Objectively-measured sleep and its association with adiposity and physical activity in a sample of Canadian children

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Abstract:

Cross-sectional associations between objectively-measured sleep duration, sleep efficiency and sleep timing with adiposity and physical activity were examined in a cohort of 567 children from Ottawa, Canada. Five-hundred and fifteen children (58.8% female; age: 10.0 ± 0.4 years) had valid sleep measurements and were included in the present analyses. Physical activity, sedentary time and sleep parameters were assessed over 7 days (actigraphy). Height, weight and waist circumference were measured according to standardized procedures. Percentage body fat was assessed using bioelectric impedance analysis. Light physical activity and sedentary time were greater in children with the shortest sleep durations ($P < 0.0001$), whereas children with the highest sleep efficiencies had lower light physical activity and more sedentary time across tertiles ($P < 0.0001$). In multivariable linear regression analyses, and after adjusting for a number of covariates, sleep efficiency was inversely related to all adiposity indices ($P < 0.05$). However, sleep duration and sleep timing were not associated with adiposity indices after controlling for covariates. Inverse associations were noted between sleep duration and light physical activity and sedentary time ($P < 0.0001$). Sleep efficiency ($P < 0.0001$), wake time and sleep timing midpoint ($P < 0.05$) were negatively associated with light physical activity, but positively associated with sedentary time. In conclusion, only sleep efficiency was independently correlated with adiposity in this sample of children. Participants with the shortest sleep durations or highest sleep efficiencies had greater sedentary time. More research is needed to develop better sleep recommendations in children that are based on objective measures of sleep duration, sleep efficiency and sleep timing alike.

Keywords: anthropometric measurements | exercise | sedentary behavior | sleep patterns

Article:

Introduction

Many cross-sectional studies have previously noted that children who sleep less than the recommended 10 h per night have a greater body mass index (BMI) *z*-score (Bornhorst *et al*., 2012; Chaput *et al*., 2011; Colley *et al*., 2012; Ekstedt *et al*., 2013; Meng *et al*., 2012; Nixon *et al*., 2008; Stone *et al*., 2013), waist circumference (Chaput *et al*., 2011; Jarrin *et al*., 2013; Meng *et al*., 2012) and fat mass (Bornhorst *et al*., 2012; Chaput *et al*., 2011; Nixon *et al*., 2008) than children who sleep >10 h per night. Furthermore, studies have observed that short sleep duration (<9 or 10 h per night) is associated with an increased risk of being overweight/obese in children (adjusted odds ratios ranging from 1.29 to 4.96), independently of a number of well-known covariates such as physical activity, energy intake, family income and parental BMI (Chaput *et al*., 2011; de Jong *et al*., 2012; Meng *et al*., 2012; Nixon *et al*., 2008; Shi *et al*., 2010). Studies assessing the independent associations of sleep timing (i.e. bedtime, wake time and sleep timing midpoint) and sleep efficiency (i.e. sleep duration divided by time lying down in bed) with adiposity are scarce. More specifically, one study noted that children with a late sleep onset and late sleep end had significantly greater BMI *z*-scores compared with those with an early sleep onset and early sleep end (Golley *et al*., 2013). Similarly, multivariable regressions in 240 children and youths indicated that self-reported sleep patterns characterized by later bedtimes and wake times, poorer sleep quality and more frequent sleep disturbances were positively associated with greater BMI *z*-score and fat mass (Jarrin *et al*., 2013).

A small number of studies (Ekstedt *et al*., 2013; Pesonen *et al*., 2011; Stone *et al*., 2013) have assessed the associations between sleep duration, sleep efficiency and/or sleep timing with total physical activity and sedentary time, but have noted conflicting results. More specifically, Stone *et al*. (2013) showed that children with <9 h of sleep per night had a lower total physical activity time, spent less time in moderate-to-vigorous physical activity and had more sedentary time compared with those who slept ≥10 h per night. Ekstedt *et al*. (2013) observed that accumulating moderate-to-vigorous physical activity during the day was associated with improved sleep efficiency, but not sleep duration that night, despite no influence of sleep duration and sleep efficiency on physical activity the following day. Conversely, a study by Pesonen *et al*. (2011) observed that higher levels of physical activity during the day were associated with a lower sleep duration and sleep efficiency that night, and lower values for these same sleep variables were associated with greater physical activity the following day. A study by Nixon *et al*. (2008) did not report any significant association between sleep duration and physical activity, while the study by Ekstedt *et al*. (2013) noted that a late sleep onset and late sleep end were associated with greater total physical activity and moderate-to-vigorous physical activity, whereas early sleep onset and early sleep end were linked with longer sedentary time.

In light of the limited and conflicting evidence in the field, the present study examined the associations between objectively-measured sleep duration, sleep efficiency, bedtime, wake time and sleep timing midpoint with adiposity indices and physical activity in a cohort of children living in Ottawa, Canada.

