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RESEARCH ARTICLE

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Sleep regularity in healthy adolescents: Associations with sleep duration, sleep quality, and mental health

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Summary

Current evidence points to the importance of sleep for adolescent physical and mental health. To date, most studies have examined the association between sleep duration/quality and health in adolescence. An emerging line of research suggests that regularity in the timing of sleep may also play an important role in well-being. To address this aspect of sleep, the present study investigated daily variability of sleep, quantified using the sleep regularity index (SRI), in 46 adolescents ($M = 12.78 \pm 1.07$ years) and its association with depressive symptoms/mental health. Sleep was measured during a 6 month period ($M = 133.11 \pm 36.42$ nights) using actigraphs to quantify SRI values calculated for school days, weekends and holidays. Depressive symptoms and general psychopathology were assessed at the beginning (baseline) and end (follow-up) of the actigraphy measurements. Sleep was most regular during school days and associated with a longer total sleep time, shorter sleep onset latency, and higher sleep efficiency. Moreover, a higher SRI on school days was associated with fewer depressive symptoms at follow-up, whereas higher SRI on weekends was associated with less overall psychopathology at follow-up. Furthermore, the change in overall psychopathology, but not depressive symptoms across the two assessments was correlated with sleep regularity index. Our results suggest that regular timing of sleep is associated with sleep that is of longer duration and higher quality and may be protective of adolescent mental health. Therefore, adolescents should be encouraged not only to get enough sleep, but also to retain regular sleeping patterns to promote well-being and mental health.

KEYWORDS
actigraphy, adolescence, depressiveness, index, intraindividual variability of sleep, mental health, sleep regularity

1 | INTRODUCTION

Sleep behaviour changes drastically during adolescence, and one of its most prominent characteristics is the tendency for later sleep timing (Crowley et al., 2007; Crowley et al., 2014). This preference for later bedtimes during adolescence has been reported in countries world-wide, suggesting a biological basis to this phenomenon (Gradisar et al., 2011). Despite the delayed bedtimes, wake times during the school week remain stable, as they are dictated by school start times (Crowley et al., 2014). However, the situation is different on weekends where both bed and rise times are significantly later than on schooldays with a weekend bedtime delay of 1–2 h (Crowley et al., 2007). Weekend rise time is also approximately 1.5–3 h (Zoccola et al., 2009) later as adolescents attempt to catch up on the sleep lost during the school week (Anderson et al., 2009). Therefore, many adolescents experience quick shifts in their sleep/wake schedules between school and free days. These shifts are called social jet lag and result in extremely irregular sleep patterns and high variability in sleep and waking times (Touitou, 2013).

A large body of research has investigated the detrimental effects of inadequate sleep on mental health and mood, focusing mainly on sleep duration and sleep quality (Fuligni & Hardway, 2006; Kahn et al., 2013; Roberts & Duong, 2014). However, recent studies suggest that the intraindividual variability (IIV) of sleep is just as important for psychological well-being as sleep duration. A systematic review of daily IIV, termed sleep regularity, found more variable sleep was associated with worse physical health, higher BMI, more stressful life events, and more psychopathology, especially bipolar and depressive symptomology in adults (Bei et al., 2016) and adolescents (Bei et al., 2017). Despite providing initial evidence for the role of sleep variability in adolescent mental health, the above-mentioned studies have several limitations, including the measurement of sleep during a relatively short period and/or the use of subjective sleep assessment. Only one study by Bei et al. (2017) used actigraphy to record sleep parameters in a sample of 146 adolescents (mean age = 16.2 years, *SD* = 1.0) throughout a 15 day vacation period (Bei et al., 2017) and found that more variable time in bed and sleep onset latency were associated with depressive symptomatology and anxiety.

One mechanism by which irregular sleep timing may impact mental health is through sleep onset latency (SOL). Theoretically, a regular sleep pattern will entrain the circadian clock, allowing for ease of falling asleep and short sleep onset latency. Along these lines, in their meta-analysis, Lovato and Gradisar (2014) proposed that increased wakefulness before sleep onset could promote rumination and reinforce depressive thinking styles, which in turn, perpetuates longer sleep latency.

The aim of the current study was to use long-term (6 months) actigraphy data to examine the impact of sleep regularity on sleep quality, depressiveness, and psychopathology in a non-clinical sample of young adolescents. In order to quantify the regularity of sleep, this study used a novel metric first introduced by Phillips et al., 2017 – the Sleep Regularity Index (SRI) (Phillips et al., 2017). Based on findings from previous studies (Phillips et al., 2017), we first hypothesised that there will be a substantial difference in sleep regularity between school days, weekends, and vacations, with a higher regularity during school days and the lowest regularity during vacations. Second, we hypothesised that lower sleep regularity predicts more depressive symptomatology and worse overall mental health after a 6 month sleep measurement period. Third, we hypothesised that the association between the sleep regularity index and depression is mediated by sleep onset latency.

