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Cross-sectional associations between objectively measured sleep characteristics and body mass index in European children and adolescents

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ABSTRACT

Background: Short sleep duration has been found to be associated with a higher risk for overweight and obesity. However, previous studies have mainly relied on subjective measures of sleep duration and other sleep characteristics (e.g. quality, timing) have often been neglected. Therefore, we aimed to investigate associations between several, mainly objectively measured sleep characteristics and body mass index (BMI). Further, we aimed to identify distinct sleep subtypes based on these sleep characteristics and to study their association with BMI.

Methods: Children aged 9-16 years participating in the European I.Family study (N=559, 51.2% girls, 32.9% overweight/obese) wore an accelerometer for one week on their wrist and recorded their daily wake-up and lights-off times in a sleep diary. Information on sleep duration, sleep efficiency and sleep latency was derived. To identify sleep subtypes, we conducted a latent class analysis using all five sleep variables. Associations between single sleep variables, sleep subtype and age- and sex-specific BMI z-score were investigated using linear mixed-effects regression models to accommodate clustering among siblings.

Results: No statistically significant associations were observed between the single sleep variables (sleep duration, sleep efficiency, sleep latency, wake-up and lights-off times) and BMI z-score. Four sleep subtypes were identified and children were assigned to one of the groups based on their highest probability for latent group membership: "early birds" (17.5% of the sample), "short sleep duration" (14.7%), "optimal sleep" (47.6%) and "poor sleep quality" (20.2%). Sleep subtype was not associated with BMI z-score.

Conclusions: Using objective sleep data, we did not find convincing evidence for associations between the sleep variables under investigation and BMI.

Keywords obesity, sleep patterns, accelerometry, Actigraph

1. Introduction

The prevalence of overweight and obesity in European children is still at a high level, even though the rising trend over the last decades has levelled off in some countries.[1] This parallels with the trend of decreasing sleep duration among European children and adolescents over the last 103 years, as reported by a systematic literature review.[2] To date there exist many cross-sectional and longitudinal studies that found an association between short sleep duration and higher odds of overweight and obesity in young populations.[3-6] Some studies also indicate that poor sleep quality and unfavourable sleep timing are associated with higher odds of overweight and obesity.[7,8]

Although the mechanisms explaining these associations are still not fully understood, it has been hypothesised that short sleep duration might be associated with overweight and obesity through a dysregulation of appetite hormones such as leptin and ghrelin.[9,10] These hormonal changes along with the increased opportunities to eat during longer waking hours and the consequent increased energy intake may increase the risk for weight gain.[11] Furthermore, studies have shown that indicators of poor sleep quality such as a reduced amount of restorative slow-wave sleep and sleep fragmentation (in the presence of unaltered total sleep duration) increase cortisol release, sympathetic nervous system activity and feelings of appetite and decrease insulin sensitivity.[12,13] It has been proposed that these physiological and hormonal changes contribute to a positive energy balance through stimulating food intake resulting in storage of excessive energy in body fat and ultimately weight gain.[14] Sleep timing may also be related to weight status through a behavioural pathway. For instance, later bedtime was found to be associated with risk factors for overweight and obesity such as a poorer diet quality, skipping breakfast and less physical activity.[15-17]

The vast majority of studies investigating associations between sleep and weight status in pediatric populations relies on self-reports. However, it has been shown that adolescents overestimate their sleep duration in questionnaires in comparison to accelerometers such as Actigraphs that are used to measure sleep objectively.[18] A review identified 23 studies that investigated the association between objectively measured sleep duration and obesity indices.[19] Most of these studies found longer sleep duration to be associated with a more favourable weight status. According to a meta-analysis,[7] only three studies used Actigraphs to study the association between sleep quality indicators and weight status in pediatric populations.[20-22] These three and other recent studies reported mixed findings. For instance, whereas some studies reported a negative association between sleep efficiency, i.e. the percentage of time asleep while in bed, and body mass index (BMI),[23-25] other studies did not find an association.[21,22,26] In addition, evidence for an association between aspects of sleep timing and weight status from studies using objective methods is weak.[23,25-27] Lastly, most previous studies have investigated aspects of sleep with BMI separately although sleep duration, sleep quality and sleep timing are associated with each other.

Therefore, the first aim of this study was to investigate the associations between sleep duration, sleep quality indicators and sleep timing and BMI, separately. The second aim was to classify children into distinct sleep subtypes by integrating information on sleep duration, sleep quality and sleep timing and to study the association between sleep subtype and BMI.

2. Materials and methods

2.1 Study population

Children from eight European countries (Belgium, Cyprus, Estonia, Germany, Hungary, Italy, Spain and Sweden) participating in the IDEFICS/I.Family cohort contributed data. For the IDEFICS study, children were first examined in 2007/2008 when they were 2-9 years old (N=16,229) and again two years later after an intervention for the prevention of childhood obesity was completed (N=13,586).[28] For the I.Family study, 7,117 children who already participated in IDEFICS and 2,501 newly recruited siblings were examined in 2013/2014 with the aim to investigate the determinants of eating behaviour in European families.[29] Once the I.Family follow-up examination was concluded, a subsample of participants with divergent weight trajectories over a six-year observation period ("stable normal weight", "stable overweight/obesity", "excessive weight gain") were selected for further measurements of sleep and other factors in 2015. Hence, participants with overweight and obesity were overrepresented in these so-called contrasting groups. The present investigation uses data from the contrasting groups.

2.2 Procedures

Data were collected by physical examinations, accelerometers and questionnaires. Approaches used to promote high data quality were amongst others central trainings of field staff, detailed standard operating procedures documented in the I.Family General Survey Manual and site visits during the field phase.[30] Questionnaires were developed in English, translated into local languages and then back-translated to maintain comparability across languages. Parents filled in all questionnaires if their children were younger than 12 years old while older children reported for themselves. Further details on questionnaire development are provided by Bammann et al.[30] Before children entered the study, parents provided informed written consent. Moreover, children 12 years and older provided simplified written consent. Younger children gave verbal assent for examinations. Ethical approval was obtained by the appropriate Ethics Committees by each of the eight study centres conducting fieldwork.

2.3 Anthropometry

One measurement of participants' weight and one measurement of participants' height were taken in a fasting state according to a standardised manual in all centres. Body height was measured to the nearest 0.1 cm without shoes with a calibrated stadiometer (SECA 225, seca GmbH & Co. KG, Hamburg, Germany). Weight was measured with subjects wearing only light underwear by means of a segmental scale accurate to 0.1 kg (TANITA BC 418 MA, Tanita Europe GmbH, Sindelfingen, Germany). Inter- and intra-observer reliability of weight and height measurements were assessed in the framework of the IDEFICS study and found to be excellent (all coefficients of reliability [R] % $\geq$ 99%).[31] BMI was calculated as weight divided by height squared and converted to age- and sex-specific z-scores according to Cole and Lobstein[32].

