16 ± 0.19 h, $p < .001$) nights; **sleep onset latency**, with longer latencies on Saturday (0.29 ± 0.09 h, $p = .001$) nights; **total sleep time**, with longer sleep durations on Thursday (0.30 ± 0.15 h, $p = .046$), Friday (1.10 ± 0.16 h, $p < .001$), and Saturday (0.58 ± 0.17 h, $p < .001$) nights; **light sleep**, with longer durations (0.87 ± 0.12 h, $p < .001$) and more percentage points on Friday (3.02 ± 0.89%, $p < .001$) and longer durations on Saturday (0.44 ± 0.12 h, $p < .001$) nights; **deep sleep**, with fewer percentage points on Friday (−2.54 ± 0.76%, $p < .001$) and Saturday (−2.28 ± 0.76%, $p = .003$) nights; **REM sleep**, with longer durations on Tuesday (0.12 ± 0.06 h, $p = .048$), Thursday (0.15 ± 0.06 h, $p = .021$), Friday (0.21 ± 0.07 h, $p = .002$) and Saturday (0.20 ± 0.07 h, $p = .004$) nights; and **sleep efficiency**, with fewer percentage points on Saturday (−4.14 ± 1.09%, $p < .001$) nights. Fig. 2 shows the day-to-day changes in sleep.

3.3. Sex differences in social jetlag

Multi-level analyses showed significant interactions between sex and days of the week for **sleep onset**, with girls falling asleep earlier on Friday (−00:41 ± 00:11 hh:mm, $p < .001$) and Saturday (−00:29 ± 00:20 hh:mm, $p = .006$) nights than boys; **sleep onset latency**, with shorter latency to sleep on Saturday (−0.25 ± 0.11 h, $p = .024$) nights among girls vs. boys; **wake after sleep onset**, with longer time awake on Friday (0.17 ± 0.07 h, $p = .020$) nights among girls vs. boys; and **sleep efficiency**, with girls having higher sleep efficiency on Saturday (3.23 ± 1.39 h, $p = .019$) nights than boys. Fig. 2 shows sex differences in social jetlag.

Cohen's f^2m values indicated large effect of sleep offset, and medium effect of sleep onset and time in bed. There was no effect of deep sleep (h) and respiration rate. The remaining models showed small effects. Cohen's f^2c values indicated medium effect of deep

