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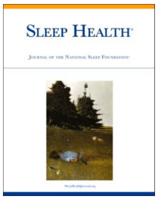

Time use and dimensions of healthy sleep: A cross-sectional study of Australian children and adults

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ABSTRACT

Background: Sleep is increasingly recognized as a multidimensional construct that occurs within the 24-hour day. Despite advances in our understanding, studies continue to consider the relationship between sleep, sedentary time and physical activity separately, and not as part of the 24-hour day.
Aims: To determine the association between the 24-hour activity composition and dimensions of healthy sleep.
Methods: This study examined data on 1168 children (mean age 12 years; 49% female) and 1360 adults (mean age 44 years; 87% female) collected as part of the Child Health CheckPoint study. Participants were asked to wear a GENEActiv monitor (Activinsights, Cambs, UK) on their nondominant wrist for eight consecutive days to measure 24-hour time-use. Compositional data analysis was used to examine the association between time use (actigraphy-derived sleep duration, sedentary time, light physical activity and moderate-vigorous physical activity) and dimensions of healthy sleep. Healthy sleep was conceptualized in terms of continuity/efficiency, timing, alertness/sleepiness, satisfaction/quality, and regularity. Time allocations were also examined.
Results: The 24-hour activity composition was significantly associated with all objectively measured and self-report dimensions of healthy sleep in both children and adults. Allocating more time to sleep was associated with earlier sleep onsets, later sleep offsets, less efficient and more consistent sleep patterns for both children and adults.
Conclusion: This study highlights the integral relationship between daily activities and dimensions of sleep. Considering sleep within the 24-hour day activity composition framework may help inform lifestyle decisions to improve sleep health.

Introduction

Sleep is essential for health and well-being. While the fundamental importance of sleep is consistent across all ages, the factors influencing it, as well as its patterns and implications, can differ between children and adults. Poor sleep, typically characterized in terms of short sleep duration, delayed sleep timing and poor sleep quality, has been associated with a wide range of negative health outcomes.[1-3] The importance of sleep for health has gained considerable attention, with efforts and interventions to promote sleep increasingly viewed as a public health priority.[4,5]

The term "sleep health" was proposed by Buysse[5] as a metric for health promotion. This framework recognizes that there are different dimensions of sleep, including duration, continuity/efficiency, timing, alertness/sleepiness, satisfaction/quality and more

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recently, sleep regularity.[5,6] At the same time, recent advances in time-use epidemiology suggest that sleep may be just as important as physical activity when considering modifiable lifestyle behaviors.[7,8] It is now recognized that sleep, physical activity and sedentary time are mutually exclusive and exhaustive parts of the 24-hour day.[7] That is, if physical activity is increased, there must be an equal and opposite reduction in sleep, sedentary time or both. Furthermore, it is likely that children and adults may prioritize these components differently, based on factors like school, work, and social commitments. This realization steers us away from viewing these behaviors in isolation. Instead, it emphasizes the need to perceive the day in terms of an "activity composition." Recommendations that focus on physical activity (eg, ensure 30 minutes of physical activity a day) are consequently being superseded by recommendations that consider trade-offs in how people spend their time.[7]

Although conceptualizing sleep as part of an activity composition is relatively new, the interaction between sleep, physical activity and sedentary time has long been recognized. For example, the associations between sleep, physical activity and sedentary time have often been discussed as a mechanism to help explain associations between sleep and adiposity.[9,10] Specifically, short sleep duration is thought to induce daytime fatigue and reduce capacity for physical activity, while evening sedentary activities (eg, watching television) are thought to delay sleep timing and curtail sleep duration.[9,10] Relatively new methods for examining sleep as a component of time suggest that the activity composition is an important predictor of adiposity[11] as well as other health outcomes.[12] While it may make intuitive sense to consider sleep duration as part of an activity composition, it (1) assumes we can simply trade time awake for more or less sleep, (2) ignores that there are sleep characteristics other than duration that may be important to consider (such as quality and timing) and (3) ignores findings that time use, typically considered in terms of physical activity and sedentary behaviors, may influence different dimensions of sleep.