Methods and procedures

Participants

The International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE) is a multi-national, cross-sectional study conducted in 12 different countries. The study design and methods used for data collection are described in more detail elsewhere (Katzmarzyk *et al*., 2013). This paper presents the data collected from the Canadian ISCOLE site. Data were collected in 26 schools in Ottawa on 567 children in the 5th grade (57.1% female; aged 9–11 years) between September 2012 and May 2013. Schools were stratified into four groups according to the names of the participating School Boards located in the Ottawa area: English Public (n = 393; 69.3%); French Public (n = 60; 10.6%); English Catholic (n = 75; 13.2%); and French Catholic (n = 39; 6.8%). The population of Ottawa is predominantly English-speaking; however, there is a large French-speaking minority. Of these 567 participants, 515 participants (58.8% female) had valid sleep measurement endpoints (i.e. data collected from at least 3 nights of sleep, including 1 weekend night) and were included in the present analyses. This project was approved by the research ethics board at the Children's Hospital of Eastern Ontario and the participating school boards. Written informed parental consent and child assent were obtained from all participants.

Anthropometric measurements

Anthropometric data were collected in schools during school hours according to standardized procedures by trained ISCOLE staff (Katzmarzyk *et al*., 2013). Weight and percentage body fat were measured to the nearest 0.1 kg/% using a portable Tanita SC-240 Body Composition Analyzer (Arlington Heights, IL, USA). Participants were asked to remove outer clothing, heavy pocket items, footwear and socks for these measurements. The portable Tanita SC-240 provides valid estimates of percentage body fat, compared with dual-energy X-ray absorptiometry, and its use has been supported in field studies on children under free living conditions (Barreira *et al*., 2013). Standing height was measured to the nearest 0.1 cm with a SECA 213 portable stadiometer. Waist circumference was measured with a standard, non-elastic measuring tape placed horizontally halfway between the last floating rib and the top of the iliac crest, and the measurement was taken at the end of a normal expiration. For weight, percentage body fat, height and waist circumference, two measurements were recorded unless the results differed by >0.5 kg (weight), >2.0% (percentage body fat) or >0.5 cm (height and waist circumference), respectively, in which case a third measurement was recorded and the closest two values were averaged. BMI z-scores were computed according to World Health Organization guidelines (World Health Organization, 2014). Waist-to-height ratio was also computed. This variable represents a valid indicator of central adiposity, and has been shown to be a useful indicator of cardiometabolic risk in children (Maffeis *et al*., 2008). Of the 515 children included in data analyses, all children had valid height measurements, 514 children had valid weight, waist circumference, BMI z-score and waist-to-height ratio measurements, and 494 children had valid percentage body fat measurements.

Sleep, physical activity and sedentary time measurements

The Actigraph GT3X+ (ActiGraph LLC, Pensacola, FL, USA) was used to assess nightly sleep duration (time asleep), sleep efficiency (total sleep duration divided by time lying down in bed), bedtime (first five consecutive minutes defined as sleep), wake time (first 10 consecutive minutes defined as wake after a sleep period) and daily physical activity (light, moderate and vigorous intensity). The participants wore the device around their waist at the right mid-axillary line 24 h per day, for seven consecutive days (Katzmarzyk *et al*., 2013). They were, however, asked to remove the device when bathing/showering or taking part in aquatic activities. Study staff conducted in-person verifications 2–4 days after providing the accelerometers to the participants, and contacted the parents/guardians of the participants on two separate occasions (1 weekday and 1 weekend call) to ensure proper accelerometer wear and compliance. Accelerometry data were collected at a sampling rate of 80 Hz, downloaded in 1-s epochs, and were aggregated to 15-s epochs (Evenson *et al*., 2008). A detailed description of a novel algorithm used to determine sleep duration, sleep efficiency, bed time and wake time from 24 h wear time in a sample of children from the US ISCOLE site is available elsewhere (Tudor-Locke *et al*., 2014). Briefly, algorithm 3 was used in the present study, which, in addition to the functions developed in algorithms 1 (based on an algorithm developed by Sadeh *et al*. (1994) that is able to discriminate between sleep and wake time with wrist-worn accelerometers by recording differences between movements and non-movements) and 2 (refines sleep duration measurements by making use of the inclinometer function; sleep is identified when there is no movement and the inclinometer is in the off position), is able to automatically identify bedtime and wake time via the accelerometer, without self-reported measurements. These algorithms were implemented in SAS (version 9.3; SAS Institute, Cary, N.C., USA), and are publicly available at: www.pbrc.edu/pdf/PBRCSleepPeriodTimeMacroCode.pdf. Wake time and sleep duration were used to compute sleep timing midpoint (wake time – ½ of total sleep duration). Physical activity cut-points used in this study were based on those developed by Evenson *et al*. (2008) (sedentary: ≤25 counts per 15 s; light physical activity: 26–573 counts per 15 s; moderate physical activity: 574–1002 counts per 15 s; vigorous physical activity: ≥1003 counts per 15 s; moderate-to-vigorous physical activity: ≥574 counts per 15 s). Further details on the accelerometry data reduction procedures employed are described elsewhere (Katzmarzyk *et al*., 2013). Of the 515 children included in data analysis, 507 children had valid physical activity measurement endpoints (i.e. at least 4 days including 1 weekend day, each with ≥10 h of waking wear time).