2 | METHODS

The data presented here were collected as part of a longitudinal study designed to investigate genetic and environmental influences on sleep in adolescents (Castiglione-Fontanellaz et al., 2022; Hamann et al., 2019; Inderkum & Tarokh, 2018; Markovic et al., 2018; Markovic et al., 2020a; Markovic et al., 2020b; Markovic et al., 2022; Rusterholz et al., 2018). Participants were recruited through flyers, advertisements, and direct mailings to schools in the German-speaking part of Switzerland. The study was performed in accordance with the Declaration of Helsinki and the ethics commission of the canton of Zurich approved the study. Participants and the participants' parents provided written informed consent.

2.1 | Participants

The sample consisted of 46 adolescents (23 boys and 23 girls) aged 10–14 (*M* = 12.78, *SD* = 1.07 years) years at baseline data acquisition. All participants had a body mass index in the normal range for adolescents at both time points (mean at baseline = 17.73; range at baseline = 13.88–22.03; SD at baseline = 1.96; mean at follow up = 17.96; range = 14.22–21.63; SD at follow up = 1.64). Participants with a known chronic or current illness, sleep disorders, use of medication impacting sleep, and preterm birth before gestation week 30 were excluded from the study.

2.2 | Material

2.2.1 | Actigraphy

Jawbone UP is a commercial wrist-worn actigraphy device, tracking body movements through micromechanical triaxial accelerometers. A button is pressed in order to switch from wake to sleep mode when going to bed, and to switch from sleep to wake mode upon waking. Previous studies (de Zambotti et al., 2015; Toon et al., 2016) have validated the Jawbone device against polysomnography for use in adolescent samples and shown good sensitivity (0.92) and accuracy (0.86) of Jawbone UP when compared with polysomnography (Toon et al., 2016). Through proprietary algorithms the Jawbone UP calculates with minute precision the total duration of sleep (TST), sleep onset latency (SOL), sleep start time (SST), sleep end time (SET), time in bed (TIB), and total time awake after button press (TWT). Wake after sleep onset (WASO) was calculated by subtracting SOL from TWT and sleep efficiency (SE; the ratio of time asleep to time in bed) was calculated by dividing TST by TIB. Social jet lag was calculated using the following formula:

$$= \left((MS_{we} - MS_{sd}) \times \frac{d_{we}}{d_{we} + d_{hd}} \right) + \left((MS_{hd} - MS_{sd}) \times \frac{d_{we}}{d_{we} + d_{hd.}} \right)$$

where MS_{we} is the mean of midsleep on weekends; MS_{sd} is the mean of midsleep on school days; MS_{hd} is the mean midsleep on holidays; d_{we} is all measured days on weekends; d_{sd} is all measured days on school days; d_{hd} is all measured days on holidays. The formula was taken from Wittmann et al. (2006) and adapted in order to take all free days (weekends and holidays) into account and to correct for the differing quantity of measured weekend and holiday nights (Wittmann et al., 2006). Midsleep was calculated as the mid-point between sleep onset (SST) and sleep end time (SET) of the respective day type.

2.2.2 | Sleep habits survey (SHS)

The German version of the sleep habits survey (Wolfson & Carskadon, 1998) was used to assess sleep–wake habits and daytime functioning over the previous 2 weeks. The 63 item School Sleep Habits Survey collects information about demographic data, sleep and mental and physical health. Evidence for the validity of the SHS in adolescents is given by comparisons with diary and actigraphy (Wolfson et al., 2003).

2.2.3 | Chronotype

The superscience morningness/eveningness scale is a subscale of the sleep habits survey and measures chronotype on a 10 item scale. It is adapted for children and adolescents of the composite morningness questionnaire. The items are based on the Morningness-Eveningness questionnaire (MEQ; originally by Horne & Ostberg, 1976) and a diurnal type scale by Torsvall and Akerstedt (Shahid et al., 2012). It has an internal consistency of 0.87 (Smith et al., 1989).

2.3 | Depressive symptomatology and mental health

2.3.1 | Centre for epidemiologic studies depression scale (CES-D)

The CES-D (Kahn et al., 2013; Lovato & Gradisar, 2014; Radloff, 1977) is a 20 item self-rating measure to assess symptoms associated with depression. Values on this scale range between 0 and 60, with scores above 16 indicating a high risk for clinical depression. The CES-D demonstrated acceptable screening accuracy in the general population (sensitivity of 0.87 ad specificity of 0.70). A meta-analysis of 28 studies (Vilagut et al., 2016) showed support for its reliability and validity in children and adolescents.

2.3.2 | Strength and difficulties questionnaire (SDQ)

The SDQ is a screening questionnaire for child mental health problems on five dimensions: conduct problems, emotional symptoms, hyperactivity, peer problems, and prosocial behaviour. The total difficulties scores used in this study (higher scores indicating greater psychological difficulty) can be calculated by summing the scores obtained on four of the subscales, excluding the prosocial behaviour dimension (Goodman, 2001). The SDQ has good internal consistency ($\alpha = 0.73$) and retest stability (0.62) (Goodman, 2001).

2.4 | Procedure

Participants were instructed to wear the actigraph daily for a period of 6 months and only remove it when swimming. Neither participants nor their parents were given instructions on bed and rise times. Before and after the 6 months of actigraphy data acquisition, participants filled out the SHS, CES-D, and SDQ. The purpose of this study was to investigate if sleep regularity was associated with depressive symptomatology and psychopathology, therefore we examined the association between sleep regularity index and follow-up measurements (after the 6 month period of sleep measurement). Furthermore, we determined whether the SRI predicts changes in mental health by examining the association between sleep regularity index and changes in mental health across the two time points.