There are a number of ways that time use could be linked with sleep. For instance, children might have their sleep patterns influenced by school schedules and parental guidelines, whereas adults navigate around work hours and societal commitments. Displacement models suggest daily activities may either hinder or promote sleep depending on how they are organized. For instance, watching television or playing video/computer games that extend into the evening will displace time spent in sleep by delaying bedtimes. Similarly, life constraints, such as school and work hours may dictate sleep times and duration. Psychophysical models on the other hand, suggest that there are a range of nonsleep factors (such as foods, drugs, stress, and time use) that may influence the amount and quality of sleep. In terms of time use, the amount, type and timing of physical activity, as well as blue light exposure from electronic devices during sedentary behaviors are thought to influence sleep. High levels of physical activity have been suggested to promote better sleep quality[13,14] and longer sleep durations,[14] while blue light exposure has been shown to suppress melatonin, increases alertness and delay sleep onset.[15,16]

Although the inter-related nature of sleep, sedentary time and physical activity is often acknowledged, we are unaware of any attempts to determine whether integrated time use (eg, the activity composition) is associated with different dimensions of sleep. Given increasing efforts to conceptualize sleep in this way,[7,8,17] it is timely to integrate concurrent advances in sleep medicine. This study aims to examine cross-sectional associations between the activity composition and the different dimensions of sleep. Specifically, we aimed to:

1. Determine the association between the activity composition and dimensions of sleep proposed by Buysse[5] that occur within a 24-hour period (continuity/efficiency, timing, alertness/sleepiness, satisfaction/quality, regularity).
2. Examine the associations of allocating time in sleep versus moderate-vigorous physical activity (MVPA), sedentary time, and light physical activity (LPA) with the different dimensions of sleep (continuity/efficiency, timing, alertness/sleepiness, and satisfaction/quality, regularity).

Methods

Participants

Data examined in this study were collected as part of the Australian Child Health CheckPoint (CheckPoint) study. The CheckPoint study was conducted between February 2015 and March 2016 as a cross-sectional study nested within the Longitudinal Study of Australian Children (LSAC). Details of the LSAC and CheckPoint study have been reported elsewhere.[18,19] Briefly, the LSAC study commenced in 2004 with the recruitment of two birth cohorts (B and K), which have since been followed biennially. During Wave 6 of LSAC, the B-cohort families were introduced to the upcoming CheckPoint study and 42% agreed to take part (37% of original cohort). Participation in the CheckPoint study involved each participating child, with one parent or caregiver (usually the biological mother) to attend an assessment center or home visit where trained research assistants collected a wide range of measures and fitted participants with a GENEActiv activity monitor (Activinsights, Cambs, UK). This study examines the publicly available CheckPoint study dataset.

Ethics and consent

The CheckPoint study protocol was approved by The Royal Children's Hospital Melbourne Human Research Ethics Committee (33225D) and the Australian Institute of Family Studies Ethics Committee (14-26). The attending parent/caregiver provided written informed consent for themselves and their child to participate in the study.

Measures

Predictor variable: The activity composition

The activity composition was considered in terms of sleep duration, time spent in sedentary time, LPA and MVPA, measured using the tri-axial GENEActiv activity monitors. Participants were fitted with an activity monitor on their nondominant wrist and asked to wear the monitor for eight consecutive days and complete an activity record to document bed and wake times and any times the monitor was removed. Children were instructed how to complete the activity record, but may have received help from their parents.