2.4 Sleep assessment and sleep variables

Sleep was assessed using wrist-worn accelerometers in combination with a sleep diary. Accelerometers (GT3X+, Actigraph LLC, Pensacola, FL, USA) were set to record data at 30HZ and participants were asked to wear the accelerometer on the non-dominant wrist for up to seven consecutive days and nights (night wear only was also acceptable). Using a sleep diary, participants recorded the type of day (school day, day off, sick day, etc.), the time the lights were turned off (in the instructions "lights-off time" was defined as the time the light in the participant's bedroom was turned off and electronic devices such as TV, computer and mobile phone were not used any longer) and their wake-up time for each day. After seven days, data were downloaded from the accelerometer in raw format (gt3x file) and then converted to a 60 second epoch for further analysis using ActiLife 6 software (Actigraph LLC, Pensacola, FL, USA). To generate sleep variables, the lights-off and wake-up times for each night reported in the sleep diary were manually entered. Files were then processed using the Sadeh algorithm to score individual epochs as either sleep or non-sleep and thus to generate sleep variables for each night.[33] The main variables of interest were (i) sleep duration: hours and minutes actually slept per night, subtracting periods of wakefulness, (ii) sleep latency: minutes between reported lights-off time and sleep onset (as detected by the algorithm), (iii) sleep efficiency: percentage of time spent asleep between lights-off and wake-up time calculated as sleep duration/(reported wake-up time – reported lights-off time)*100, (iv) reported wake-up time and (v) reported lights-off time. Hence, for each participant data were collapsed at the individual level by first calculating the arithmetic mean across all available weekdays of a given sleep variable (e.g. sleep duration) and the arithmetic mean across all available weekend days. In a second step, the weighted mean of weekdays and weekend days was calculated such as: (mean sleep duration on weekdays*5 + mean sleep duration on weekend days*2)/7. In addition, for sleep duration, wake-up time and lights-off time age-specific z-scores were calculated based on the final analytic sample, i.e. these measures were internally standardised. This was done to account for their age-dependency as for example, sleep duration naturally decreases as children get older.[34] Children were further categorised as having long sleep latency and late lights-off time (scoring above the respective 75th percentile) and short sleep duration, early wake-up time and poor sleep efficiency (scoring below the respective 25th percentile).

2.5 Covariates

Covariates assessed by questionnaires included age (years and one decimal place), sex and pubertal status using questions adapted from Carskadon and Acebo[35]. Pubertal status was defined by menarche in girls and voice mutation in boys. Highest level of parental education was defined according to the "International Standard Classification of Education" (levels 0-2=low, 3-5=medium and 6-8=high).[36]

For a secondary analysis, we used information on lifestyle factors collected by questionnaires which included consumption frequencies of fruit and vegetables (times/week),[37-39] time spent being physically active in a sports club (hours/week)[40] and the weighted mean of hours of computer and TV time during weekdays and weekend days.

2.6 Analysis dataset

Sleep measures were initially obtained from 800 children providing a total of 4,946 nights of sleep measurements. We excluded measurements obtained from sick days and restricted our sample to participants who provided at least 4 nights of sleep measurements (minimum 1 weekend night and minimum 2 weekday nights) (N=605) (Figure 1). After exclusion of a participant with severe underweight and participants younger than 9 years and older than 16 years as well as those with incomplete information on covariates (N=33) and BMI (N=2), our final analytic sample comprised 559 children of whom the vast majority (87%) provided 6 or 7 nights of measurements. The largest proportion of families included were singleton families (N=440). Further, 55 families with two children were included and three families with three children.

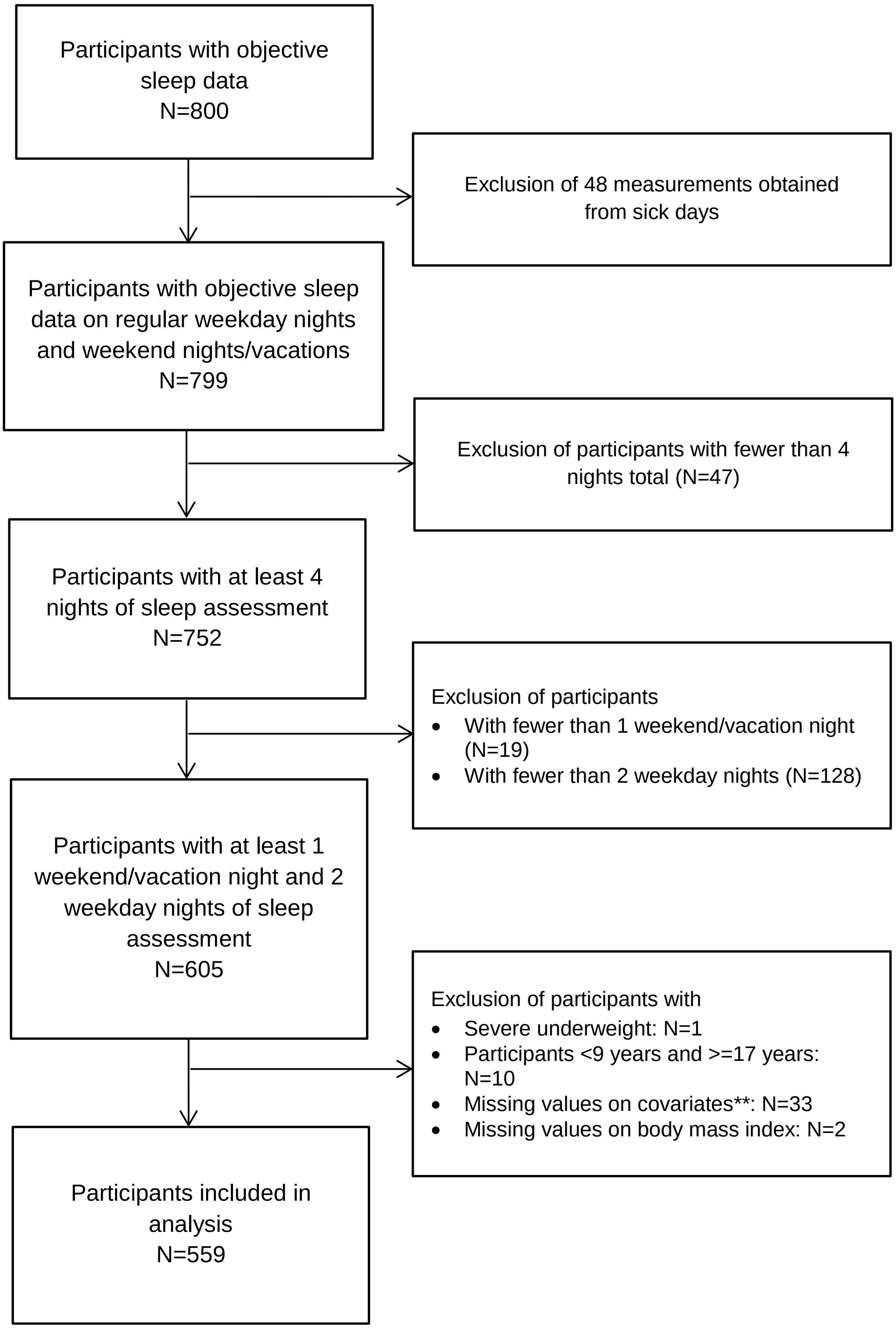

Figure 1: Flowchart of participants; *in total 24 persons had at least one measurement taken on a sick day, 1 person contributed only measurements from sick days; **age, sex, pubertal status, highest educational level of parents and country