2.5 | Data analysis

2.5.1 | Sleep measures

Rest and activity patterns of the actigraphy data were visually inspected, and each night was examined individually to check data quality according the criteria outlined in the study of Inderkum and Tarokh (Inderkum & Tarokh, 2018). In total only 5% of all nights (consisting of 53% school days and 47% free days) were removed from the analysis for this reason. Therefore, 6123 nights were analysed in this study, the number of measured nights per subject varied from 50 to 193 nights ($M = 133{,}11$, $SD = 36.42$ nights). This wide range is due to varying compliance between subjects. On average across the participants, no data were available on 3305 nights (35.1% of all nights, $M = 71.85$, $SD = 36.32$), mainly because the actigraph was not worn (89.9% of all nights, range: 0–24), or more rarely, because data had to be excluded (5.45% of all nights, range: 15–149). Nights were labelled as “school day” if the following day was a school day (Sunday through Thursday) and “weekend” if the following day was a weekend day (Friday and Saturday). If there were several consecutive nights with no school the next day, the first two nights were labelled “weekend” and beginning from the third night they were defined as “holidays”. We assume that after school days, 2 nights of recovery sleep are following (i.e. weekends) and therefore sleep patterns are still indirectly affected by school times. We postulate that if there are no school times dictating sleep patterns, and after this recovery phase of 2 days, biological tendencies of sleep can fully unfold (i.e. holidays). Weekends and holidays together are referred to as “free days” in the following sections. Of the 6123 nights, 3341 (54.6%, $M = 72.63$, $SD = 22.25$, range: 15–122 nights per individual) were schooldays, 1322 (21.6%, $M = 28.74$, $SD = 9.99$, range: 6–49 nights per individual) weekends and 1460 (23.8%, $M = 31.74$, $SD = 13.78$, range: 3–71

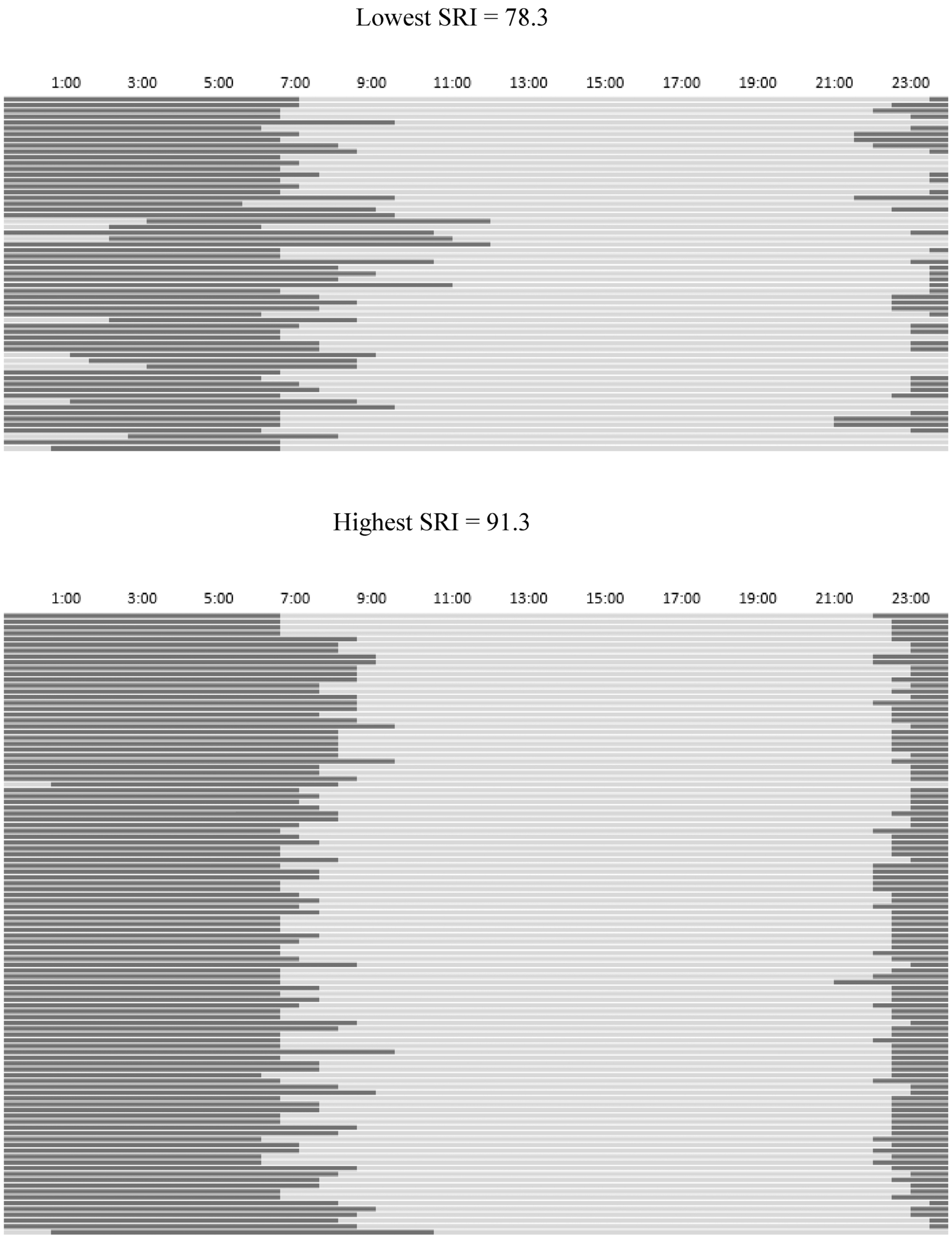

FIGURE 1 Sleep patterns of the participant with the highest SRI and the participant with the lowest SRI. Each line represents one 24 h period. Missing nights were excluded.