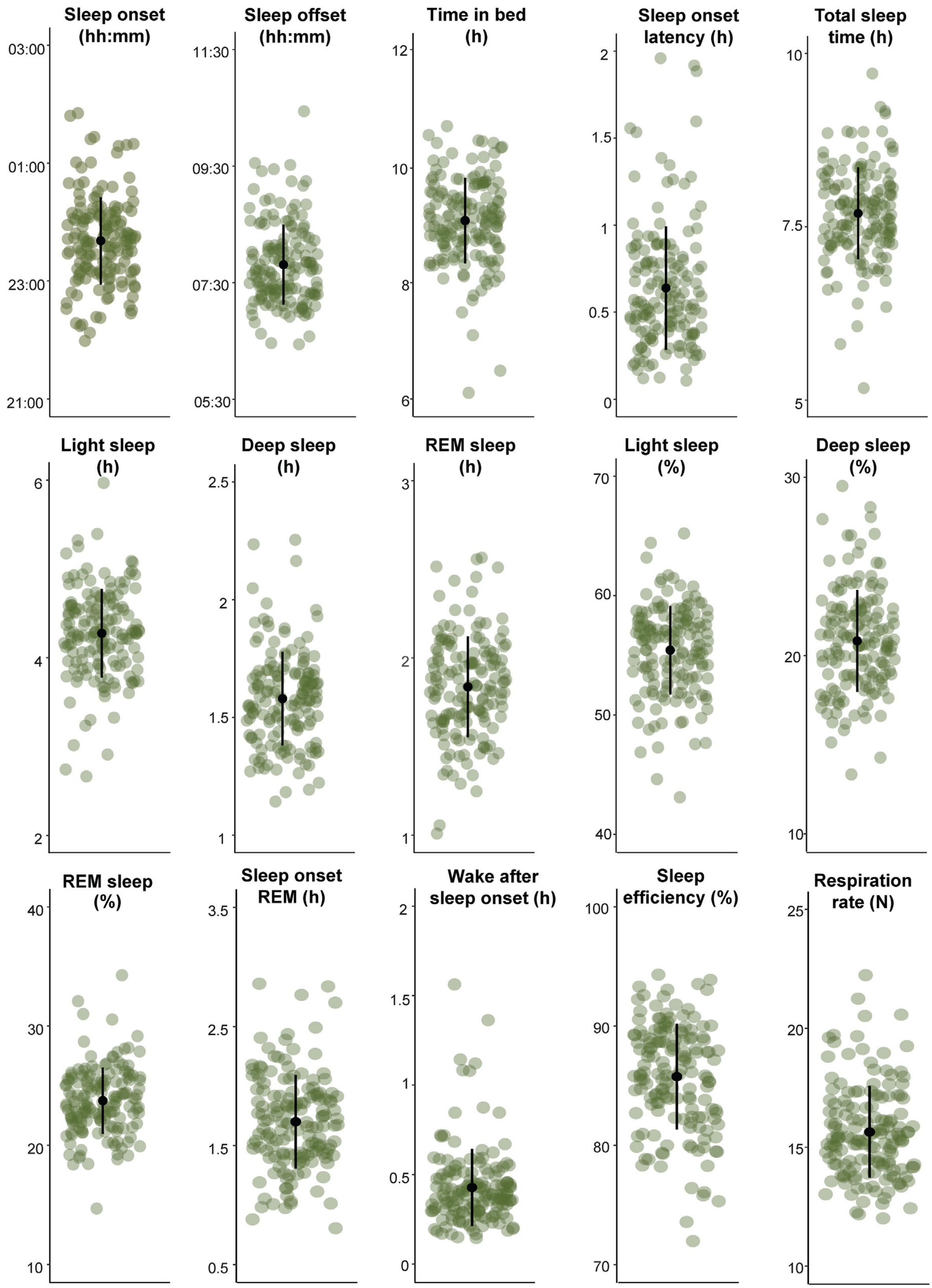

Fig. 1. Average values of the sleep variables obtained from 156 Norwegian teenagers using the SOMNOFY® sleep monitor across a maximum period of 10 consecutive days. Each data point represents each participant's mean score in the respective sleep variable. Filled black dots represent the mean, while S.D. is represented by error bars intersecting the mean.