Covariates

Demographic questionnaires completed by parents were used to determine children's age, sex and ethnicity (White/Caucasian, African American, Asian, First Nations, East Indian, do not know, or other), as well as total annual family income (eight options ranging from <$14 999 to ≥$140 000), and the highest level of parental education (less than high school, some high school, high school diploma/GED, diploma or 1–3 years of college, bachelor's degree or graduate degree (Master's or PhD)/professional degree). Maturity offset, which estimates a child's age from peak height velocity, was calculated (Mirwald *et al*., 2002). Moderate-to-vigorous physical activity, percentage body fat, sleep duration, sleep efficiency and sleep timing midpoint were also considered as covariates when not the outcome. These covariates were chosen because of their associations with the exposures and/or outcomes in the literature (Colley *et al*., 2012; Foley *et al*., 2013; Jarrin *et al*., 2013; Magee *et al*., 2014; Must and Parisi, 2009; Scholle *et al*., 2011).

The variance inflation factors for all covariates in all models were <5, suggesting that multicollinearity was not a problem in the models presented.

Statistical analyses

Statistical analyses were performed using SPSS (version 17.0; SPSS, Chicago, IL, USA). No significant sex interactions were noted between sleep duration, sleep efficiency, or sleep timing measures and the outcome variables, and so data for both sexes were combined for all analyses. Additionally, no significant differences in sleep variables were noted between weekdays and weekend days after adjusting for covariates (results not shown), so only the analyses for combined weekdays and weekend days (i.e. the mean value of all valid nights for each participant) are reported. Multivariable linear regression analyses were used to examine associations between sleep duration, sleep efficiency, bedtime, wake time and sleep timing midpoint with all anthropometric, physical activity and sedentary time measurements. In the adjusted analyses, age, sex, ethnicity, total annual family income, highest level of parental education and maturity offset were included in the model to determine whether the observed associations are independent of these covariates. We also adjusted for percentage body fat, moderate-to-vigorous physical activity, sleep duration, sleep efficiency and sleep timing midpoint in the models when they were not the outcome. A multiple analysis of covariance (mancova), adjusted for the abovementioned covariates, was also used to determine the main effects of sleep duration, sleep efficiency, bedtime, wake time and sleep timing midpoint (divided according to tertiles) on all anthropometric, sedentary and physical activity measurements. Data are presented as means ± standard deviations, and P-values <0.05 were considered statistically significant.

Results

Participant characteristics are presented in Table 1. Children were predominantly white/Caucasian, with high socioeconomic status (81.7% live in a household with an annual family income of at least $60 000 per year or more, which is within or above the national average of $79 600 reported by Statistics Canada (2013)) and averaged 9.1 h ± 51 min of sleep per night with 96.2% sleep efficiency. Most participants included in the present analyses (79.6%) had 6 valid nights of accelerometry measurements.

Table 1. Participant characteristics

	Mean	SD	n (%)
Age (years)	10.0	0.4	515
Sex	NA	NA	
Boys			212 (41.2%)
Girls			303 (58.8%)
Ethnicity	NA	NA	
White/Caucasian			341 (67.1%)
African American			12 (2.4%)
Asian			50 (9.8%)
First Nations			2 (0.4%)
East Indian			4 (0.8%)
Do not know			1 (0.2%)

	Mean	SD	n (%)
Other			98 (19.3%)
Total			508
Total annual family income	NA	NA	
<$14 000			14 (2.8%)
$15 000–29 999			27 (5.5%)
$30 000–39 999			16 (3.2%)
$40 000–59 999			34 (6.9%)
$60 000–89 999			67 (13.6%)
$90 000–109 000			70 (14.2%)
$110 000–139 999			73 (14.8%)
$140 000 and above			193 (39.1%)
Total			494
Highest level of parental education	NA	NA	
Less than high school			2 (0.4%)
Some high school			8 (1.6%)
High school diploma/GED			36 (7.1%)
Diploma or 1–3 years of college			100 (19.6%)
Bachelor's degree			159 (31.2%)
Graduate/professional degree			204 (40.1%)
Total			509
Maturity offset[a]	−1.9	0.9	514
Body weight (kg)	38.2	9.2	514
BMI *z*-score	0.42	1.20	514
Waist circumference (cm)	63.1	8.5	514
Body fat (%)	20.7	7.5	494
Waist circumference-to-height ratio	0.44	0.05	514
Moderate-to-vigorous physical activity participation ($min \cdot day^{-1}$)[b]	58.5	19.4	507
Vigorous physical activity participation ($min \cdot day^{-1}$)[b]	16.8	9.1	507
Moderate physical activity participation ($min \cdot day^{-1}$)[b]	41.7	12.1	507
Light physical activity participation ($min \cdot day^{-1}$)[b]	304.9	45.2	507
Sedentary time ($min \cdot day^{-1}$)[b]	512.8	61.4	507
Self-reported screen time ($h \cdot day^{-1}$)	2.5	2.1	515
Sleep duration ($min \cdot day^{-1}$)[b]	544.8	50.9	515
Sleep efficiency (%)[b]	96.2	1.3	515
Sleep timing midpoint (time)[b]	02:41 hours	40 min	515
Bedtime (time)[b]	21:35 hours	3:22 h	515
Wake time (time)[b]	07:13 hours	45 min	515

[a] Maturity offset is an estimation of maturation in children that assesses age from peak height velocity by taking into account each child's height, sitting height, body mass and chronological age.
[b] The mean and standard deviation values over 7 days.
BMI, body mass index; NA; non-applicable; SD, standard deviation.