per individual) holidays. For each subject, the mean values for TST, SOL, WASO, STT, SET, and SE (mTST, mSOL, mWASO, mSST, mSET, mAwakenings) were calculated separately over all days (AD), schooldays (SD), weekends (WE), and holidays (HD). There was a significant relationship between the number of missing nights and SRI values, with lower SRI values associated with more missing nights (SRI all days, $r = -0.335$, $p = 0.028$; SRI on weekdays, $r = -0.367$, $p = 0.016$; SRI on weekends, days $r = 0.309$, $p = 0.044$; SRI on holidays, $r = -0.351$, $p = 0.021$). No other relationship between the number of missing nights and any of the outcome variable (e.g. CES-D, SDQ, SOL) was found.

2.5.2 | Sleep Regularity Index (SRI)

The SRI quantifies sleep regularity by comparing an individual's recorded sleep/wake pattern with the same pattern shifted by 24 h and thereby the degree of overlap between those two patterns is calculated (see Figure 1). It is computed as the likelihood of any two time-points (minute-by-minute) 24 h apart showing the same sleep/wake state, across all recorded days. The value is scaled to give a range of 0–100 to provide an intuitive range. Although theoretically negative values are possible, they are very unlikely to be observed (e.g. asleep for 24 h, awake for 24 h). Empirically observed sleep patterns of individuals will range between a SRI of 0 (sleeps at random) and 100 (sleeps and awakes at exactly the same time every day) (Phillips et al., 2017). For this study, a matrix was composed for each subject, in which each minute of the day (1440 min) was coded either "asleep" (1) or "awake" (−1) for every valid day of the observation period. Next, for each subject, four different SRIs were calculated using code written by A.J. Phillips et al. (2017) on MATLAB R2018b: one for all days of the data acquisition period (SRI-AD), one for school days (SRI-SD), one for weekends (SRI-WE), and one for holidays (SRI-HD). SRI-HD had to be excluded from further analysis for one subject since only 3 holiday nights were recorded, meaning that the minimum of 5 nights required for SRI to be a reliable estimator of sleep regularity (Lunsford-Avery et al., 2018) was not reached.

2.5.3 | Statistics

The remaining data analysis was conducted using IBM SPSS Statistics 25. In a first step, three-way mixed model ANOVAs (day type × gender × age) were conducted for SRI, TST, SOL, WASO, SST, SET, and SE per night with day type (SD/WE/HD) as a within-subjects factor. Between-subjects factors were gender and age. If Mauchly's test indicated a lack of sphericity, Huynh-Feldt corrections were used, and all post-hoc tests were Bonferroni adjusted. Effect sizes for ANOVAs (partial eta-square [ηp^2]) were interpreted with $0.01 > \eta p^2 < 0.059$ as a small, $0.06 > \eta p^2 < 0.139$ as a medium, and $\eta p^2 \geq 0.14$ as a large effect. Furthermore, CES-D, SDQ, and chronotype were investigated for possible differences in gender and age. All variables were tested for normal distribution with visual inspection and the Shapiro–Wilk test. If distributions were normal, two-sided independent *t*-tests were calculated, otherwise nonparametric Mann–Whitney *U*-tests were applied. The following variables were not normally distributed: SRI-AD, SRI-HD, WASO, CES-D.

For age, univariate ANOVAs were calculated. Associations between SRI, other sleep parameters, depressive symptomatology, and mental health were conducted using Pearson partial correlations, always controlling for age and gender. Finally, mediation analyses were conducted using PROCESS. The significance of the indirect effects was tested using bootstrapping procedures. Unstandardised indirect effects were computed for each of 5000 bootstrapped samples. Effect sizes were interpreted according to Cohen (1988) with $r = 0.10$ and $f = 0.10$ indicating a small effect size, $r = 0.30$ and $f = 0.25$ indicating a medium effect size, and $r = 0.50$ and $f = 0.40$ indicating a large effect size. For all statistical tests, the level of significance was stated at $p < 0.05$.

3 | RESULTS

3.1 | Participants characteristics

As shown in Table 1, there was no difference in morningness-eveningness across gender and age. Problematic sleeping behaviour as measured by a subset of SHS items was relatively low ($M = 17.86$, $SD = 4.10$) and did not differ between gender and age groups. Considering the mean SDQ scores of 6.59 ($SD = 4.5$), mental health of the investigated sample can be interpreted as within the non-clinical range (Goodman, 2014), with no significant differences for gender. With regards to depressive symptoms (CES-D), scores were equal across male and female participants. Five subjects (10.87%) exceeded the cut-off of 16 (scores above identify a high risk for clinical depression).