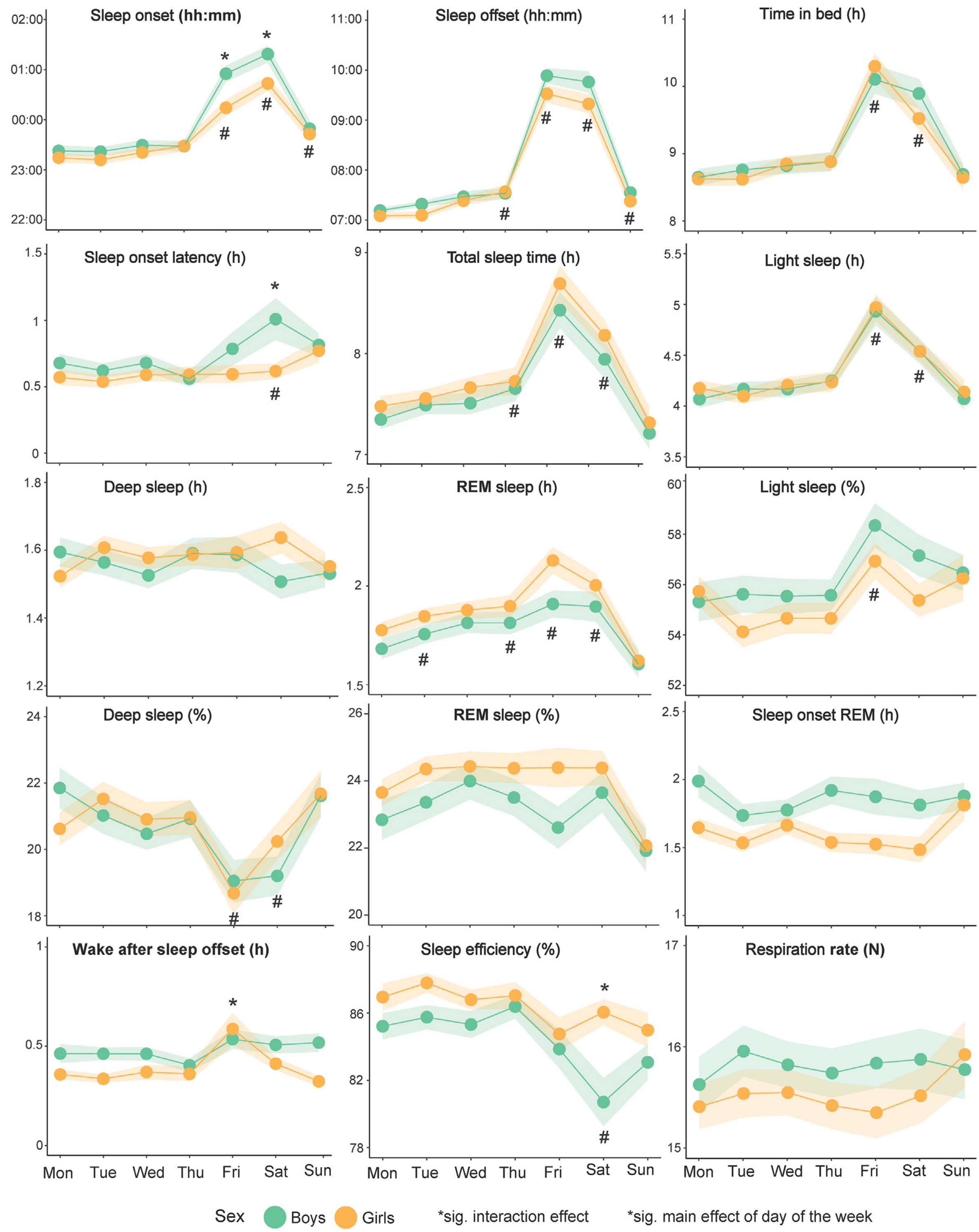

Fig. 2. Sex differences in social jetlag. Data is based on sleep monitoring in 156 Norwegian teenagers across a maximum period of 10 consecutive days. Each dot represents the mean score of each sex on each night of the week in the respective sleep variables. The shaded areas represent the S.E. Girls are shown in yellow, and boys in green. The x-axis shows the day the sleep was initiated, i.e., Mon represents nights of sleep starting on Monday, and ending on Tuesday. * represents a significant interaction term, and # represents a significant main effect of day of the week, controlled for the effects of sex. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sleep (h and %), sleep onset REM and wake after sleep onset. The remaining models showed large effects. The discrepancies between f^2m vs. f^2c may be attributed to the between-level participant variation. Fig. 3 shows the magnitude of effects for the multi-level analyses testing sex differences in social jetlag.

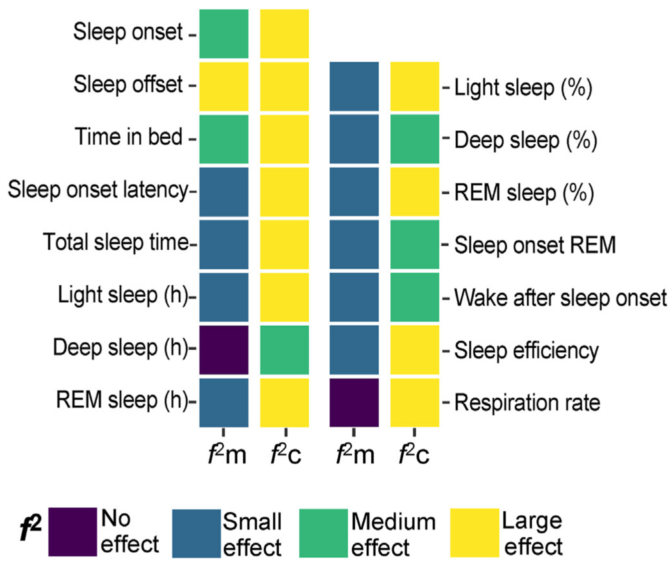

Fig. 3. Magnitudes of effect identified in the multi-level analyses investigating sex differences in social jetlag. Data is based on sleep monitoring in 156 Norwegian teenagers across a maximum period of 10 consecutive days. REM = rapid eye movement sleep; f^2m = marginal Cohen's f^2, f^2c = conditional Cohen's f^2.