2.7 Statistical analysis

As a preliminary analysis, we examined correlations among the five continuous sleep variables. In case both values were normally distributed, a Person correlation was computed, in case the distribution of at least one variable was skewed, a Spearman's correlation was computed. Next, associations between the five continuous sleep variables and BMI z-score were investigated using linear mixed-effects models,[41] where a random effect for family affiliation was added to account for the inclusion of siblings in the sample. In Models 1a to 1e, the association between each sleep variable and BMI z-score adjusting for age, sex, highest educational level of parents, pubertal status and country was investigated. Using a second model, we investigated the associations between the single sleep quality (sleep latency, sleep efficiency) and sleep timing indicators (wake-up time z-score, lights-off time z-score), respectively, and BMI z-score independent of sleep duration z-score. Hence, Models 2a, 2b, 2d and 2e were adjusted for the same covariates as Models 1a to 1e plus sleep duration z-score. Model assumptions of normally and symmetrically distributed residuals were checked and found to be fulfilled.

We conducted several secondary analyses. First, we adjusted all models for lifestyle factors (consumption frequencies of fruit and vegetables as an indicator for dietary intake, time spent being physically active in a sports club and computer/TV time as indicators of physical activity and sedentary behaviour) that have been suggested to mediate or confound associations between sleep characteristics and weight status to investigate their impact on effect estimates.[19,42] Second, we ran all models stratified by age (children: 9-12 years old, adolescents: 13-16 years old). Further, we (i) estimated the models using either weekday or weekend sleep values as the exposure in the model instead of weighted mean sleep values. We also investigated the association between weekend "catch-up sleep" (calculated as mean sleep duration on weekends minus mean sleep duration on weekdays) and BMI z-score and examined whether this association depends on the amount of weekday sleep duration, i.e. whether weekday sleep duration acts as an effect modifier in the association between "catch-up sleep" and BMI.

For the identification of sleep subtypes we conducted a latent class analysis (LCA) using the five dichotomous sleep variables.[43,44] Models with one to five latent classes were estimated. For the decision on the number of classes, i.e. subtypes, the following statistical criteria were considered: (i) the sample-size adjusted Bayesian Information Criterion [aBIC]) as a model fit index, (ii) entropy as an index of classification accuracy and (iii) the result of the parametric bootstrapped likelihood ratio test (BLRT). Models with smaller aBIC and entropy values approaching 1.0 indicate better fit. P-values below 0.05 of the BLRT indicate that the current model with k classes fits better than the previous model with $k – 1$ classes. In addition, the decision on the number of subtypes was also guided by theoretical considerations, i.e. that subtypes are interpretable and clearly distinguishable from each other as indicated by different patterns of item-response probabilities. Subsequently, the association between sleep subtype and BMI z-score was investigated in terms of a linear mixed-effects model. The LCA was conducted with Mplus 7.[45] For all other data analyses we used the Statistical Analysis System (SAS) software package (Version 9.3; SAS Institute, Cary, NC, USA). Statistical significance level was set to $\alpha=0.05$ for a two-tailed test.

3. Results

Participant characteristics are shown in Table 1. Approximately half of the boys (52.0%) and girls (55.2%) had entered puberty. The majority of children were categorised as having normal weight (65.1%). Two percent of children were categorised as thin, 21.8% as overweight and 11.1% as obese. Values of sleep variables did not differ substantially between underweight/normal weight children as compared to overweight/obese children. Correlations between sleep variables themselves were mostly weak to moderate, i.e. most correlation coefficients ranged between 0.20 and 0.59 (Table 2).[46]

Results of the linear mixed regression models are displayed in Table 3. Confidence intervals for associations between sleep variables and BMI z-score adjusted for covariates were wide and included the null (Models 1a to 1e, Table 3). For instance, the following effect estimates for sleep duration z-score and sleep efficiency were obtained: $\beta_{\text{Model 1c}}$=-0.056, 95% confidence interval [CI] [-0.138; 0.027] and $\beta_{\text{Model 1b}}$=-0.032, 95% CI [-0.105; 0.040], respectively. Associations of sleep latency, sleep efficiency, wake-up time z-score and lights-off time z-score with BMI z-score remained statistically non-significant after adjustment for sleep duration z-score (Models 2a, 2b, 2d and 2e, Table 3).

Results of the secondary analyses are displayed in Supplementary Tables S1-S6. Adjustment for lifestyle factors of associations between the single sleep variables and BMI z-score did not remarkably alter results (Supplementary Table S1). The age-stratified analysis revealed a positive association between sleep latency and BMI z-score in adolescents ($\beta_{\text{Model 1a}}$=0.076, 95% CI [0.007; 0.144] (Supplementary Table S3) but the 95% confidence interval included the null after adjustment for sleep duration. Other sensitivity analyses by age group and weekday/weekend day did not reveal any marked differences (Supplementary Tables S2-S5). Also weekend “catch-up” sleep was not associated with BMI z-score (Supplementary Table S6) and there was no indication of effect modification of this association by weekday sleep duration z-score.

Table 1: Characteristics of study participants included in the analysis stratified by weight status

	Whole analysis group N=559	Underweight/ normal weight‡ N=375	Overweight/obese‡ N=184
Sleep latency (minutes), median (25th-75th percentile)*	10.4 (5.5-16.7)	10.8 (5.5-18.3)	9.0 (5.4-14.6)
Sleep efficiency (%), mean (SD)†	83.5 (5.8)	83.4 (5.8)	83.8 (5.9)
Sleep duration (hours), mean (SD)	7.2 (0.7)	7.3 (0.7)	7.2 (0.7)
Wake-up time (hour:minute), mean (SD)	7:26 (0:38)	7:28 (0:38)	7:22 (0:38)
Lights-off time (hour:minute), mean (SD)	22:44 (0:56)	22:43 (0:58)	22:46 (0:52)
Age, mean (SD)	12.8 (1.8)	12.9 (1.8)	12.7 (1.7)
Girls, n (%)	286 (51.2)	197 (52.5)	89 (48.4)
Highest educational level of parents, n (%)§			
Low	23 (4.1)	7 (1.9)	16 (8.7)
Medium	252 (45.1)	162 (43.2)	90 (48.9)
High	284 (50.8)	206 (54.9)	78 (42.4)
Country, n (%)			
Italy	141 (25.2)	67 (17.9)	74 (40.2)
Estonia	111 (19.9)	71 (18.9)	40 (21.7)
Cyprus	15 (2.7)	8 (2.1)	7 (3.8)
Belgium	14 (2.5)	12 (3.2)	2 (1.1)
Sweden	52 (9.3)	51 (13.6)	1 (0.5)
Germany	81 (14.5)	53 (14.1)	28 (15.2)
Hungary	67 (12.0)	47 (12.5)	20 (10.9)
Spain	78 (14.0)	66 (17.6)	12 (6.5)
Pubertal status, n (%)			
Non-pubertal	259 (46.3)	176 (46.9)	83 (45.1)
Pubertal	300 (53.7)	199 (53.1)	101 (54.9)