Raw acceleration data, collapsed into 60-second epochs, were processed using *Cobra* custom software.[20] The van Hees[21] sleep algorithm was used to detect sleep and wake between self-reported bedtime and wake times, which were visually inspected for accuracy and manually marked when activity log data were not available. Data were collapsed into 1-minute epochs, classified as sleep or wake depending on whether the contained a majority of sleep or wake 5-second epochs, respectively. In cases where there were an equal numbers of 5-second epochs scored as sleep and wake, the 1-minute epoch was classified as sleep. Sleep onset was defined as the start of the first three consecutive minutes scored as sleep. Sleep offset was defined as the end of the last five consecutive minutes scored as sleep. The difference between sleep onset and sleep offset was used to derive sleep period, to reflect sleep duration. Measures of sleep duration in this study therefore captures periods of nighttime awakenings. Sedentary time and time spent in MVPA, used cutpoints defined by Phillips et al[22] for children and Esliger et al[23] for adults. Visual inspection of activity traces was used to mark periods of nonwear. Where available, activity logs were used to impute estimates for nonwear coded as "sport."[20] Sport was imputed as 50% MVPA, 30% LPA, and 20% sedentary time.[20] Participants were included for analysis if they had an average sleep duration > 200 minutes for at least four nights of sleep data recorded and at least one weekend night (Fri-Sat) of sleep data. Further details of data processing have been reported elsewhere.[20,24]

Outcome variables: Dimensions of sleep, excluding sleep duration

The sleep health framework proposed by Buysse[5] guided the selection of outcome variables to reflect the different dimensions of sleep. Activity monitor data were used to determine sleep timing, continuity/efficiency and regularity, while self-report data were used to determine satisfaction/quality and alertness/sleepiness. Sleep timing was measured in terms of sleep onset and offset while sleep efficiency was measured as the percent of minutes scored as sleep within the sleep period (sleep onset-sleep offset). Sleep regularity (variability of night-to-night sleep length) was measured as the coefficient of variation of the measurements of sleep period. A five-point Likert scale questionnaire was used to determine how often participants experienced troubled sleep over the last month and how tired they felt on the day of assessment (preceding objectively measured time-use assessment). Self-reported troubled sleep and tiredness were used to assess dimensions of satisfaction/quality and alertness/sleepiness, respectively. Children and adults were provided with the same questions. For troubled sleep, participants were asked: "Over the last month, how often do you have trouble sleeping" with five responses: never, almost never, sometimes, often, all the time (scored 1 through to 5, respectively). For tiredness, participants were asked to report how they were feeling at the time of assessment: "For each question, read all the choices and decide which one is most like you today," with responses: "I don't feel tired today," "I feel a little bit tired today," "I feel a bit tired today," "I feel quite tired today," "I feel very tired today" (scored 1 through to 5, respectively). Measures of troubled sleep and tiredness were treated as a continuous measure with 1 reflecting low levels of troubled sleep and tiredness and 5 reflecting high levels of troubled sleep/tiredness.[25,26]

Covariates

Analyses were adjusted for potential confounders of socio-economic position (SEP), sex, age (for adult analyses), pubertal stage (for children's analyses) and season of data collection. Children were of similar age (mean 12 years, SD 0.4 years) and so pubertal stage, measured using the Puberty Development Scale, was used as a measure of maturity stage. The Puberty Development Scale is a validated self-report questionnaire where higher scores reflect advanced pubertal development.[27] SEP was operationalized as a composite z-score consisting of parent-reported income, education and occupation for both children and adults, which was derived from Wave 6 of the LSAC dataset.[28] Using this scale, higher scores represent higher socio-economic position.

Statistical analysis

Compositional data analyses (CoDA) were performed in R (http://cran.r-project.org) using "compositions" package.[29] Measures of sleep duration, sedentary time, MVPA and LPA, averaged using a 5:2 weighting for a weeknight (Sunday-Thursday) and weekend (Friday-Saturday and school holidays for children), were used to create 24-hour day activity compositions. Data were checked for zero values and no zero values were identified. The average wear time of children and adults was 1433 (SD 30) and 1434 (SD 32) minutes, respectively. The geometric mean of each activity behavior was linearly adjusted so that all parts summed to a total of 1440 (minutes in a 24-hour period). Following the procedure in Chastin et al,[30] the composition was expressed as four sets of three isometric log ratios (ilr) co-ordinates. The ilr coordinates are also termed "pivot ilrs" as they capture variation in one activity, relative to all remaining activities.