Sleep and anthropometric outcomes

The associations between sleep duration, sleep efficiency, bedtime, wake time and sleep timing midpoint with anthropometric outcomes are presented in Table 2. Sleep efficiency was negatively associated with weight, waist circumference, percentage body fat, BMI *z*-score and waist-to-height ratio in the adjusted models. These effect sizes were small (≤0.05). Conversely, sleep duration and sleep timing midpoint were only significantly associated with anthropometric outcomes in the unadjusted models. No significant differences in all anthropometric outcomes were noted between sleep duration ($F_{10,898}$ = 1.54, P = 0.12; Wilk's Λ = 0.97, partial η^2 = 0.02), sleep efficiency ($F_{10,898}$ = 1.34, P = 0.20; Wilk's Λ = 0.97, partial η^2 = 0.02), bedtime ($F_{10,900}$ = 0.82, P = 0.61; Wilk's Λ = 0.98, partial η^2 = 0.01), wake time ($F_{10,900}$ = 1.25, P = 0.25; Wilk's Λ = 0.97, partial η^2 = 0.01) and sleep timing midpoint ($F_{10,898}$ = 1.07, P = 0.39; Wilk's Λ = 0.98, partial η^2 = 0.01) tertiles following adjustments for covariates.

Table 2. The standardized parameter coefficients (β) for the associations between sleep duration, sleep efficiency and sleep timing with anthropometric and physical activity measurements

	Sleep duration β	**Sleep efficiency** β	**Sleep timing midpoint** β	**Bedtime** β	**Wake time** β
Anthropometric measurements					
Body weight (kg)					
Model 1	−0.20[c]	−0.09[a]	0.08	−0.04	−0.04
Model 2	−0.04	−0.08[b]	−0.01	0.01	−0.01
Waist circumference (cm)					
Model 1	−0.18[c]	−0.10[a]	0.07	−0.05	−0.04
Model 2	−0.03	−0.09[b]	−0.01	−0.01	−0.00
BMI *z*-score					
Model 1	−0.16[c]	−0.12[a]	0.06	−0.00	−0.04
Model 2	−0.03	−0.09[a]	−0.01	0.04	−0.01
Body fat (%)					
Model 1	−0.12[b]	−0.04	0.13[a]	−0.04	0.05
Model 2	−0.05	−0.09[a]	0.02	0.03	0.02
Waist-to-height ratio					
Model 1	−0.14[b]	−0.12[b]	0.07	−0.04	−0.02
Model 2	−0.04	−0.11[b]	0.01	−0.00	0.02
Physical activity measurements					
Moderate-to-vigorous physical activity (min·day^{-1})					
Model 1	−0.01	−0.09	−0.11[a]	0.06	−0.10[a]
Model 2	0.02	−0.03	−0.04	0.03	−0.06
Vigorous physical activity (min·day^{-1})					
Model 1	0.06	−0.03	−0.06	0.05	−0.01
Model 2	0.08	0.00	0.01	0.03	0.00
Moderate physical activity (min·day^{-1})					
Model 1	−0.06	−0.12[a]	−0.13[b]	0.06	−0.15[b]
Model 2	−0.02	−0.04	−0.08	0.03	−0.09
Light physical activity (min·day^{-1})					
Model 1	−0.18[c]	−0.23[c]	−0.11[a]	0.08	−0.20[c]
Model 2	−0.20[c]	−0.22[c]	−0.11[a]	0.10[a]	−0.13[a]
Sedentary time (min·day^{-1})					
Model 1	−0.44[c]	0.18[c]	0.16[b]	−0.13[b]	−0.10[a]
Model 2	−0.43[c]	0.16[c]	0.08[a]	−0.06	0.10[a]

[a] $P < 0.05$.
[b] $P < 0.01$.
[c] $P < 0.0001$.
Anthropometric measurements: all effect sizes for these analyses are small (0.05 or lower).

Physical activity measurements: all effect sizes for these analyses are small (0.05 or lower), except for the associations between sleep duration and sedentary time (large effect sizes; 0.14 or higher).
Model 1: unadjusted.
Model 2 (when anthropometric measurements are the outcome): adjusted for age, sex, ethnicity, total family income, highest level of parental education, maturity offset, moderate-to-vigorous physical activity, as well as sleep duration, sleep efficiency and sleep timing, which are mutually adjusted for one another.
Model 2 (when physical activity measurements are the outcome): adjusted for age, sex, ethnicity, maturity offset, total family income, highest level of parental education, body fat percentage, as well as sleep duration, sleep efficiency and sleep timing, which are mutually adjusted for one another.
BMI, body mass index.