SD: standard deviation
‡ categorisation according to the International Obesity Task Force (IOTF) cut-offs[30]
* calculated as minutes between reported lights-off time and sleep onset (as detected by the algorithm)
† calculated as percentage of time spent asleep while in bed: sleep duration/(reported wake-up time – reported lights-off time)*100
§ categorisation according to the "International Standard Classification of Education" (levels 0-2=low, 3-5=medium and 6-8=high)[33]

Table 2: Mutual correlation coefficients and p-values between sleep latency, sleep efficiency, sleep duration z-score, wake-up time z-score and lights-off time z-score (N=559)

	Sleep latency	**Sleep efficiency**	**Sleep duration z-score**	**Wake-up time z-score**	**Lights-off time z-score**
Sleep latency	1.00				
Sleep efficiency	**-0.393* <0.001**	1.00			
Sleep duration z-score	-0.033* 0.44	**0.439 <0.001**	1.00		
Wake-up time z-score	-0.014* 0.75	**-0.102 0.02**	**0.164 <0.001**	1.00	
Lights-off time z-score	**-0.252* <0.001**	**0.257 <0.001**	**-0.452 <0.001**	**0.518 <0.001**	1.00

All correlation coefficients are Pearson correlation coefficients except those labelled with a * which are Spearman correlation coefficients; figures in bold indicate statistically significant correlations

Table 3: Results of linear mixed-effects regression model on cross-sectional associations between sleep latency, sleep efficiency, sleep duration z-score, wake-up time z-score, lights-off time z-score and BMI z-score (N=559)

		BMI z-score				**BMI z-score**		
	Model	**β**	**95% CI**	**p-value**	*Model*	**β**	**95% CI**	**p-value**
Sleep latency§	*1a*	-0.013	-0.056; 0.030	0.55	*2a*	-0.015	-0.057; 0.028	0.50
Sleep efficiency‡	*1b*	-0.032	-0.105; 0.040	0.38	*2b*	-0.012	-0.095; 0.070	0.77
Sleep duration z-score	*1c*	-0.056	-0.138; 0.027	0.18		---	---	---
Wake-up time z-score	*1d*	-0.040	-0.135; 0.054	0.40	*2d*	-0.027	-0.124; 0.070	0.58
Lights-off time z-score	*1e*	0.009	-0.089; 0.107	0.86	*2e*	-0.029	-0.141; 0.082	0.60

§ 1 unit ≙ 5 minutes
‡ 1 unit ≙ 5%
Models 1a - 1e are adjusted for age, sex, highest level of parental education, pubertal status and country and include a random effect for family affiliation
Models 2a, 2b, 2d and 2e are adjusted for the same variables as Models 1a – 1e plus sleep duration z-score and include a random effect for family affiliation
CI: confidence interval

Among the five latent class models estimated, the 4-class model was considered as the best solution based on statistical criteria (aBIC, entropy and BLRT) and theoretical considerations (Table 4). Children having a 100% probability for an early wake-up time (N=98, 17.5% of the sample) were assigned to the subtype labelled as “early birds” (Table 5). Children having a 100% probability of having short sleep duration were assigned to the subtype labelled “short sleep duration” (N=82, 14.7% of the sample). The third subtype was labelled “optimal sleep” (N=266, 47.6% of the sample) including children with a high probability (at least 75%) to belong to the most favourable category of each sleep variable. Lastly, the fourth subtype was labelled “poor sleep quality” (N=113, 20.2% of the children). It comprises children who showed a high probability of having long sleep latency (56.9%) and poor sleep efficiency (100%). The confidence interval for the association between belonging to the “poor sleep quality” subtype in comparison to belonging to the “optimal sleep” subtype was wide and included the null with the point estimate being negative (β=-0.138 [-0.359; 0.083]) (Table 6). Also for the other two sleep subtypes no statistically significant associations with BMI z-score were observed with the point estimates being close to zero.

Table 4: Fit indices of latent class solutions

	Sample-size adjusted BIC	BLRT p-value	Entropy
1 Class Model	3153.15	---	---
2 Class Model	3087.37	<0.001	1.00
3 Class Model	3039.33	<0.001	1.00
4 Class Model	3029.57	<0.001	0.92
5 Class Model	3038.62	0.16	0.78

BIC: Bayesian information criterion; BLRT: Parametric Bootstrapped Likelihood Ratio Test

Table 5: Item-response probabilities of participants assigned to one of the four sleep subtypes. Numbers indicate the probabilities of children to belong to either of the two categories for every sleep variable (N=559)

	Sleep subtype			
	Early birds N=98 (17.5%)	**Short sleep duration** N=82 (14.7%)	**Optimal sleep** N=266 (47.6%)	**Poor sleep quality** N=113 (20.2%)
	Prob (%)	Prob (%)	Prob (%)	Prob (%)
Lights-off time early/average	97.4	30.7	75.0	100.0
Lights-off time late§	2.6	69.3	25.0	0.0
Wake-up time average/late	0.0	85.5	100.0	64.8
Wake-up time early‡	100.0	14.5	0.0	35.2
Sleep duration average/long	84.6	0.0	100.0	66.0
Sleep duration short*	15.4	100.0	0.0	34.0
Sleep latency short/average	87.7	79.7	78.8	43.1
Sleep latency long†	12.3	20.3	21.2	56.9
Sleep efficiency good/average	100.0	68.0	91.2	0.0
Sleep efficiency poor¶	0.0	32.0	8.8	100.0

Prob: probability

§ Late: lights-off time later than 22:42 (9 year olds), 22:43 (10 year olds), 23:00 (11 year olds), 23:04 (12 year olds), 23:22 (13 year olds), 23:43 (14 year olds), 00:05 (15 year olds), 00:13 (16 year olds)

‡ Early: wake-up time earlier than 7:03 (9 year olds), 6:57 (10 year olds), 7:05 (11 year olds), 7:01 (12 year olds), 7:06 (13 year olds), 6:54 (14 year olds), 7:07 (15 year olds), 6:42 (16 year olds)