Multiple linear regression models (one for each set of ilrs) were used to determine the association between the 24-hour activity composition and dimensions of sleep. Pivot ilrs were used to determine associations between each component of time (relative to remaining) and outcome measure.[31] *P*-values and confidence intervals are Bonferroni corrected within each modeled outcome to ensure a family-wise type 1 error $\leq \alpha = 0.05$ per analysis. Results of the analyses are presented with and without covariate (sex, season, age for parents, puberty stage for children) adjustment.

Time reallocations were examined using *one-for-remaining* reallocations. The one-for-remaining simulations reallocated time to one domain by drawing on each of the other domains according to the size of those domains (ie, proportionally). One-for-remaining reallocations and their 95% CIs were plotted using the R package "codaredistlm."[32] Separate analyses were performed for children and adults. The analysis code is available at: https://github.com/LisaMatrix/CodaSleepDimensions.

Results

This study involved 1168 children and 1360 adults from the 1874 child-parent pairs involved in the CheckPoint study, for which complete 24-hour activity and sleep dimension data were available. As shown in Table 1, the children and adults (mostly mothers) sampled had relatively healthy sleep profiles——sleeping, on average, the recommended amount.[33] Compared to the population-based LSAC B cohort participants, participants had a higher SEP z-score (mean = 0.32, SD = 0.90 vs. mean = 0.00, SD = 1.00).

Activity composition and dimensions of healthy sleep

The association between the activity composition and each dimension of healthy sleep for children and adults are presented in Table 2. As shown, after adjusting for covariates, the overall 24-hour activity composition was significantly associated with all sleep characteristics in both children and adults. In children, all components of the activity composition were significantly associated with sleep offset, while sleep duration and sedentary time were associated with sleep onset, efficiency, and variability. Children's LPA (relative to remaining) was also associated with efficiency and variability, but not onset. In adults, all components of the activity composition were significantly associated with sleep onset and offset, while sleep duration and sedentary time were associated with sleep efficiency and variability. In adults, MVPA (relative to remaining) was the only allocation that was significantly associated with subjective dimensions of sleep (tiredness).

The direction of associations were the same for children and adults. Allocating more time to sleep (relative to remaining) was associated with lower sleep efficiency, earlier sleep times and later wake times, while allocating more time to sedentary and MVPA time was associated with higher sleep efficiency, earlier sleep times, later wake times and less variable sleep patterns in both children and adults. Among adults, allocating more time to MVPA (relative to remaining) was associated with less tiredness. Allocating more time to sleep duration was not associated with subjective dimensions of healthy sleep in children or adults.

Allocations of time

Figs. 1 and 2 illustrate one-for-remaining time "reallocation" simulations, that is, the association between time-use component (sleep, sedentary time, LPA, and MVPA) and each dimension of sleep