4. Discussion

By monitoring the sleep of 156 Norwegian teenagers using a novel IR-UWB sleep monitor, we aimed to gain a descriptive insight into teenagers' sleep patterns and to quantify sex differences in social jetlag of this age group. In line with the hypotheses, the observed sleep patterns reflected healthy, albeit somewhat short sleep. There was convincing evidence of social jetlag, with poorer sleep on weekends vs. weekdays. Girls exhibited less severe social jetlag than boys.

4.1. Teenagers' sleep patterns

The average sleep duration of the sample was ~7 h 40 min, in line with normative actigraphy sleep data in the 15–18 years age group [26]. As such, the average sleep duration was below the recommendations (i.e., 8–10 h of sleep [7]), with only 34.6% of the sample typically obtaining at least 8 h of sleep. Given the average time in bed of ~9 h, the average sleep efficiency was ~85%, at the threshold for what is considered good sleep quality [14]. Overall, 60.3% of the sample typically exhibited sleep efficiency above 85%. The average sleep stage distribution was in accordance with normative values: light sleep at 55.5%, deep sleep at 20.3% and REM sleep at 23.8% per night. Overall, our data indicate that teenagers' sleep patterns reflected healthy, albeit somewhat short sleep. The well-established shift in delayed sleep preference among teenagers [9], coupled with early rise-times during the school week, may be limiting the possibility for longer sleep durations. In addition, other sleep-related and social factors, such as school-related stress, sleep hygiene and the use of technology in bed, might also contribute to the somewhat short sleep durations in this sample [37].

4.2. Evidence of social jetlag

Investigating the day-to-day changes in sleep, while accounting for the effect of sex, compelling evidence of social jetlag was found. On weekend nights starting on Friday and Saturday, participants fell asleep and woke up later, resulting in longer time in bed and longer sleep durations. Light sleep (h and %) and REM sleep (h) increased concurrently, albeit at the expense of deep sleep (%), which was reduced. Sleep onset latencies were longer and sleep efficiency decreased (Saturday nights only). These results are in line with previous actigraphic research in samples of similar age [15,16,26], but show additionally the day-to-day changes in sleep stage distributions during the week. Given deep sleep's role in declarative memory consolidation [20], and endocrine, cardiovascular, and muscular recovery [21], the consequences of the weekend reductions in deep sleep at the expense of light sleep should be investigated in future research.

The present results of social jetlag seem somewhat less severe than in other adolescent samples. For instance, the average sleep duration of at least 8 h was achieved by 28.8% of our sample on weekday nights and 59.6% on weekend nights, while the split was 9.4% and 38.3%, respectively, in a previous study [25]. The reason for the discrepancy in the severity of social jetlag between studies may be due to differing school start times, and thus the opportunity for varying sleep duration [38]. Average sleep onset was comparable between studies, but sleep offset in our sample was considerably later, both on weekdays and weekends, implying that school times were later in the present sample, thus offering the opportunity for longer sleep durations [25]. In addition, the role of chronotype (i.e., evening types), eating patterns (e.g., difference in first meal timing during weekdays vs. weekends) [39], and the sleep debt accumulated during the school week have been highlighted as potential contributing factors to social jetlag [38]. As social jetlag may have detrimental consequences on adolescents' anxiety levels [40], its impact in relation to the current mental health epidemic among children and adolescents [41] should be investigated in future research.