* Short: sleep duration shorter than 7.1 hours (9 year olds), 7.2 hours (10 year olds), 7.1 hours (11 year olds), 7.0 hours (12 year olds), 6.8 hours (13 year olds), 6.5 hours (14 year olds), 6.4 hours (15 year olds), 5.8 hours (16 year olds)

† Long: sleep latency longer than 17 minutes

¶ Poor: sleep efficiency less than 80%

Table 6: Results of linear mixed-effects regression model on cross-sectional association between sleep subtype and BMI z-score (N=559)

	BMI z-score		
	β	**95% CI**	**p-value**
Subtype "Early birds"	-0.010	-0.243; 0.223	0.93
Subtype "Short sleep duration"	-0.001	-0.244; 0.241	0.99
Subtype "Poor sleep quality"	-0.138	-0.359; 0.083	0.22
Subtype "Optimal sleep" (reference)	0		

Model is adjusted for age, sex, highest level of parental education, pubertal status and country and includes a random effect for family affiliation

4. Discussion

To our knowledge, our study is one of very few investigating the association between multiple objectively measured sleep characteristics combined with diary entries and BMI. Further, to our knowledge it is the first study that classified study subjects into distinct sleep subtypes ("early birds", "short sleep duration", "optimal sleep" and "poor sleep quality") to investigate their association with BMI. Neither the single sleep variables nor sleep subtypes were markedly associated with BMI in our study.

In general, mean values obtained for sleep duration, sleep efficiency and sleep latency were similar to those observed in other studies in young populations using Actigraphs for sleep assessment.[47] Likewise, mean lights-off and wake-up times were largely consistent with Actigraphy-recorded sleep onset and offset times in other studies.[47]

Our observation of a statistically non-significant association between objectively measured sleep duration and BMI z-score is in line with the studies by McNeil et al.[23] and Gomes et al.[48] who investigated such an association in 9-11 year old Canadian (N=514) and Portuguese (N=686) children participating in the "International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE)". Likewise, null results were reported by small studies conducted in US American (8-17 years old, N=125),[27] Belgian (6-12 years old, N=193)[22] and Icelandic (15-16 years old, N=281)[26] children and adolescents. However, other studies have reported an inverse association between objectively measured sleep duration and BMI. In the whole ISCOLE population (N=6,025)[49] and in Canadian 8-10 year old children (N=550)[50] longer objectively measured sleep duration was cross-sectionally associated with lower odds of obesity. Likewise, Cespedes Feliciano et al.[24] also found an inverse association between objectively measured sleep duration and BMI in 827 US American adolescents (11-16 years old) as did Taylor et al.[25] in 823 New Zealand children (6-10 years old). Inverse associations were also reported by smaller studies (fewer than 400 participants) conducted in the United Kingdom and the USA.[20,21,51] Apart from the larger sample size of some studies reporting statistically significant negative associations in comparison to our study,[24,49] another reason for the differing results may lie in the composition of the study population as most of them were conducted in multi-ethnic groups.[20,21,24,25,49] Sleep duration has been found to be more strongly associated with weight status in certain ethnic groups.[52] Furthermore, studies reporting an association were often conducted in children rather than adolescents.[20,25,49,51] However, the literature seems to be inconsistent with respect to differential associations across age groups and also our age-stratified analysis did not show stronger associations in the younger age group.

In agreement with our results, many previous studies did not find an association between sleep efficiency and BMI.[21,22,26] Nevertheless, McNeil et al.[23], Cespedes Feliciano et al.[24] and Taylor et al.[25] observed an inverse association between sleep efficiency and BMI z-score. However, in the study by Cespedes Feliciano et al.[24] this association was attenuated in models with either additional adjustment for obesity-related behaviours (physical activity, etc.) or additional adjustment for sleep duration. The number of studies investigating the association between objectively measured sleep latency and BMI is very limited. Similar to our study, Michels et al.[22] and Rognvaldsdottir et al.[26] did not observe an association between sleep latency and BMI. Further, the apparent absence of associations between lights-off and wake-up time, respectively, and BMI seems to be in agreement with the results of previous studies.[23,25-27]

As already mentioned, no study has yet grouped children/adolescents into sleep subtypes using objectively measured sleep variables to study their association with BMI. There are, however, studies in young populations that applied LCA using subjectively measured sleep variables and investigated the association between sleep subtype and BMI[53] and other outcomes.[54,55] However, sleep variables used in these studies are different to the ones used in our study hampering comparison of the identified sleep subtypes.

One of the strengths of our study is the inclusion of children and adolescents from eight European countries. Even though the study population may not be representative of the child/adolescent population in these countries, the cross-national nature of the study potentially enhances generalisability of the results to other European populations with a similar socio-demographic profile and associations examined in the present paper should be robust to selection effects. Another strength is the standardised data collection including objective sleep assessment with accelerometers. Accelerometers overcome some of the major limitations of self-reports as they are not prone to multiple biases such as recall and social desirability biases.[18] They have been validated against polysomnography, the gold standard in sleep research, and it has been found that accelerometers are able to correctly identify sleep periods although it has to be mentioned that their ability to detect periods of wakefulness is more limited.[56,57] Hence, sleep duration and sleep efficiency might have been overestimated in our study. Further, we implemented a sleep diary in which respondents entered "lights-off time" which allowed us to calculate sleep latency,[58] a measure rarely investigated in previous studies with BMI as the outcome. For the LCA, cut-offs for the single sleep variables were subjectively chosen based on values of our own sample (25th and 75th percentiles, respectively). However, existing sleep duration recommendations may not be appropriate to define cut-offs for short sleep duration measured by Actigraphs as the recommendations are mainly derived from studies that used self- or parent-reported sleep duration.[59] Although sleep quality recommendations for children and adolescents provided by the National Sleep Foundation were derived by experts under consideration of studies using objective methods, there are still uncertainties about which values are optimal[60] and to our knowledge no recommendations with respect to optimal sleep timing exist. Lastly, the contrasting groups were a subsample of a large cohort study and we used all data that were available, i.e. the contrasting groups were not specifically powered for the presents' study question. Even though we did not observe statistically significant associations, some of the obtained effects estimates may be considered to be of clinically relevant size. For instance, for a 12 year girl, a 0.056 lower BMI z-score for a one standard deviation longer sleep duration (which corresponds to approximately 45 minutes) would translate into 0.15 BMI points. Hence, our results may not be interpreted as a null finding from a clinical perspective. Larger studies using objective methods for sleep assessment are needed before firm conclusions can be drawn.