Table 1
Sample characteristics of children and adults included for analysis

	Children	Adults
n	1168	1360
Female (n (%))	572 (49)	1189 (87)
Age (mean (SD))	12.0 (0.4)	44.4 (5.1)
BMI (mean (SD))[a]	0.3 (1.0)	27.4 (5.8)
SEP (mean (SD))	0.24 (0.99)	0.21 (1.00)
Pubertal stage (n, %)		
Prepubertal	117 (10)	
Early puberty	293 (25)	
Mid-puberty	599 (51)	
Late puberty	153 (13)	
Post puberty	6 (0.5)	
Daily activity characteristics (mean (SD))[b]		
MVPA (min)	62 (35)	123 (58)
LPA (min)	251 (57)	266 (60)
Sedentary time (min)	554 (81)	547 (97)
Activity compositional mean		
MVPA (min)	53	113
LPA (min)	250	266
Sedentary time (min)	561	553
Sleep duration (min)	577	508
Daily sleep characteristics (mean (SD))[b]		
Sleep duration[c] (min)	566 (47)	498 (56)
Sleep efficiency (%)	84 (6)	86 (7)
Sleep onset (24 h:min)	21:56 (0:57)	22:40 (1:03)
Sleep offset (24 h:min)	7:23 (0:51)	7:03 (0:59)
Sleep-length variability (%)	8 (6)	10 (8)
Trouble sleeping over the last month (n, %)		
Always	41 (4)	36 (3)
Almost always	116 (10)	166 (12)
Sometimes	264 (23)	497 (37)
Almost never	393 (34)	520 (38)
Never	354 (30)	141 (10)
Feel tired on the day of assessment (n, %)		
Very tired	12 (1)	18 (1)
Quite tired	59 (5)	90 (7)
A bit tired	197 (17)	168 (12)
A little bit tired	559 (48)	649 (48)
I don't feel tired	341 (29)	435 (32)

BMI, body mass index; LPA, light physical activity; MVPA, moderate-vigorous physical activity; SEP, socioeconomic position.

[a] BMI z-score (calculated using the Centers for Disease Control CDC reference dataset[34]) is reported for children.

[b] Daily activity estimates have been calculated using 5:2 weighting for weekdays and weekends.

[c] Sleep duration was measured in terms of sleep period, the difference between sleep onset and offset.

when it is increased or decreased in proportion with the remaining components (eg, a 30-minute increase in sleep duration with a concurrent pro-rata decrease in sedentary time, LPA and MVPA, together totaling 30 minutes). As shown, except for troubled sleep, the direction of associations were consistent for both children and adults. Aallocating more time to sleep was (as expected) associated with earlier sleep onsets (model predicted change for +30 minutes sleep $\text{est}_{\text{children}} = -15.81$, CI: $-18.10, -13.51$; $\text{est}_{\text{adults}} = -14.15$, CI: $-16.18, -12.11$) and later wake times (model predicted change for +30 minutes sleep $\text{est}_{\text{children}} = 11.20$, CI: 9.06, 13.34; $\text{est}_{\text{adults}} = 13.19$, CI: 11.32, 15.05), as well as less efficient (model predicted change for +30 minutes sleep $\text{est}_{\text{children}} = -0.62$, CI: $-0.90, -0.35$; $\text{est}_{\text{adults}} = -0.46$, CI $-0.71, -0.22$) and more consistent sleep patterns (model predicted change for +30 minutes sleep $\text{est}_{\text{children}} = -0.53$, CI: $-0.81, -0.24$; $\text{est}_{\text{adults}} = -0.35$, CI $-0.63, -0.07$) in both children and adults. Allocating more time to MVPA (relative to remaining) was associated with more efficient sleep, earlier wake times and less tiredness, while allocating more time to sedentary behaviors was associated with more efficient sleep, less consistent sleep schedules, earlier wake and later sleep times. Allocating more time to LPA (relative to remaining) was associated with earlier wake times and later sleep times.

Discussion

To our knowledge, this is the first study to examine the association between the 24-hour activity composition and dimensions of sleep in a sample of healthy children and adults. The activity composition was significantly associated with actigraphy-derived sleep timing, efficiency, and variability. The activity composition was also significantly associated with self-report troubled sleep and tiredness in both children and adults.

When focusing on children, the findings show a significant association between their activity composition and sleep offset, with sleep duration and sedentary time playing a significant role in their sleep onset, efficiency, and variability. It's also noteworthy to highlight the role of LPA in children's sleep patterns. Comparatively, for adults, the activity composition was also significantly associated with dimensions of sleep, with MVPA playing an important role in their sleep onset, sleep offset, and efficiency, as well as tiredness.