Sleep and physical activity outcomes

The associations between sleep duration, sleep efficiency, bedtime, wake time and sleep timing midpoint with physical activity outcomes are also presented in Table 2. Light physical activity and sedentary time were negatively associated with sleep duration in the adjusted models. Sleep efficiency, wake time and sleep timing midpoint were negatively associated with light physical activity, and positively associated with sedentary time in the adjusted models. Bedtime was also positively associated with light physical activity in the adjusted model. The associations between sleep duration with sedentary time are large (≥0.14), whereas only small effect sizes (≤0.05) were noted for all other significant associations. In the between-groups analyses, following adjustments for covariates, a significant main effect was noted for outcomes between sleep duration ($F_{8,902} = 45.73$, $P = 0.0001$; Wilk's $\Lambda = 0.51$, partial $\eta^2 = 0.03$), sleep efficiency ($F_{8,902} = 3.06$, $P = 0.002$; Wilk's $\Lambda = 0.95$, partial $\eta^2 = 0.03$) and wake time ($F_{8,904} = 2.19$, $P = 0.03$; Wilk's $\Lambda = 0.96$, partial $\eta^2 = 0.02$) tertiles. More specifically, light physical activity and sedentary time were lower in participants with the longest sleep durations (Fig. 1). With respect to sleep efficiency, light physical activity was greater, but sedentary time lower, in those with the lowest sleep efficiencies (Fig. 1). As for wake time, only light physical activity was significantly greater in those with an earlier wake time (Fig. 1). No significant differences in physical activity outcomes between bedtime ($F_{8,904} = 0.95$, $P = 0.47$; Wilk's $\Lambda = 0.98$, partial $\eta^2 = 0.01$) and sleep timing midpoint ($F_{8,902} = 1.45$, $P = 0.17$; Wilk's $\Lambda = 0.98$, partial $\eta^2 = 0.01$) tertiles were noted after adjusting for covariates.