3.2 | Analysis of sleeping behaviour

Table 2 shows means and standard deviations for average TST, SOL, WASO, SST, SET, and SE per night separately for school days, weekends, and holidays. As shown previously (Inderkum & Tarokh, 2018), all sleep parameters differed significantly depending on day type (SD/WE/HD), except for sleep efficiency. In line with the previous literature (reviewed in Fontanellaz-Castiglione et al., 2020), sleep duration was later and longer on the weekends/holidays compared with the schooldays (sleep start time: 23:13 h on weekends, 23:33 h on holidays, 22:16 h on schooldays; mean total sleep time 8.65 h on weekends, 8.56 h on holidays, 8.20 h on schooldays). There was less WASO on school days compared with weekends (14 min) and holidays (15 min). For all sleep parameters, there were no significant interactions between day type and age and day type and gender.

No main effects were found for gender, however, significant age-dependent changes were found for most sleep parameters. A general pattern of progressively later bedtimes and shorter sleep was

TABLE 1 Participant characteristics, gender, and age differences

					Gender				Age	
Measure	M	SD	Min	Max	*t*	*p*	*U*	*p*	*F*	*p*
MEQ	36.9	4.87	26	45	0.32	0.752			1.38	0.259
Problematic sleep (SHS)	17.86	4.10	13	52	−0.73	0.469			2.33	0.073
SDQ	6.59	4.5	0	20			207.00	0.205	4.30	0.005
CES-D	7.78	5.715	0	24			241.00	0.604	4.03	0.008

Note: MEQ values above 44 indicate a morning-type (Shahid et al., 2012).
Abbreviation: CES-D, center for epidemiologic studies depression scale; MEQ, morningness-/eveningness scale; SDQ, strength and difficulties questionnaire; SHS, sleep habits survey.

TABLE 2 Mean values, standard deviations, and results of mixed models ANOVA for SRI and sleep parameters

	Day type (within)					Gender (between)		Age (between)	
	School days	Weekends	Holidays	F	ηp^2	F	ηp^2	F	ηp^2
SRI	91.32 (2.55)	83.12 (3.58)	84.50 (5.24)	78.82**	0.675	0.10	0.003	1.57	0.142
mTST (h)	8.20 (0.49)	8.65 (0.54)	8.56 (0.46)	9.47**	0.200	0.552	0.014	7.44**	0.439
mSOL (min)	33.61 (11.60)	27.45 (9.30)	31.05 (12.73)	10.19**	0.211	0.135	0.004	2.066	0.179
mWASO (min)	33.55 (13.48)	47.75 (20.65)	49.21 (23.47)	20.22**	0.347	1.658	0.042	3.73*	0.282
mAwakenings	1.46 (0.80)	1.42 (0.74)	1.76 (1.00)	3.43*	0.083	2.106	0.053	4.16*	0.305
mSE (%)	89.35 (6.40)	90.76 (5.50)	89.68 (4.73)	1.45	0.037	1.743	0.044	4.22*	0.308
mSST (time)	22:16 (0.61)	23:13 (0.68)	23:33 (0.80)	111.33**	0.746	0.014	0.000	5.74*	0.377
mSET (time)	06:45 (0.35)	08:10 (0.67)	08:29 (0.71)	128.86**	0.772	0.025	0.001	1.00	0.095

Abbreviation: m, mean; SE, sleep efficiency; SOL, sleep onset latency; SRI, sleep regularity index; SSE, sleep end time; SST, sleep start time; TST, total sleep time; WASO, wake after sleep onset.
*$p < 0.05$; **$p < 0.01$.

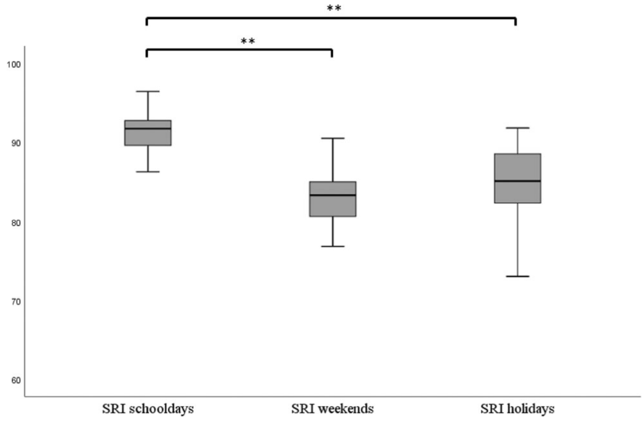

FIGURE 2 Box plots of SRI for schooldays, weekends, and holidays; **$p < 0.001$

observed on schooldays, weekends, and holidays with increasing age. Due to school start times, rise time did not change with age on school days, but was later on weekends and holidays with increasing age.