Consistent with previous literature, allocating more time to sleep was associated with less efficient sleep, and (as expected) earlier bedtimes and later wake times.[35] These findings are likely to reflect mathematical necessity, or in-bed waking activities such as reading. Since sleep duration was measured as the difference between sleep onset and offset, an increase in sleep duration can only occur if sleep onset is earlier or offset is later (or both). Similarly, associations detected for other components of time may also be attributed to mathematical necessity. For example, allocating more time to sedentary behaviors was associated with delayed bedtimes and earlier wake times. Since an in increase in sedentary time will necessarily result in shortened sleep duration (while holding physical activity constant), so too will sleep onset and offset change.

Interestingly, while certain associations like sleep efficiency and variability with activity composition seem to be consistent across both children and adults, there were nuanced differences. For instance, adults showed a more distinct relationship between MVPA and subjective dimensions of sleep, suggesting different physiological and behavioral dynamics between the two age groups.

We also observed that allocating more time to sleep was associated with less variable sleep. This may reflect physiological need——as sleep duration decreases, efforts are made to "catch-up" on lost sleep. Allocating more time to sleep was also associated with less efficient sleep. Although this finding may initially seem surprising, this finding is consistent with sleep extension studies[36] and may reflect a physiological sleep need——despite allocating more time in bed to sleep, there is only a certain amount required, resulting in less efficient sleep. Findings may also relate to how sleep was operationalized. Although sleep period, the difference between sleep onset and offset is a common approach to conceptualizing sleep duration, it captures night-time awakenings and it is therefore unsurprising that associations between sleep duration and efficiency were found. Given that individuals have more control over their sleep period (than total sleep time), conceptualizing sleep in this way may arguably be a more realistic approach to considering sleep in the context of 24-hour day, because it recognizes the importance of allocating and exchanging 24-hour time-use behaviors.

Physiological reasons, such as serotonin release, may also help explain the associations detected between MVPA and various subjective dimensions of sleep. Engaging in MVPA has been shown to stimulate the release of serotonin, a neurotransmitter that plays a key role in mood regulation and the sleep-wake cycle.[37] The increased serotonin levels could potentially improve sleep efficiency and lower levels of tiredness, as serotonin is known to have both mood-boosting and sleep-enhancing properties.[38,39]

This study found that allocating more time to MVPA (relative to remaining sedentary) was associated with lower levels of tiredness in adults, despite also being associated with more efficient sleep (although the effect sizes were very small). This may seem counterintuitive, as

Table 2
The association between 24-hour activity behaviors and dimensions of healthy sleep using compositional data analysis