4.3. Sex differences in social jetlag

Interaction analyses of sex differences in social jetlag showed that girls fell asleep earlier than boys on Friday and Saturday nights and had shorter sleep latency on Saturday nights. Despite girls exhibiting longer time awake during the night on Friday nights than boys, girls' sleep efficiency was higher on Saturday nights. Effect size estimations indicate that the interaction between sex and social jetlag has a meaningful practical relevance for the observed variation in sleep onset (medium effect). The estimated effect of sleep onset latency, sleep efficiency and wake after sleep onset may be attributed to the between-level participant variation. Overall, these results point to less severe social jetlag among girls than boys and are in line with actigraphic measures of sleep showing better overall sleep patterns among female adolescents [25,33], but contrary to subjective measures of sleep indicating less severe social jet lag among boys than girls [28].

To the authors' knowledge, this is the first day-to-day investigation of sex differences in social jetlag in a teenage sample using objective sleep measurements. It expands the findings of earlier studies [25,33] by showing that social jetlag affected the sexes differently especially in terms of overall sleep on Saturday night, and the timing of falling asleep on Fridays and Saturdays, but not wake-up time. In addition to sleep pressure, falling asleep is determined by a conscious decision of going to bed. Avoiding severe social jetlag by falling asleep at a reasonable hour even in the weekends may thus be dependent on the individuals' cognition, rather than solely wake-up time. Indeed, girls are more organized and have higher conscientiousness scores than boys [42], and the earlier onset of puberty among girls [43,44] may also play a role in these associations. In addition to the biological underpinnings of sex differences, factors pertaining to gender roles such as the social roles of the two sexes, social opportunities, and lifestyle regularity [28,45,46] have all been hypothesized to contribute to the sex differences in behavioral time structure, which may also have an effect on the observed sex differences in social jetlag. However, with the lack of explanatory variables in the current study (e.g., factors pertaining to teenagers' mental health, bedtime procrastination (going to bed later than intended without having external reasons to do so [47]), stress levels, gender roles, eating patterns, sleep hygiene, engagement in physical activity, chronotype, gaming, and social media use in bed), we cannot with certainty stipulate the mechanisms for the observed sex differences in teenagers' sleep. These should be explored in future research.

4.4. Limitations

Data in this study was collected during the Covid-19 pandemic. Notably, Norway did not implement the most constraining infection-control measures seen in other European countries (e.g., curfews). Data from the initial short period of school lockdown were removed. However, it is still likely to assume that the overall situation of a global pandemic has affected the teenagers' sleep. In addition, even though participants were instructed to keep their sleep patterns as usual, unaffected by their sleep monitoring, we cannot with certainty rule out the possibility that the sleep monitoring in itself may have affected the participants' sleep patterns.

4.5. Conclusion

This study extends our current understanding of teenagers' objectively quantified sleep/wake patterns and sleep stages, focusing on social jetlag and the sex differences therein. We found that sleep durations were close to, but not quite at the recommended levels of 8–10 h per night and sleep efficiency was at the threshold of what is considered good sleep quality. Moreover, sleep stage distributions of our sample were in line with normative data. We found convincing evidence of social jetlag, with later sleep onset and sleep offset, longer time in bed, sleep onset latencies and sleep duration. Moreover, light sleep increased at the expense of deep sleep, and poorer sleep efficiency was observed on Friday and Saturday nights. Girls exhibited less severe social jetlag than boys, with earlier sleep onset on Friday and Saturday nights, and shorter sleep onset latency and higher sleep efficiency on Saturday nights. The estimated effect sizes indicate that sex differences in social jetlag may represent practically meaningful predictors of variation in teenagers' sleep onset, while the effect of the remaining variables may be better attributed to the between-level participant variation. While future research needs to explore the mechanisms facilitating these associations, our study is the first to provide day-to-day insight into sex differences in social jetlag. Further, this study contributes to the body of evidence showing considerable social jetlag among teenagers, and that overall, girls seem to have more favorable sleep patterns, when quantified with objective sleep measurements, than boys.