3.3 | Sleep regularity index

Table 2 shows means and standard deviations for sleep regularity index separately for school days, weekends, and holiday. The sleep regularity index over all days (SRI-AD) ranged from 78.28 to 91.30 ($M = 86.12$, $SD = 2.99$). The mean SRI levels showed a statistically significant difference between day types (see Figure 2), with the highest SRI for schooldays (SRI-SD; $M = 91.45$, $SD = 2.56$, range: 83.88–96.47), followed by weekends (SRI-WK; $M = 83.11$, $SD = 3.58$, range: 72.55–90.51), and finally holidays (SRI-HD; $M = 84.50$, $SD = 5.24$, range: 67.18–91.83). The sleep regularity index for school days was significantly higher ($p < 0.001$) than for weekends (8.918, 95%-CI [7.605–10.231]), and higher ($p < 0.001$) than for holidays (7.232, 95%-CI [5.125–9.339]). There was no difference between weekends and holidays ($p = 0.067$). There were no significant interactions for day type and age (F (7.83, 74.39) $= 1.89$, $p = 0.078$) and gender (F (1.96, 74.39) $= 0.13$, $p = 0.873$), nor main effects for age and gender (see Table 2). We also did not find any significant correlations between body mass index and the SRI on all day types.

3.4 | SRI in relation to other sleep parameters

For each day type of sleep regularity index (e.g. school day) partial correlations controlling for age and gender (see Table 3) were performed with the corresponding sleep parameter (e.g. school day), thus performing correlations within a day type. The following correlations between sleep regularity index and sleep parameters were conducted: TST, SOL, WASO, SST, SET, and SE. On school days, more regular

TABLE 3 Partial Pearson correlation coefficients for SRI on schooldays, weekends, and holidays

		SRI		
	n	School days	Weekends	Holidays
mTST (h)	46	0.39*	−0.07	0.00
mSOL (min)	46	−0.45*	−0.09	0.02
mWASO (min)	46	−0.16	0.15	0.13
mSE (%)	46	0.43*	−0.10	0.13
mSST (h)	46	−0.51**	−0.30	−0.54**
mSET (h)	46	−0.27	−0.19	−0.48**
Social jet lag	46	−0.25	−0.17	−0.29
Chronotype	45	−0.18	0.01	−0.10
Problematic sleep	44	−0.45*	−0.29	−0.34*
CES-D	46	−0.31*	−0.29	−0.14
SDQ	46	−0.15	−0.33*	−0.12

Abbreviation: CES-D, center for epidemiologic studies depression scale; m, mean; sd, standard deviation; SDQ, strength and difficulties questionnaire; SE, sleep efficiency; SOL, sleep onset latency; SRI, sleep regularity index; SSE, sleep end time; SST, sleep start time; TST, total sleep time; WASO, wake after sleep onset;
*$p < 0.05$; **$p < 0.01$.

TABLE 4 Questions about problematic sleeping behaviour, taken from the Sleep Habits Survey. Participants were asked how often (every day/night, several times, twice, once, or never) in the last two weeks did they engage in the listed behavior.

1. Arrived late to class because you overslept?
2. Fallen asleep in a morning class?
3. Fallen asleep in an afternoon class?
4. Awakened too early in the morning and could not get back to sleep?
5. Stayed up until at least 3 am?
6. Stayed up all night?
7. Slept in past noon?
8. Felt tired, dragged out, or sleepy during the day?
9. Needed more than one reminder to get up in the morning?
10. Had an extremely hard time falling asleep?
11. Had nightmares or bad dreams during the night?
12. Gone to bed because you just could not stay awake any longer?
13. Done dangerous things without thinking?

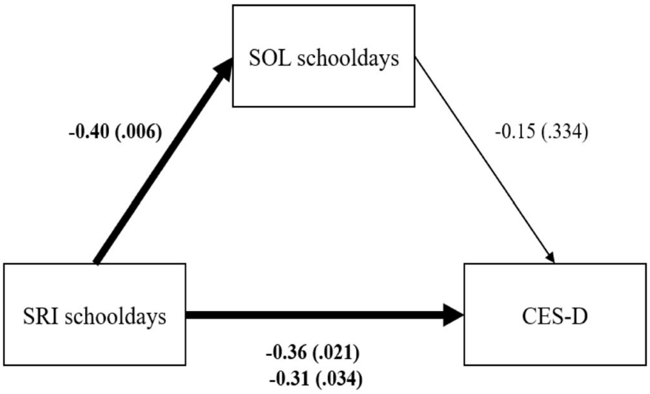

FIGURE 3 Standardised regression coefficients (*p*-values) for the relationship between SRI and CES-D as mediated by SOL. The standardised regression coefficient (*p*-value) between SRI and CES-D, controlling for SOL is in parenthesis

sleep was associated with markers of better sleep, including longer sleep duration, earlier sleep times, shorter sleep onset latency, and greater sleep efficiency.

Higher sleep regularity index values on holidays were associated with earlier sleep times and rise times. Social jet lag was not associated with any of the day-specific SRIs, yet it was highly correlated with the sleep regularity index over all days ($r = -0.55$, $p < 0.001$). Chronotype was not correlated to sleep regularity index (Table 3), however, participants who endorsed more problematic sleep (see Table 4 for a list) had a lower sleep regularity on school days and holidays (Table 1).