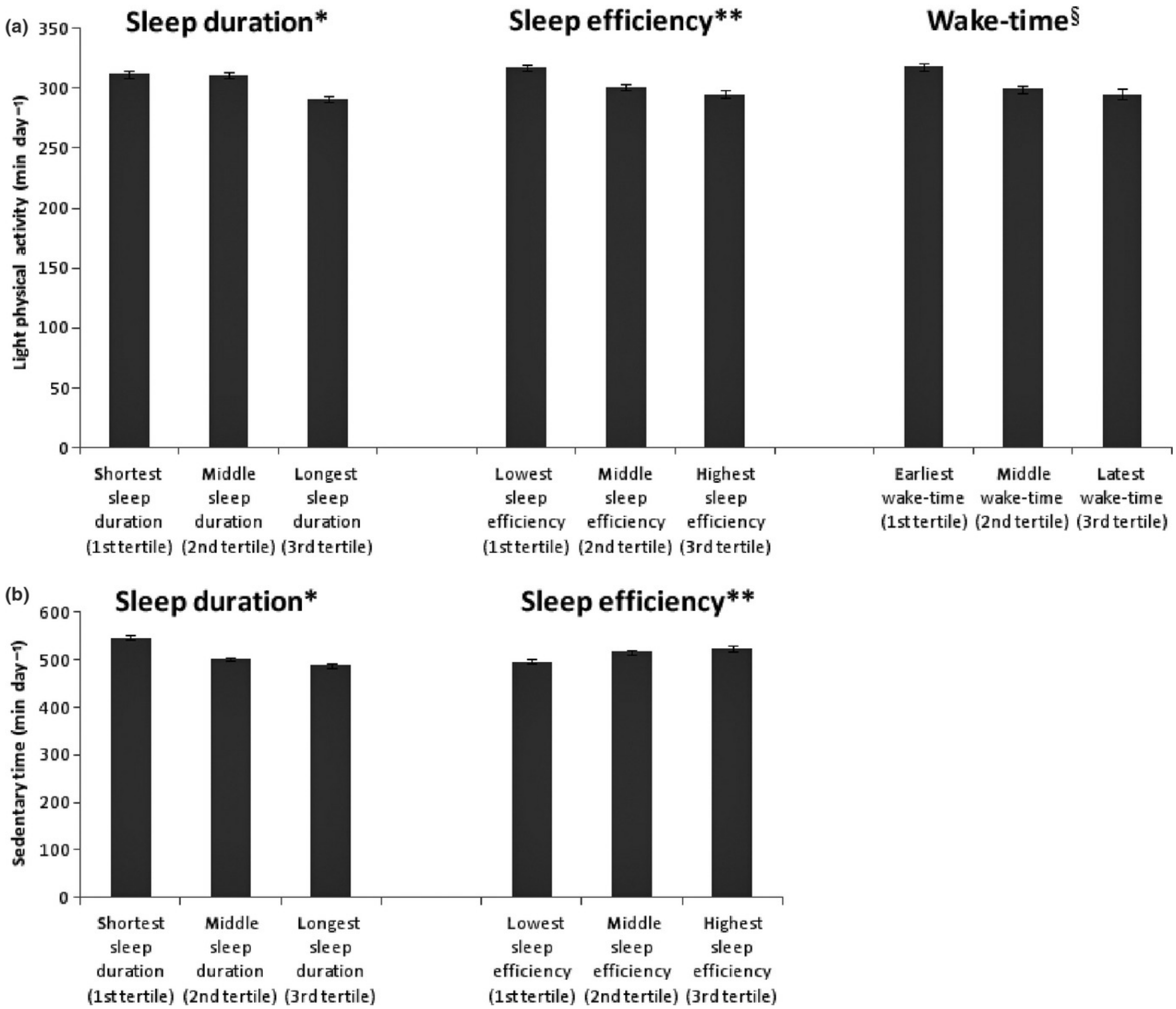

Figure 1. Differences in light physical activity (a) and sedentary time (b) between participants with the shortest (1st tertile: 489.2 ± 34.3 min), middle (2nd tertile: 550.6 ± 15.3 min) and longest (3rd tertile: 594.5 ± 26.3 min) sleep durations; lowest (1st tertile: 94.8 ± 0.7%), middle (2nd tertile: 96.2 ± 0.4%) and highest (3rd tertile: 97.6 ± 0.5%) sleep efficiencies; as well as earliest (1st tertile: 6 h 23 min ± 23 min), middle (2nd tertile: 7 h 12 min ± 10 min) and latest (3rd tertile: 8 h 02 min ± 26 min) wake times. Values are presented as means for 156, 157 and 154 participants in the 1st, 2nd and 3rd tertiles, respectively, for sleep duration; 156 participants in both the 1st and 2nd tertiles, and 155 participants in the 3rd tertile for sleep efficiency; 158, 162 and 147 participants classified as having the earliest, middle and latest wake times, respectively. The standard errors of the mean are represented by vertical bars in each case. *$P = 0.0001$ between the 1st and 2nd versus 3rd tertiles. **$P = 0.001$ between the 1st and 2nd tertiles; $P = 0.0001$ between the 1st and 3rd tertiles. §$P = 0.003$ between the 1st and 3rd tertiles; $P = 0.004$ between the 2nd and 3rd tertiles.

Discussion

The present study objectively-measured sleep duration, sleep efficiency, bedtime, wake time and sleep timing midpoint within the same study design, and investigated the independent associations between these variables with adiposity indices and physical activity in a cohort of children living in Ottawa, Canada. The present study is also one of relatively few that objectively measured sleep and physical activity parameters with the same device.

Participants had a mean sleep duration of 9.1 h ± 51 min, which is in line with others that objectively measured sleep duration (Harrington, 2013; Holley *et al*., 2010; Scholle *et al*., 2011; Spruyt *et al*., 2010). Additionally, this cohort had relatively higher sleep efficiencies (i.e. mean sleep efficiency of 96.2%) compared with other studies that objectively measured this variable in children (i.e. range from 83% to 90%; Holley *et al*., 2010; Scholle *et al*., 2011), which may be in part explained by the fact that the children in this cohort are relatively active and healthy (i.e. mean BMI *z*-score of 0.42 and moderate-to-vigorous physical activity participation of 58.5 min). Results from the present study also suggest that sleep efficiency, rather than sleep duration or sleep timing midpoint, has greater, independent associations with adiposity, explaining 8–11% of the variance in adiposity indices. These results are consistent with past research (Jarrin *et al*., 2013) that reported attenuations in associations between sleep duration and adiposity following adjustments for covariates, but significant associations between sleep disturbances and adiposity in the unadjusted and adjusted models. Physiological evidence suggests that nocturnal awakenings or poor sleep efficiency are associated with reductions in parasympathetic nervous system activity, coupled with increased sympathetic nervous system activity, which may cause increases in heart rate, blood pressure, norepinephrine and cortisol release (Hanlon and Van Cauter, 2011). Recurrent awakenings may also lead to reductions in sleep quality, predominantly decreases in slow-wave sleep, which may decrease growth hormone secretion, insulin sensitivity and increase morning cortisol levels (Ekstedt *et al*., 2004; Stamatakis and Punjabi, 2010). These physiological alterations, if left untreated, may evolve into eventual sleep disorders and weight gain that can be carried over into adulthood (Hanlon and Van Cauter, 2011).

The present study noted negative associations between light physical activity and sedentary time with sleep duration, which was also supported by significantly greater light physical activity and sedentary time in participants with the shortest sleep durations. Furthermore, the partial eta squared (η^2) values noted in the regression models indicate that associations between sleep duration and sedentary time are large, whereas only small effect sizes were noted for the associations between sleep efficiency and sleep timing midpoint with light physical activity and sedentary time. Stone *et al*. (2013) noted that children with the shortest sleep durations (<9 h of sleep per night) had relatively more sedentary time compared with those who slept ≥10 h per night. However, Stone *et al*. (2013) also noted lower total physical activity and moderate-to-vigorous physical activity in children with a sleep duration <9 h per night versus ≥10 h per night, which is not supported by results in the present study. Although Stone *et al*. (2013) objectively measured physical activity outcomes, parental self-report was used to assess sleep duration, which may in part explain the relatively high number of participants with ≥10 h of sleep per night (40% versus 12% in the present study), and the discrepancy in physical activity results between sleep duration groups in both studies.