CRediT authorship contribution statement

Maria Hrozanova: Conceptualization, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Jan Arvid Haugan:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Ingvild Saksvik-Lehouillier:** Methodology, Investigation, Writing – review & editing. **Věra Skalická:** Writing – review & editing. **Lukas Krondorf:** Data curation, Investigation, Writing – review & editing. **Frode Stenseng:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision, Project administration. **Frode Moen:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

Authors MH, JAH, ISL, VS, FS and FM have no conflicts of interest to declare. LK is employed at VitalThings AS, the company developing the SOMNOFY® sleep monitor used in this study. VitalThings AS has received funding for the study from a joint collaboration between Trondheim municipality and Sparebank1 SMN. The funders were not involved in designing or conducting this study.

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Appendix

Multi-level analyses, adjusted for effects of day of the week, showed main effects of sex for **sleep onset REM**, with girls having shorter latencies to REM (-0.28 ± 0.11 h, $p = .010$) than boys; and **wake after sleep onset**, with girls having less time awake during the night (-0.11 ± 0.05 h, $p = .043$) than boys.

References

[1] Maret S, et al. Sleep and waking modulate spine turnover in the adolescent mouse cortex. Nat Neurosci 2011;14(11):1418–20.
[2] Taki Y, et al. Sleep duration during weekdays affects hippocampal gray matter volume in healthy children. Neuroimage 2012;60(1):471–5.
[3] Telzer EH, et al. Sleep variability in adolescence is associated with altered brain development. Develop Cogn Neurosci 2015;14:16–22.
[4] Crowley SJ, et al. An update on adolescent sleep: new evidence informing the perfect storm model. J Adolesc 2018;67:55–65.
[5] Tarokh L, et al. Physiology of normal sleep in adolescents. Adolesc Med State Art Rev 2010;21(3):401–17 [vii].
[6] Carskadon MA. Sleep in adolescents: the perfect storm. Pediatr Clin 2011;58(3). 637-+.
[7] Hirshkowitz M, et al. National Sleep Foundation's sleep time duration recommendations: methodology and results summary. Sleep Health 2015;1(1):40–3.
[8] Seton C, Fitzgerald DA. Chronic sleep deprivation in teenagers: practical ways to help. Paediatr Respir Rev 2021;40:73–9.
[9] Crowley SJ, et al. A longitudinal assessment of sleep timing, circadian phase, and phase angle of entrainment across human adolescence. PLoS One 2014;9(11):e112199.
[10] Dewald JF, et al. The influence of sleep quality, sleep duration and sleepiness on school performance in children and adolescents: a meta-analytic review. Sleep Med Rev 2010;14(3):179–89.
[11] Talbot LS, et al. Sleep deprivation in adolescents and adults: changes in affect. Emotion 2010;10(6):831–41.
[12] Tarokh L, Saletin JM, Carskadon MA. Sleep in adolescence: physiology, cognition and mental health. Neurosci Biobehav Rev 2016;70:182–8.
[13] Arain M, et al. Maturation of the adolescent brain. Neuropsychiatric Dis Treat 2013;9:449–61.
[14] Ohayon M, et al. National Sleep Foundation's sleep quality recommendations: first report. Sleep Health 2017;3(1):6–19.
[15] Rognvaldsdottir V, et al. Sleep deficiency on school days in Icelandic youth, as assessed by wrist accelerometry. Sleep Med 2017;33:103–8.
[16] Berry KM, et al. Weekend night vs. school night sleep patterns, weight status, and weight-related behaviors among adolescents. Sleep Health 2021;7(5):572–80.
[17] American Academy of Sleep Medicine. International classification of sleep disorders, Diagnostic and coding manual. 3 ed. Westchester, IL: American Academy of Sleep Medicine; 2014.
[18] Vyazovskiy VV, Delogu A. NREM and REM sleep: complementary roles in recovery after wakefulness. Neuroscientist 2014;20(3):203–19.
[19] Czisch M, et al. Acoustic oddball during NREM sleep: a combined EEG/fMRI study. PLoS One 2009;4(8):1–11.
[20] Plihal W, Born J. Effects of early and late nocturnal sleep on declarative and procedural memory. J Cognit Neurosci 1997;9(4):534–47.
[21] Dijk DJ. Regulation and functional correlates of slow wave sleep. J Clin Sleep Med 2009;5(2 Suppl):S6–15.
[22] Cai DJ, et al. REM, not incubation, improves creativity by priming associative networks. Proc Natl Acad Sci U S A 2009;106(25):10130–4.
[23] Wagner U, Gais S, Born J. Emotional memory formation is enhanced across sleep intervals with high amounts of rapid eye movement sleep. Learn Mem 2001;8(2):112–9.