In conclusion, we did not find convincing evidence for an association between objectively measured sleep duration, sleep quality and sleep timing, respectively, and BMI in European children and adolescents. Previous studies that are comparable to ours have either reported inverse or no associations. In addition, we did not observe statistically significant differences in BMI between four distinct sleep subtypes. Nevertheless, our approach of integrating various aspects of sleep by creating sleep subtypes might inspire future studies. Particularly in adolescent studies differences in sleep characteristics across weekdays and weekend days (e.g. in terms of social jetlag) might be considered as factors determining sleep subtypes.

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Conflict of interest

None.

References

1. Garrido-Miguel M, Cavero-Redondo I, Álvarez-Bueno C, et al. Prevalence and trends of overweight and obesity in European children from 1999 to 2016: A systematic review and meta-analysis. *JAMA Pediatr.* 2019:e192430.
2. Matricciani L, Olds T, Petkov J. In search of lost sleep: secular trends in the sleep time of school-aged children and adolescents. *Sleep Med Rev.* 2012;16(3):203-211.
3. Fatima Y, Doi SA, Mamun AA. Longitudinal impact of sleep on overweight and obesity in children and adolescents: a systematic review and bias-adjusted meta-analysis. *Obes Rev.* 2015;16(2):137-149.
4. Ruan H, Xun P, Cai W, He K, Tang Q. Habitual sleep duration and risk of childhood obesity: systematic review and dose-response meta-analysis of prospective cohort studies. *Sci Rep.* 2015;5:16160.
5. Magee L, Hale L. Longitudinal associations between sleep duration and subsequent weight gain: a systematic review. *Sleep Med Rev.* 2012;16(3):231-241.
6. Hense S, Pohlabeln H, De Henauw S, et al. Sleep duration and overweight in European children: is the association modified by geographic region? *Sleep.* 2011;34(7):885-890.
7. Fatima Y, Doi SA, Mamun AA. Sleep quality and obesity in young subjects: a meta-analysis. *Obes Rev.* 2016;17(11):1154-1166.
8. Miller AL, Lumeng JC, LeBourgeois MK. Sleep patterns and obesity in childhood. *Curr Opin Endocrinol Diabetes Obes.* 2015;22(1):41-47.
9. Reutrakul S, Van Cauter E. Interactions between sleep, circadian function, and glucose metabolism: implications for risk and severity of diabetes. *Ann N Y Acad Sci.* 2014;1311:151-173.
10. Knutson KL. Sleep duration and cardiometabolic risk: a review of the epidemiologic evidence. *Best Pract Res Clin Endocrinol Metab.* 2010;24(5):731-743.
11. Chaput JP. Sleep patterns, diet quality and energy balance. *Physiol Behav.* 2014;134:86-91.
12. Hanlon EC, Van Cauter E. Quantification of sleep behavior and of its impact on the cross-talk between the brain and peripheral metabolism. *Proc Natl Acad Sci U S A.* 2011;108 Suppl 3:15609-15616.
13. Ekstedt M, Akerstedt T, Soderstrom M. Microarousals during sleep are associated with increased levels of lipids, cortisol, and blood pressure. *Psychosom Med.* 2004;66(6):925-931.
14. Rutters F, Gonnissen HK, Hursel R, Lemmens SG, Martens EA, Westerterp-Plantenga MS. Distinct associations between energy balance and the sleep characteristics slow wave sleep and rapid eye movement sleep. *Int J Obes (Lond).* 2012;36(10):1346-1352.
15. Golley RK, Maher CA, Matricciani L, Olds TS. Sleep duration or bedtime? Exploring the association between sleep timing behaviour, diet and BMI in children and adolescents. *Int J Obes (Lond).* 2013;37(4):546-551.
16. Harrex HAL, Skeaff SA, Black KE, et al. Sleep timing is associated with diet and physical activity levels in 9-11-year-old children from Dunedin, New Zealand: the PEDALS study. *J Sleep Res.* 2018;27(4):e12634.
17. Agostini A, Lushington K, Kohler M, Dorrian J. Associations between self-reported sleep measures and dietary behaviours in a large sample of Australian school students (n = 28,010). *J Sleep Res.* 2018;27(5):e12682.
18. Arora T, Broglia E, Pushpakumar D, Lodhi T, Taheri S. An investigation into the strength of the association and agreement levels between subjective and objective sleep duration in adolescents. *PloS One.* 2013;8(8):e72406.
19. Felső R, Lohner S, Hollody K, Erhardt E, Molnár D. Relationship between sleep duration and childhood obesity: Systematic review including the potential underlying mechanisms. *Nutr Metab Cardiovasc Dis.* 2017;27(9):751-761.
20. Bagley EJ, El-Sheikh M. Familial risk moderates the association between sleep and zBMI in children. *J Pediatr Psychol.* 2013;38(7):775-784.
21. Arora T, Taheri S. Associations among late chronotype, body mass index and dietary behaviors in young adolescents. *Int J Obes (Lond).* 2015;39(1):39-44.