3.5 | Depressive symptomatology and mental health

To test the hypothesis that sleep regularity index was associated with depressive symptoms and mental health after the 6 months period, partial correlations were conducted with CES-D and SDQ, all at follow-up measurement. Table 3 indicates that those adolescents who showed more regular sleep on school days, as indicated by a higher SRI score, showed lower depressive symptomatology (lower CES-D) at follow-up. Furthermore, more regular sleep on weekends was correlated with better overall mental health (lower SDQ) at follow-up. We then conducted partial correlations to examine the association between changes in mental health (CES-D and SDQ) during the 6 month interval with SRI. For these analyses, we subtracted the sum values of the questionnaires at time 1 (e.g. sum score of the CES-D) from the same questionnaire scales at time 2 (e.g. sum score of the CES-D) and correlated these differences with the SRI values on school days, weekends, and holidays, controlling for age and sex. We found that higher SRI values on weekends was associated with a worsening of overall mental health as reflected in the change in the sum score of the SDQ between time 1 and time 2 ($r = -0.39$, $p = 0.01$). No associations for the change in the CES-D score and SRI were observed.

3.6 | SOL as a mediator of the relationship between SRI and depressive symptoms on schooldays

Sleep onset latency is thought to play a major role in the connection between sleep and depressiveness. The prior analysis showed that only SRI-SD was correlated to SOL, which means that only on school days, but not on free days, more variable sleep timing (lower SRI) is associated with a longer sleep onset latency. To test the hypothesis that SOL plays a mediating role in the connection between sleep regularity index and depressive symptomatology for school days, mediation models were calculated. As Figure 3 illustrates, for CES-D as the outcome variable, the standardised regression coefficient between sleep regularity index and sleep onset latency was statistically significant (F (1, 44) $= 8.49$, $p = 0.006$). However, SOL in return does not predict CES-D score ($t = -0.98$, $p = 0.334$). The standardised indirect effect of sleep regularity index and sleep onset latency was 0.06, the bootstrapped unstandardised indirect effect was 0.14, and the 95% confidence interval ranged from -0.09 to 0.52 and is thus not significant. These results indicate that a higher sleep regularity index during school days predicts longer sleep onset latency during school days and higher CES-D scores. However, sleep onset latency does not predict CES-D scores, and the indirect effect of sleep regularity index and sleep onset latency does not explain depressive symptoms.

4 | DISCUSSION

The present study investigated sleep regularity in adolescents on schooldays, weekends, and holidays, and its association with depressive symptoms and mental health. Sleep regularity was calculated with a novel measure, the sleep regularity index (SRI), using objective sleep data (actigraphy) over a period of 6 months. Overall, the results demonstrated that sleep regularity is higher on school days than on free days (weekends and holidays) and does not change with increasing age. Furthermore, higher sleep regularity on school days is associated with lower depressive symptoms, whereas more regular sleep on weekends is correlated to better mental health. This effect of sleep regularity on depressiveness and mental health was not explained by a mediating role of sleep onset latency. In contrast to other studies (e.g. Bei et al., 2016) we found no significant association between higher SRI with body mass index. This may be due to the smaller sample size in our study and the narrow range of BMI values in the current study.

4.1 | Sleep and sleep regularity on school days, weekends, and holidays

This is one of the first studies to introduce and validate the sleep regularity index in a sample of school-aged children. As expected, our findings demonstrate that adolescents show differences in sleep regularity between school nights compared with nights where they can freely choose their bed and rise times. Rise times during the school week are predetermined by school start times, which in turn make sleep more regular. Still, more regular sleep was associated with earlier sleep times, longer sleep duration, shorter sleep onset latency, and greater sleep efficiency. These effects were medium to large, highlighting the importance of regular sleep timing during the school week to obtain sufficient sleep of good quality.

Unexpectedly, sleep regularity was constant across all age groups. As shown in our data, weekday–weekend shifts became more pronounced with older age. Importantly, the sleep regularity index does not describe weekend/holiday oversleep and delay, but the *daily* variability of sleep on either schooldays, weekends, or holidays. Hence, in contrast to social jet lag, the phenomenon of day-to-day regularity of sleep seems to be independent of age. Similarly, sleep regularity was independent of chronotype. This may seem surprising at first glance, as evening-types are thought to accumulate more sleep debt during the week and hence show greater weekend delays (Doi et al., 2015). But again, the day-specific SRIs do not depict sleep regularity on a weekly scale and thus have explanatory power beyond chronotype or social jet lag. Indeed, none of the day-specific sleep regularity indexes were correlated to social jet lag. In contrast, the sleep regularity index over *all days* (school and free days) contains weekday–weekend delay and oversleep and was highly correlated to social jet lag.

Furthermore, irregular sleep on school days and weekends was associated with problematic sleeping behaviour, especially with feeling tired during the day and needing more than one reminder to get up in the morning. Irregular sleeping patterns thus seem to impact both subjective and objective measures of sleep quality.

4.2 | Sleep regularity and depressive symptomatology and mental health

Our second and third hypotheses were that sleep regularity is correlated with depressive symptomatology and mental health. Our data showed that irregular sleep on school days was associated with more depressive symptoms. This association between irregular sleep and depressiveness is in line with previous studies (e.g. in adults (Lemola et al., 2013); in adolescents (Fuligni & Hardway, 2006)). However, the question of why this association is only present for sleep regularity on school days, but not weekends and holidays remains open. One possible explanation is that irregular sleep during the school week, results in sleep disturbances and daytime sleepiness, and further interacts with school-week-specific stressors and eventually lead to elevated levels of depressiveness. Furthermore, as can be seen in our data, irregular sleep on school days (but not on free days) is correlated with sleep parameters that are well known to be associated with depressiveness in adolescents, such as reduced sleep duration (Roberts & Duong, 2014) and increased sleep onset latency (Dahl, 1996).