Children characterized as more sleep efficient in the present study spent less time in light physical activity and had more sedentary time compared with those characterized as less sleep efficient. Ekstedt *et al*. (2013) observed that poorer sleep efficiency was related to greater moderate-to-vigorous physical activity and total physical activity time. Furthermore, a positive correlation was noted between sleep efficiency and sedentary time (Ekstedt *et al*., 2013), which supports the results of the present study. Although we cannot determine the exact causes of these associations, it is possible that children who are less sleep efficient, potentially caused by frequent repositioning, restlessness or even wakefulness and getting out of bed throughout the night, may have less sedentary time in exchange for increased light physical activity. It may also be hypothesized that children who do not sleep well may consciously move more during the day as a means of fighting off fatigue. However, these are simply untested hypotheses and would warrant further investigation.

Sleep timing midpoint and wake time were negatively associated with light physical activity, and positively associated with sedentary time. Participants with an earlier wake time also had greater light physical activity time, whereas no differences in physical activity outcomes were noted between sleep timing midpoint tertiles. These results contrast those previously noted by Ekstedt *et al*. (2013; i.e. earlier sleep onset and earlier sleep end were linked with greater sedentary time the following day), but add to those noted by Olds *et al*. (2011; i.e. greater self-reported moderate-to-vigorous physical activity participation in children with late bedtimes and wake times versus children with early bedtimes and wake times, independently of sleep duration). More studies are needed to reproduce these results, as well as experimentally assess the effects of sleep timing midpoint, independently of sleep duration, on measures of physical activity in children.

The present findings are limited to Canadian children from the Ottawa area, which limits the generalization of these results. The accelerometers used in the present study are limited in their ability to capture movement during certain activities, such as swimming, cycling and weight training, and sedentary time derived from accelerometry does not provide information on the type of sedentary behaviour performed (e.g. screen time). Accelerometers may also be limited in their ability to properly distinguish between sleep and waking state, as they are mostly based on movement analysis (Soric *et al*., 2013). Furthermore, waist-worn accelerometers have been shown to overestimate sleep duration and sleep efficiency comparatively to wrist-worn devices (Hjorth *et al*., 2012), which may in part explain the high sleep efficiency values observed in this cohort. Nonetheless, the use of one single accelerometer to assess both physical activity and sleep parameters is less cumbersome for children, and will still provide valid proxy measurements of sleep (Hjorth *et al*., 2012). Finally, cause-and-effect relationships cannot be inferred with cross-sectional data, and there is always the possibility of residual confounding in observational studies.

In conclusion, sleep efficiency was negatively associated with adiposity in this sample of children, whereas associations of sleep duration and sleep timing with adiposity were no longer significant after adjustment for covariates. Participants with the shortest sleep durations or highest sleep efficiencies had greater sedentary time. More research using objective measures of physical activity and sleep are needed to not only confirm the results presented in the present study, but also to develop better sleep recommendations in children that are based on objective measures of sleep duration, sleep efficiency and sleep timing alike.

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Author contributions

J. M. participated in data collection, data analyses and writing the manuscript. M. S. T. and J. P. C. conceived the study design, oversaw its coordination and contributed to data interpretation. G. L., C. B., P. B., A. G. L. and M. M. B. participated in study management, data collection and data cleaning. All authors critically revised the paper and approved the final version.

Conflict of interest

The authors of this paper declare no conflict of interest.

References

Barreira, T. V., Staiano, A. E. and Katzmarzyk, P. T. Validity assessment of a portable bioimpedance scale to estimate body fat percentage in white and African-American children and adolescents. *Pediatr. Obes.*, 2013, **8**: e29– e32.

Bornhorst, C., Hense, S., Ahrens, W. *et al*. From sleep duration to childhood obesity – what are the pathways? *Eur. J. Pediatr.*, 2012, **171**: 1029– 1038.

Chaput, J. P., 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**: 369– 374.

Colley, R. C., Wong, S. L., Garriguet, D., Janssen, I., Connor Gorber, S. and Tremblay, M. S. Physical activity, sedentary behaviour and sleep in Canadian children: parent-report versus direct measures and relative associations with health risk. *Health Rep.*, 2012, **23**: 45– 52.

Ekstedt, M., Akerstedt, T. and Soderstrom, M. Microarousals during sleep are associated with increased levels of lipids, cortisol, and blood pressure. *Psychosom. Med.*, 2004, **66**: 925– 931.

Ekstedt, M., Nyberg, G., Ingre, M., Ekblom, O. and Marcus, C. Sleep, physical activity and BMI in six to ten-year-old children measured by accelerometry: a cross-sectional study. *Int. J. Behav. Nutr. Phys. Act.*, 2013, **10**: 82.

Evenson, K. R., Catellier, D. J., Gill, K., Ondrak, K. S. and McMurray, R. G. Calibration of two objective measures of physical activity for children. *J. Sports Sci.*, 2008, **26**: 1557– 1565.

Foley, L. S., Maddison, R., Jiang, Y., Marsh, S., Olds, T. and Ridley, K. Presleep activities and time of sleep onset in children. *Pediatrics*, 2013, **131**: 276– 282.

Golley, R. K., Maher, C. A., Matricciani, L. and Olds, T. S. Sleep duration or bedtime? Exploring the association between sleep timing behaviour, diet and BMI in children and adolescents *Int. J. Obes. (Lond.)*, 2013, **37**: 546– 551.