[24] Wittmann M, et al. Social jetlag: misalignment of biological and social time. Chronobiol Int 2006;23(1–2):497–509.
[25] Mitchell JA, et al. Changes in sleep duration and timing during the middle-to-high school transition. J Adolesc Health 2020;67(6):829–36.
[26] Galland BC, et al. Establishing normal values for pediatric nighttime sleep measured by actigraphy: a systematic review and meta-analysis. Sleep 2018;41(4).
[27] Keller LK, et al. Not later, but longer: sleep, chronotype and light exposure in adolescents with remitted depression compared to healthy controls. Eur Child Adolesc Psychiatr 2017;26(10):1233–44.
[28] Diaz-Morales JF, Escribano C. Social jetlag, academic achievement and cognitive performance: understanding gender/sex differences. Chronobiol Int 2015;32(6):822–31.
[29] Russo PM, et al. Sleep habits and circadian preference in Italian children and adolescents. J Sleep Res 2007;16(2):163–9.
[30] Lin LN, et al. Sex differences in sleep patterns and changes in 7th to 12th graders: a longitudinal follow-up study in Taiwan. Sleep 2018;41(3).
[31] Polugrudov AS, et al. Wrist temperature and cortisol awakening response in humans with social jetlag in the North. Chronobiol Int 2016;33(7):802–9.
[32] Laberge L, et al. Development of sleep patterns in early adolescence. J Sleep Res 2001;10(1):59–67.
[33] Tremaine RB, Dorrian J, Blunden S. Subjective and objective sleep in children and adolescents: measurement, age, and gender differences. Sleep Biol Rhythm 2010;8(4):229–38.
[34] Toften S, et al. Validation of sleep stage classification using non-contact radar technology and machine learning (Somnofy®). Sleep Med 2020;75:54–61.
[35] Bates D, et al. Fitting linear mixed-effects models using lme4. J Stat Software 2015;67(1):1–48.
[36] Cohen J. Statistical power for the behavioral sciences. Hillsdale, NJ: Laurence Erlbaum and Associates; 1988.
[37] Bauducco SV, et al. Sleep duration and patterns in adolescents: correlates and the role of daily stressors. Sleep Health 2016;2(3):211–8.
[38] Roenneberg T, et al. Chronotype and social jetlag: a (self-) critical review. Biology 2019;8(3).
[39] Sasawaki Y, et al. Association of social jetlag and eating patterns with sleep quality and daytime sleepiness in Japanese high school students. J Sleep Res 2023;32(2):e13661.
[40] Mathew GM, et al. Sleep duration and social jetlag are independently associated with anxious symptoms in adolescents. Chronobiol Int 2019;36(4):461–9.
[41] Shim R, Szilagyi M, Perrin JM. Epidemic rates of child and adolescent mental health disorders require an urgent response. Pediatrics 2022;149(5).
[42] Ni Y, et al. Maturation or disruption? Conscientiousness development in the transition into adolescence. International Journal of Behavioral Development; 2022.
[43] Petersen AC, et al. A self-report measure of pubertal status: reliability, validity, and initial norms. J Youth Adolesc 1988;17(2):117–33.
[44] Baker FC, Yűksel D, Zambotti Md. Sex differences in sleep. In: Sleep disorders in women. Springer; 2020. p. 55–64.
[45] Monk TH, et al. Morningness-eveningness and lifestyle regularity. Chronobiol Int 2004;21(3):435–43.
[46] Motohashi Y, Higuchi S, Maeda A. Men's time, women's time–sex differences in biological time structure. Appl Human Sci 1998;17(4):157–9.
[47] Kuhnel J, Syrek CJ, Dreher A. Why don't you go to bed on time? A daily diary study on the relationships between chronotype, self-control resources and the phenomenon of bedtime procrastination. Front Psychol 2018;9:77.