		Sleep ilr[a]		MVPA ilr		Sedentary ilr		LPA ilr		Activity composition
		Estimate	95% CI[b]	Estimate	95% CI[b]	Estimate	95% CI[b]	Estimate	95% CI[b]	*P*-value
Children										
Troubled sleep	Model 1	− 0.03	− 0.08, 0.02	**− 0.07**	**− 0.13, − 0.01**	0.03	− 0.01, 0.06	0.02	− 0.02, 0.07	**.001**
	Model 2	− 0.02	− 0.07, 0.03	− 0.04	− 0.11, 0.03	0.03	− 0.01, 0.06	0.01	− 0.04, 0.06	**.049**
Tired	Model 1	0.00	− 0.04, 0.04	**− 0.06**	**− 0.11, − 0.01**	0.02	− 0.01, 0.05	− 0.01	− 0.05, 0.02	**< .0001**
	Model 2	0.01	− 0.03, 0.05	− 0.04	− 0.10, 0.01	0.01	− 0.02, 0.04	− 0.02	− 0.06, 0.02	**.005**
Sleep efficiency	Model 1	**− 0.62**	**− 0.90, − 0.35**	0.10	− 0.23, 0.43	**0.43**	**0.22, 0.63**	**0.29**	**0.05, 0.54**	**< .0001**
	Model 2	**− 0.70**	**− 0.97, − 0.43**	0.25	− 0.12 0.62	**0.51**	**0.30, 0.71**	0.25	− 0.01, 0.50	**< .0001**
Sleep onset	Model 1	**− 15.49**	**−17.79, − 13.19**	1.07	− 1.71, 3.86	**12.57**	**10.84, 14.30**	**4.58**	**2.52, 6.65**	**< .0001**
	Model 2	**− 15.81**	**−18.10, − 13.51**	2.18	− 0.91, 5.27	**12.89**	**11.14, 14.63**	**4.26**	**2.09, 6.42**	**< .0001**
Sleep offset	Model 1	**11.60**	**9.45, 13.75**	**− 7.59**	**−10.19, − 4.98**	**− 4.90**	**− 6.52, − 3.28**	**− 8.65**	**−10.59, − 6.72**	**< .0001**
	Model 2	**11.20**	**9.06, 13.34**	**− 6.41**	**− 9.30, − 3.53**	**− 4.48**	**− 6.11, − 2.85**	**− 9.02**	**−11.03, − 7.00**	**< .0001**
Sleep variability	Model 1	**− 0.53**	**− 0.82, − 0.25**	− 0.09	− 0.43, 0.26	**0.34**	**0.13, 0.56**	**0.34**	**0.08, 0.59**	**< .0001**
	Model 2	**− 0.53**	**− 0.81, − 0.24**	− 0.09	− 0.48, 0.29	**0.35**	**0.13, 0.57**	**0.32**	**0.05, 0.59**	**< .0001**
Adults										
Troubled sleep	Model 1	**0.04**	**0.01, 0.07**	**− 0.04**	**− 0.07, 0.00**	− 0.01	− 0.04, 0.01	− 0.02	− 0.05, 0.02	**.003**
	Model 2	0.03	− 0.00, 0.06	− 0.02	− 0.06, 0.01	− 0.00	− 0.03, 0.02	− 0.03	− 0.06, 0.01	**.007**
Tired	Model 1	0.01	− 0.02, 0.05	**− 0.05**	**− 0.09, − 0.01**	− 0.01	− 0.03, 0.01	0.02	− 0.01, 0.06	**.009**
	Model 2	0.01	− 0.03, 0.04	**− 0.04**	**− 0.08, − 0.01**	− 0.00	− 0.03, 0.02	0.02	− 0.02, 0.05	**.033**
Sleep efficiency	Model 1	**− 0.44**	**− 0.68, − 0.19**	**0.30**	**0.03, 0.57**	**0.34**	**0.17, 0.51**	− 0.02	− 0.27, 0.23	**< .0001**
	Model 2	**− 0.46**	**− 0.71, − 0.22**	**0.30**	**0.02, 0.57**	**0.34**	**0.17, 0.52**	0.01	− 0.24, 0.26	**< .0001**
Sleep onset	Model 1	**− 13.81**	**−15.85, − 11.78**	**2.46**	**0.20, 4.72**	**9.09**	**7.66, 10.53**	**5.26**	**3.17, 7.35**	**< .0001**
	Model 2	**− 14.15**	**−16.18, − 12.11**	**2.55**	**0.28, 4.82**	**9.30**	**7.84, 10.75**	**5.39**	**3.30, 7.48**	**< .0001**
Sleep offset	Model 1	**13.67**	**11.79, 15.54**	**− 6.77**	**− 8.86, − 4.69**	**− 6.56**	**− 7.88, − 5.24**	**− 6.68**	**− 8.61, − 4.76**	**< .0001**
	Model 2	**13.19**	**11.32, 15.05**	**− 6.71**	**− 8.79, − 4.63**	**− 6.30**	**− 7.63, − 4.97**	**− 6.40**	**− 8.32, − 4.49**	**< .0001**
Sleep variability	Model 1	**− 0.32**	**− 0.60, − 0.04**	0.08	− 0.23, 0.39	**0.26**	**0.06, 0.45**	0.04	− 0.24, 0.33	**.011**
	Model 2	**− 0.35**	**− 0.63, − 0.07**	0.07	− 0.24, 0.38	**0.27**	**0.07, 0.47**	0.06	− 0.23, 0.35	**.006**

LPA, light physical activity; MVPA, moderate-vigorous physical activity.
Each parameter estimate and confidence interval correspond to pivot ilrs. The estimate indicate the association of increasing in one activity, relative to the remaining activities.
Model 1 = unadjusted model, Model 2 = adjusted model (sex, season, age for parents, puberty stage for children).
Bold indicates significant associations (P-value ≤ 0.05).