22. Michels N, Verbeiren A, Ahrens W, De Henauw S, Sioen I. Children's sleep quality: relation with sleep duration and adiposity. *Public Health.* 2014;128(5):488-490.
23. McNeil J, Tremblay MS, Leduc G, et al. Objectively-measured sleep and its association with adiposity and physical activity in a sample of Canadian children. *J Sleep Res.* 2015;24(2):131-139.
24. Cespedes Feliciano EM, Quante M, Rifas-Shiman SL, Redline S, Oken E, Taveras EM. Objective sleep characteristics and cardiometabolic health in young adolescents. *Pediatrics.* 2018;142(1).
25. Taylor RW, Williams SM, Galland BC, et al. Quantity versus quality of objectively measured sleep in relation to body mass index in children: cross-sectional and longitudinal analyses. *Int J Obes (Lond).* 2020;44(4):803-811.
26. Rognvaldsdottir V, Gudmundsdottir SL, Brychta RJ, et al. Sleep deficiency on school days in Icelandic youth, as assessed by wrist accelerometry. *Sleep Med.* 2017;33:103-108.
27. Mi SJ, Kelly NR, Brychta RJ, et al. Associations of sleep patterns with metabolic syndrome indices, body composition, and energy intake in children and adolescents. *Pediatr Obes.* 2019:e12507.
28. Ahrens W, Bammann K, Siani A, et al. The IDEFICS cohort: design, characteristics and participation in the baseline survey. *Int J Obes (Lond).* 2011;35 Suppl 1:S3-15.
29. Ahrens W, Siani A, Adan R, et al. Cohort Profile: The transition from childhood to adolescence in European children-how I.Family extends the IDEFICS cohort. *Int J Epidemiol.* 2017;46(5):1394-1395j.
30. Bammann K, Lissner L, Pigeot I, Ahrens W. *Instruments for health surveys in children and adolescents.* Springer International Publishing; 2019.
31. Stomfai S, Ahrens W, Bammann K, et al. Intra- and inter-observer reliability in anthropometric measurements in children. *Int J Obes (Lond).* 2011;35(1):S45-S51.
32. Cole TJ, Lobstein T. Extended international (IOTF) body mass index cut-offs for thinness, overweight and obesity. *Pediatr Obes.* 2012;7(4):284-294.
33. Sadeh A, Sharkey KM, Carskadon MA. Activity-based sleep-wake identification: an empirical test of methodological issues. *Sleep.* 1994;17(3):201-207.
34. Thorleifsdottir B, Bjornsson JK, Benediktsdottir B, Gislason T, Kristbjarnarson H. Sleep and sleep habits from childhood to young adulthood over a 10-year period. *J Psychosom Res.* 2002;53(1):529-537.
35. Carskadon MA, Acebo C. A self-administered rating scale for pubertal development. *J Adolesc Health.* 1993;14(3):190-195.
36. UNESCO Institute for Statistics. *International Standard Classification of Education ISCED 2011*. Montreal, Canada: United Nations Educational, Scientific and Cultural Organisation 2012.
37. Lanfer A, Hebestreit A, Ahrens W, et al. Reproducibility of food consumption frequencies derived from the Children's Eating Habits Questionnaire used in the IDEFICS study. *Int J Obes (Lond).* 2011;35 Suppl 1:S61-68.
38. Bel-Serrat S, Mouratidou T, Pala V, et al. Relative validity of the Children's Eating Habits Questionnaire-food frequency section among young European children: the IDEFICS Study. *Public Health Nutr.* 2014;17(2):266-276.
39. Huybrechts I, Börnhorst C, Pala V, et al. Evaluation of the Children's Eating Habits Questionnaire used in the IDEFICS study by relating urinary calcium and potassium to milk consumption frequencies among European children. *Int J Obes (Lond).* 2011;35(1):S69-S78.
40. Verbestel V, De Henauw S, Bammann K, et al. Are context-specific measures of parental-reported physical activity and sedentary behaviour associated with accelerometer data in 2-9-year-old European children? *Public Health Nutr.* 2015;18(5):860-868.
41. Hox J. *Multilevel Analysis: Techniques and Applications.* 2nd ed. Great Britain: Routledge; 2010.
42. Cappuccio FP, Taggart FM, Kandala N-B, et al. Meta-analysis of short sleep duration and obesity in children and adults. *Sleep.* 2008;31(5):619-626.
43. Wang J, Wang X. 6 Mixture Modeling. *Structural Equation Modeling: Applications using Mplus*. First ed: Higher Education Press; 2012:289-390.

44. Kline RB. *Principles and practice of structural equation modeling.* New York, NY, USA: The Guilford Press; 2011.
45. Muthén LK, Muthén BO. *Mplus User's Guide. Seventh Edition.* Los Angeles, CA, USA: Muthén & Muthén; 1998-2012.
46. Swinscow T, Campbell M. 11. Correlation and regression. *Statistics at Square One* 1997; https://www.bmj.com/about-bmj/resources-readers/publications/statistics-square-one/11-correlation-and-regression. Accessed 14th October, 2019.
47. Galland BC, Short MA, Terrill P, et al. Establishing normal values for pediatric nighttime sleep measured by actigraphy: a systematic review and meta-analysis. *Sleep.* 2018;41(4).
48. Gomes TN, Katzmarzyk PT, dos Santos FK, Souza M, Pereira S, Maia JA. Overweight and obesity in Portuguese children: prevalence and correlates. *Int J Environ Res Public Health.* 2014;11(11):11398-11417.
49. Katzmarzyk PT, Barreira TV, Broyles ST, et al. Relationship between lifestyle behaviors and obesity in children ages 9-11: Results from a 12-country study. *Obesity (Silver Spring).* 2015;23(8):1696-1702.
50. Chaput JP, Lambert M, Gray-Donald K, et al. Short sleep duration is independently associated with overweight and obesity in Quebec children. *Can J Public Health.* 2011;102(5):369-374.
51. Wilkie HJ, Standage M, Gillison FB, Cumming SP, Katzmarzyk PT. Multiple lifestyle behaviours and overweight and obesity among children aged 9–11 years: results from the UK site of the International Study of Childhood Obesity, Lifestyle and the Environment. *BMJ Open.* 2016;6(2).
52. Collings PJ, Ball HL, Santorelli G, et al. Sleep duration and adiposity in early childhood: evidence for bidirectional associations from the Born in Bradford Study. *Sleep.* 2017;40(2).
53. Lee S, Hale L, Chang AM, et al. Longitudinal associations of childhood bedtime and sleep routines with adolescent body mass index. *Sleep.* 2019;42(1).
54. Blunden S, Magee C, Attard K, Clarkson L, Caputi P, Skinner T. Sleep schedules and school performance in Indigenous Australian children. *Sleep Health.* 2018;4(2):135-140.
55. Magee CA, Robinson L, Keane C. Sleep quality subtypes predict health-related quality of life in children. *Sleep Med.* 2017;35:67-73.
56. Meltzer LJ, Montgomery-Downs HE, Insana SP, Walsh CM. Use of actigraphy for assessment in pediatric sleep research. *Sleep Med Rev.* 2012;16(5):463-475.
57. Marino M, Li Y, Rueschman MN, et al. Measuring sleep: accuracy, sensitivity, and specificity of wrist actigraphy compared to polysomnography. *Sleep.* 2013;36(11):1747-1755.
58. Holley S, Hill CM, Stevenson J. A comparison of actigraphy and parental report of sleep habits in typically developing children aged 6 to 11 years. *Behav Sleep Med.* 2010;8(1):16-27.
59. Paruthi S, Brooks LJ, D'Ambrosio C, et al. Consensus statement of the American Academy of Sleep Medicine on the recommended amount of sleep for healthy children: methodology and discussion. *J Clin Sleep Med.* 2016;12(11):1549-1561.
60. Ohayon M, Wickwire EM, Hirshkowitz M, et al. National Sleep Foundation's sleep quality recommendations: first report. *Sleep Health.* 2017;3(1):6-19.