Hanlon, E. C. and 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. USA*, 2011, **108**: 15609– 15616.

Harrington, S. A. Relationships of objectively measured physical activity and sleep with BMI and academic outcomes in 8-year-old children. *Appl. Nurs. Res.*, 2013, **26**: 63– 70.

Hjorth, M. F., Chaput, J.-P., Damsgaard, C. T., Dalskov, S.-M., Michaelsen, K. F., Tetens, I., Sjodin, A. Measure of sleep and physical activity by a single accelerometer: Can a waist-worn Actigraph adequately measure sleep in children? *Sleep and Biological Rythms*, 2012, **10**: 328– 335.

Holley, S., Hill, C. M. and 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**: 16– 27.

Jarrin, D. C., McGrath, J. J. and Drake, C. L. Beyond sleep duration: distinct sleep dimensions are associated with obesity in children and adolescents. *Int. J. Obes. (Lond.)*, 2013, **37**: 552– 558.

de Jong, E., Stocks, T., Visscher, T. L., Hirasing, R. A., Seidell, J. C. and Renders, C. M. Association between sleep duration and overweight: the importance of parenting. *Int. J. Obes. (Lond.)*, 2012, **36**: 1278– 1284.

Katzmarzyk, P. T., Barreira, T. V., Broyles, S. T. *et al*. The International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE): design and methods. *BMC Public Health*, 2013, **13**: 900.

Maffeis, C., Banzato, C. and Talamini, G. Waist-to-height ratio, a useful index to identify high metabolic risk in overweight children. *J. Pediatr.*, 2008, **152**: 207– 213.

Magee, C., Caputi, P. and Iverson, D. Lack of sleep could increase obesity in children and too much television could be partly to blame. *Acta Paediatr.*, 2014, **103**: e27– e31.

Meng, L. P., Liu, A. L., Hu, X. *et al*. Report on childhood obesity in China (10): association of sleep duration with obesity. *Biomed. Environ. Sci.*, 2012, **25**: 133– 140.

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A. and Beunen, G. P. An assessment of maturity from anthropometric measurements. *Med. Sci. Sports Exerc.*, 2002, **34**: 689– 694.

Must, A. and Parisi, S. M. Sedentary behavior and sleep: paradoxical effects in association with childhood obesity. *Int. J. Obes. (Lond.)*, 2009, **33**: S82– S86.

Nixon, G. M., Thompson, J. M., Han, D. Y. *et al*. Short sleep duration in middle childhood: risk factors and consequences. *Sleep*, 2008, **31**: 71– 78.

Olds, T. S., Maher, C. A. and Matricciani, L. Sleep duration or bedtime? Exploring the relationship between sleep habits and weight status and activity patterns *Sleep*, 2011, **34**: 1299– 1307.

Pesonen, A. K., Sjosten, N. M., Matthews, K. A. *et al*. Temporal associations between daytime physical activity and sleep in children. *PLoS One*, 2011, **6**: e22958.

Sadeh, A., Sharkey, K. M. and Carskadon, M. A. Activity-based sleep-wake identification: an empirical test of methodological issues. *Sleep*, 1994, **17**: 201– 207.

Scholle, S., Beyer, U., Bernhard, M. *et al*. Normative values of polysomnographic parameters in childhood and adolescence: quantitative sleep parameters. *Sleep Med.*, 2011, **12**: 542– 549.

Shi, Z., Taylor, A. W., Gill, T. K., Tuckerman, J., Adams, R. and Martin, J. Short sleep duration and obesity among Australian children. *BMC Public Health*, 2010, **10**: 609.

Soric, M., Turkalj, M., Kucic, D., Marusic, I., Plavec, D. and Misigoj-Durakovic, M. Validation of a multi-sensor activity monitor for assessing sleep in children and adolescents. *Sleep Med.*, 2013, **14**: 201– 205.

Spruyt, K., Molfese, D. L. and Gozal, D. Sleep duration, sleep regularity, body weight, and metabolic homeostasis in school-aged children. *Pediatrics*, 2010, **127**: e345– e352.

Stamatakis, K. A. and Punjabi, N. M. Effects of sleep fragmentation on glucose metabolism in normal subjects. *Chest*, 2010, **137**: 95– 101.

Statistics Canada. Average income after tax by economic family types (2007–2011). 2013. Available from: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/famil21a-eng.htm

Stone, M. R., Stevens, D. and Faulkner, G. E. Maintaining recommended sleep throughout the week is associated with increased physical activity in children. *Prev. Med.*, 2013, **56**: 112– 117.

Tudor-Locke, C., Barreira, T. V., Schuna, J. M.,Jr, Mire, E. F. and Katzmarzyk, P. T. Fully automated waist-worn accelerometer algorithm for detecting children's sleep-period time separate from 24-h physical activity or sedentary behaviors. *Appl. Physiol. Nutr. Metab.*, 2014, **39**: 53– 57.

World Health Organization. Growth reference; BMI for age (5–19 years). 2014. Available from: http://www.who.int/growthref/who2007_bmi_for_age/en