Lower sleep regularity on weekends was associated with worse overall mental health (SDQ). These findings are in line with a study in 5–10 year old children that found instability of sleep/wake patterns (i.e. irregularity) to be associated with higher scores in the Strengths and Difficulties Questionnaire (Biggs et al., 2011). Yet, in this previous study an association between sleep regularity and the SDQ were found irrespective of day type (school nights vs. weekend nights). Therefore, the question arises as to why sleep irregularity on weekends, but not other days, could lead to worse mental health. We have previously shown that the genetic contribution to sleep timing is higher during weekends (Inderkum & Tarokh, 2018) – a time when adolescents are more able to express their biological rhythms due to fewer constraints on the timing and duration of sleep. Thus, we speculate that the association we find may be due to overlapping genes driving the timing of sleep and psychopathology (Logan & McClung, 2019). Furthermore, we find that SRI on weekends predicts the change in psychopathology between the two assessments 6 months apart, suggesting that sleep regularity may be an important intervention target. Further research is needed to understand the differential association between sleep regularity and mental health on weekdays and weekends.

Sleep regularity on holidays was related to neither depressive symptoms nor mental health. This stands in contrast to the study by Bei et al. (2017), in which irregular sleep during holidays was associated with a more negative mood. However, their study used the variability of time in bed, whereas our sleep regularity index unifies the variability of sleep duration *and* sleep/rise times and may, therefore, capture other aspects of sleep regularity. We are unsure, however, how to reconcile the disparate findings for holidays versus weekends.

Finally, contrary to our fourth hypothesis, sleep onset latency did not serve as a mediator between sleep regularity and depressive symptomatology/mental health. We hypothesised that irregular sleep would make it harder to fall asleep and thus lengthen sleep onset latency. First, our data showed that irregular sleep was associated with longer sleep onset latency only on school days, but not on free days. This may be explained by the fact that adolescents go to bed later on weekends. Thereby, sleep pressure is built up, and combined with the sleep deficit which was accumulated during the school week, allowing teens to fall asleep easily despite irregular sleep. Second, the mediation model for school days that we tested with sleep regularity index as a predictor and sleep onset latency as a mediator was not significant. This may in part be due to our sample size, which only allows us to detect medium effect sizes with a power of 0.8 at alpha equal to 0.05.

In sum, our results show that school schedules, while shortening sleep duration, increase sleep regularity which in turn is associated with fewer depressive symptoms. We note, however, that the effect sizes for the associations between mental health and sleep regularity index are small to medium. Future studies in adolescents should examine whether sleep regularity is a protective factor for mood disorders in adolescence.

4.3 | Limitations

Some limitations of the current study are important to note. For one overall, CES-D and SDQ scores were relatively low in this study, given that this was a non-clinical sample. Furthermore, we note that there was a high correlation between the two time points (time 1 and time 2) for the CES-D ($r = 0.73$, $p < 0.001$) and SDQ ($r = 0.78$; $p < 0.001$) scores and therefore our study design may not allow us to address more causally whether sleep regularity in the intervening 6 months impacts mental health.

Accordingly, further research is needed to investigate sleep regularity in a clinical sample of depressed adolescents. Furthermore, when studying the relationships between sleep disturbance and depression, it is important to consider the conceptual overlap between these two variables. Since disrupted sleep is a hallmark of depression, scientifically sound conclusions of the sleep–depression relationship can only be drawn if the sleep related items in the depression measure are removed prior to analysis. Regarding the characteristics of the sample, we note that participation in the study was related to high effort and long-term commitment and thus may not generalise to all adolescents, particularly those with impaired daily functioning. Additionally, our sample size was relatively small. Furthermore, a lower overall sleep regularity index was associated with more missing data ($r = -0.33$, $p = 0.027$), possibly leading to a systematic bias where those with a lower sleep regularity index show less diligence and conscientiousness, which could be associated with some of the outcome measures. An additional limitation is that we string the data together to be able to compare the SRI on school days (SRI-SD) and on weekends (SRI-WE) as well as holidays separately, meaning that e.g. multiple weekends are analysed as consecutive days.

5 | CONCLUSION

Healthy sleep behaviour is essential for adolescents' physical and mental health. In order to promote this, adolescents should not only be encouraged to get enough sleep but also to retain regular sleep–wake patterns, especially during school days. Since – to our knowledge – this is one of the first studies to use sleep regularity index in school-aged adolescents and its association with depressiveness, further research should focus on replicating our results in clinical samples.

AUTHOR CONTRIBUTIONS

CEGCF was a major contributor in writing the manuscript and was involved in the data analysis. SS was involved in the writing of the first draft of the manuscript and prepared the data for the analysis. SJEW was involved in the writing of the manuscript. CH was involved in data collection and initial analyses. MK was involved in the writing of the manuscript. LT conceived the study, was a major contributor in writing the manuscript, involved in data collection and analysis. All authors read and approved the final manuscript.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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