SUPPLEMENTARY MATERIAL

Table S1: Cross-sectional associations between sleep latency, sleep efficiency, sleep duration z-score, wake-up time z-score, lights-off time z-score and BMI z-score adjusting for lifestyle factors (N=499)

			BMI z-score				**BMI z-score**	
	Model	**β**	**95% CI**	**p-value**	*Model*	**β**	**95% CI**	**p-value**
Sleep latency[§]	*1a*	-0.015	-0.060; 0.030	0.50	*2a*	-0.016	-0.062; 0.029	0.47
Sleep efficiency[‡]	*1b*	-0.024	-0.101; 0.053	0.53	*2b*	0.003	-0.085; 0.091	0.95
Sleep duration z-score	*1c*	-0.063	-0.150; 0.024	0.15		---		
Wake-up time z-score	*1d*	-0.055	-0.153; 0.044	0.27	*2d*	-0.040	-0.142; 0.062	0.43
Lights-off time z-score	*1e*	0.012	-0.093; 0.118	0.81	*2e*	-0.029	-0.148; 0.090	0.63

[§] 1 unit ≙ 5 minutes
[‡] 1 unit ≙ 5%
Models 1a - 1e are adjusted for age, sex, highest level of parental education, pubertal status, country, consumption frequencies of fruit and vegetables (times/week), time spent being physically active in a sports club (hours/week) and computer and TV time (hours/day) and include a random effect for family affiliation
Models 2a, 2b, 2d and 2e are adjusted for the same variables as Models 1a – 1e plus sleep duration z-score and include a random effect for family affiliation
CI: confidence interval

Table S2: Cross-sectional associations between sleep latency, sleep efficiency, sleep duration z-score, wake-up time z-score, lights-off time z-score and BMI z-score in children (9-12 years old) (N=299)

			BMI z-score				**BMI z-score**	
	Model	**β**	**95% CI**	**p-value**	*Model*	**β**	**95% CI**	**p-value**
Sleep latency[§]	*1a*	-0.042	-0.101; 0.017	0.15	*2a*	-0.042	-0.102; 0.018	0.16
Sleep efficiency[‡]	*1b*	0.007	-0.105; 0.118	0.90	*2b*	-0.002	-0.133; 0.129	0.98
Sleep duration z-score	*1c*	0.017	-0.102; 0.136	0.76		---		
Wake-up time z-score	*1d*	-0.031	-0.171; 0.109	0.64	*2d*	-0.040	-0.186; 0.107	0.57
Lights-off time z-score	*1e*	-0.051	-0.200; 0.098	0.47	*2e*	-0.051	-0.219; 0.116	0.52

[§] 1 unit ≙ 5 minutes
[‡] 1 unit ≙ 5%
Models 1a - 1e are adjusted for age, sex, highest level of parental education, pubertal status and country and include a random effect for family affiliation
Models 2a, 2b, 2d and 2e are adjusted for the same variables as Models 1a – 1e plus sleep duration z-score and include a random effect for family affiliation
CI: confidence interval

Table S3: Cross-sectional associations between sleep latency, sleep efficiency, sleep duration z-score, wake-up time z-score, lights-off time z-score and BMI z-score in adolescents (13-16 years old) (N=260)

	BMI z-score				BMI z-score			
	Model	**β**	**95% CI**	**p-value**	*Model*	**β**	**95% CI**	**p-value**
Sleep latency[§]	*1a*	0.076	0.007; 0.144	0.04	*2a*	0.067	-0.008; 0.143	0.07
Sleep efficiency[‡]	*1b*	-0.072	-0.199; 0.055	0.21	*2b*	-0.045	-0.194; 0.103	0.47
Sleep duration z-score	*1c*	-0.098	-0.253; 0.057	0.17		---		
Wake-up time z-score	*1d*	-0.040	-0.215; 0.135	0.60	*2d*	-0.015	-0.204; 0.175	0.85
Lights-off time z-score	*1e*	0.020	-0.160; 0.199	0.80	*2e*	-0.048	-0.265; 0.168	0.59

[§] 1 unit ≙ 5 minutes
[‡] 1 unit ≙ 5%
Models 1a - 1e are adjusted for age, sex, highest level of parental education, pubertal status and country and include a random effect for family affiliation
Models 2a, 2b, 2d and 2e are adjusted for the same variables as Models 1a – 1e plus sleep duration z-score and include a random effect for family affiliation
CI: confidence interval

Table S4: Cross-sectional associations between weekday sleep latency, sleep efficiency, sleep duration z-score, wake-up time z-score, lights-off time z-score and BMI z-score (N=559)

	BMI z-score				BMI z-score			
	Model	**β**	**95% CI**	**p-value**	*Model*	**β**	**95% CI**	**p-value**
Sleep latency[§]	*1a*	0.002	-0.036; 0.039	0.92	*2a*	0.000	-0.037; 0.038	0.98
Sleep efficiency[‡]	*1b*	-0.015	-0.084; 0.054	0.66	*2b*	0.010	-0.070; 0.089	0.81
Sleep duration z-score	*1c*	-0.055	-0.138; 0.028	0.19		---	---	---
Wake-up time z-score	*1d*	-0.075	-0.172; 0.021	0.12	*2d*	-0.065	-0.164; 0.035	0.20
Lights-off time z-score	*1e*	0.015	-0.085; 0.115	0.76	*2e*	-0.028	-0.147; 0.090	0.63

[§] 1 unit ≙ 5 minutes
[‡] 1 unit ≙ 5%
Models 1a - 1e are adjusted for age, sex, highest level of parental education, pubertal status and country and include a random effect for family affiliation
Models 2a, 2b, 2d and 2e are adjusted for the same variables as Models 1a – 1e plus weekday sleep duration z-score and include a random effect for family affiliation
CI: confidence interval

Table S5: Cross-sectional associations between weekend sleep latency, sleep efficiency, sleep duration z-score, wake-up time z-score, lights-off time z-score and BMI z-score (N=559)

	BMI z-score				BMI z-score			
	Model	**β**	**95% CI**	**p-value**	*Model*	**β**	**95% CI**	**p-value**
Sleep latency[§]	*1a*	-0.031	-0.064; 0.002	0.06	*2a*	-0.033	-0.066; 0.001	0.06
Sleep efficiency[‡]	*1b*	-0.052	-0.113; 0.010	0.10	*2b*	-0.049	-0.115; 0.017	0.14
Sleep duration z-score	*1c*	-0.032	-0.115; 0.050	0.44		---	---	---
Wake-up time z-score	*1d*	0.012	-0.077; 0.101	0.78	*2d*	0.042	-0.063; 0.147	0.43
Lights-off time z-score	*1e*	0.003	-0.087; 0.094	0.94	*2e*	-0.008	-0.104; 0.087	0.86

[§] 1 unit ≙ 5 minutes
[‡] 1 unit ≙ 5%
Models 1a - 1e are adjusted for age, sex, highest level of parental education, pubertal status and country and include a random effect for family affiliation
Models 2a, 2b, 2d and 2e are adjusted for the same variables as Models 1a – 1e plus weekend sleep duration z-score and include a random effect for family affiliation
CI: confidence interval

Table S6: Cross-sectional associations between weekend catch-up sleep and BMI z-score (N=559)

	Model 1 BMI z-score			Model 2 BMI z-score		
	β	**95% CI**	**p-value**	**β**	**95% CI**	**p-value**
Weekend catch up sleep[§]	0.007	-0.073; 0.087	0.86	0.008	-0.072; 0.088	0.84

[§] 1 unit ≙ 1 hour
Model 1 is adjusted for age, sex, highest level of parental education, pubertal status and country and includes a random effect for family affiliation
Model 2 is adjusted for the same variables as Model 1 plus sleep duration z-score and includes a random effect for family affiliation
CI: confidence interval