[a] Sleep duration was measured in terms of sleep period, the difference between sleep onset and offset.

[b] 95% CIs are Bonferroni adjusted to be 100 × (1 − 0.05/k)% confidence intervals where k is the number of pivot ilr models hypothesis tests per model.

popular belief often holds that an increase in physical activity should promote sleep quality by inducing fatigue or tiredness.[14] However, the serotonin-mediated improvement in sleep efficiency could explain why individuals felt less tired.

Since tiredness was assessed on the day of the assessment (before measures of time use), the possibility of reverse causality should be considered. It is also important to note that feeling tired on a specific day may be influenced by the quality of sleep from the preceding night, which may differ from the "usual" sleep patterns captured in the activity composition examined in this study.

Time reallocations in naturalistic settings are likely to be complex. For example, Olds and colleagues[40] examined changes in time use across retirement and found time no longer spent at work was reallocated across a range of different behaviors at varying rates. This study suggests that time reallocations are unlikely to be direct (one-for-one) trade-offs, but instead involve complex reallocations among all remaining behaviors throughout the whole day. The one-for-remaining reallocation pattern used in this study is commonly used in CoDA studies, as it is analogous to observing variation in one behavior of interest, while "adjusting" for all the remaining behaviors equally (proportionately). It is likely that real-world reallocations of time use are more intricate and influenced by sociodemographic factors, such as gender. In particular, known gender-related differences in sleep[41,42] and activity patterns[43,44] may contribute to gender-specific differences in time reallocations. Given that the adults examined in this study are mostly mothers, our findings may carry nuances specific to this population. However, interactions with gender were only detected for bedtime and troubled sleep (results not presented).

Strengths and limitations

To our knowledge, this is the first study that examines the association between the 24-hour activity composition and dimensions of healthy sleep in a large sample of Australian children and adults. This study has a number of strengths, including its large sample size, high-quality sampling strategy, examination of both children and adults, assessment of a range of objective and subjective sleep characteristics and the use of compositional data analysis, a holistic method of analyzing 24-hour time-use data. However, there are also a number of limitations that need to be acknowledged. Firstly, the adult participants appeared to be notably active, partaking in over 2 hours of MVPA daily. While this might initially suggest an exceptionally active sample, it's essential to consider that these high values could be influenced by the accelerometry cutpoints used in the study. Thus, the perceived elevated activity levels is likely to be more a reflection of the methodology rather than indicating that the sample was extraordinarily active. Additionally, since the adults in this study were predominantly mothers with children aged 11-12 years, generalizing the findings to a broader adult population may not be appropriate. It is also important to note that CheckPoint participants displayed a higher SEP compared to the broader LSAC cohort, which may influence the generalizability of our findings to populations with varied socioeconomic backgrounds. Secondly, although we attempted to examine each dimension of sleep as proposed by Buysse,[5] there is currently no standard way of measuring each dimension and it could be argued that our measures of sleep alertness/sleepiness (ie, feeling tired) and satisfaction/quality (ie, troubled sleep) are limited. Further, although similar, it should be noted that the dimensions proposed for children[45] are slightly different to those proposed for adults and this study only took into account dimensions that are applicable to both children and adults. Thirdly, while the "one-for-remaining" approach is a commonly used method to examine time use reallocations and provides a broad overview, real-world reallocations of time use are potentially more intricate. Further, although the GENEActiv monitor has been used in previous studies to examine sleep[11,24,46–48,49,50] and validated in adults[46,51,52] it has not yet been validated in children. Lastly, this study is cross-sectional and results cannot imply causality.

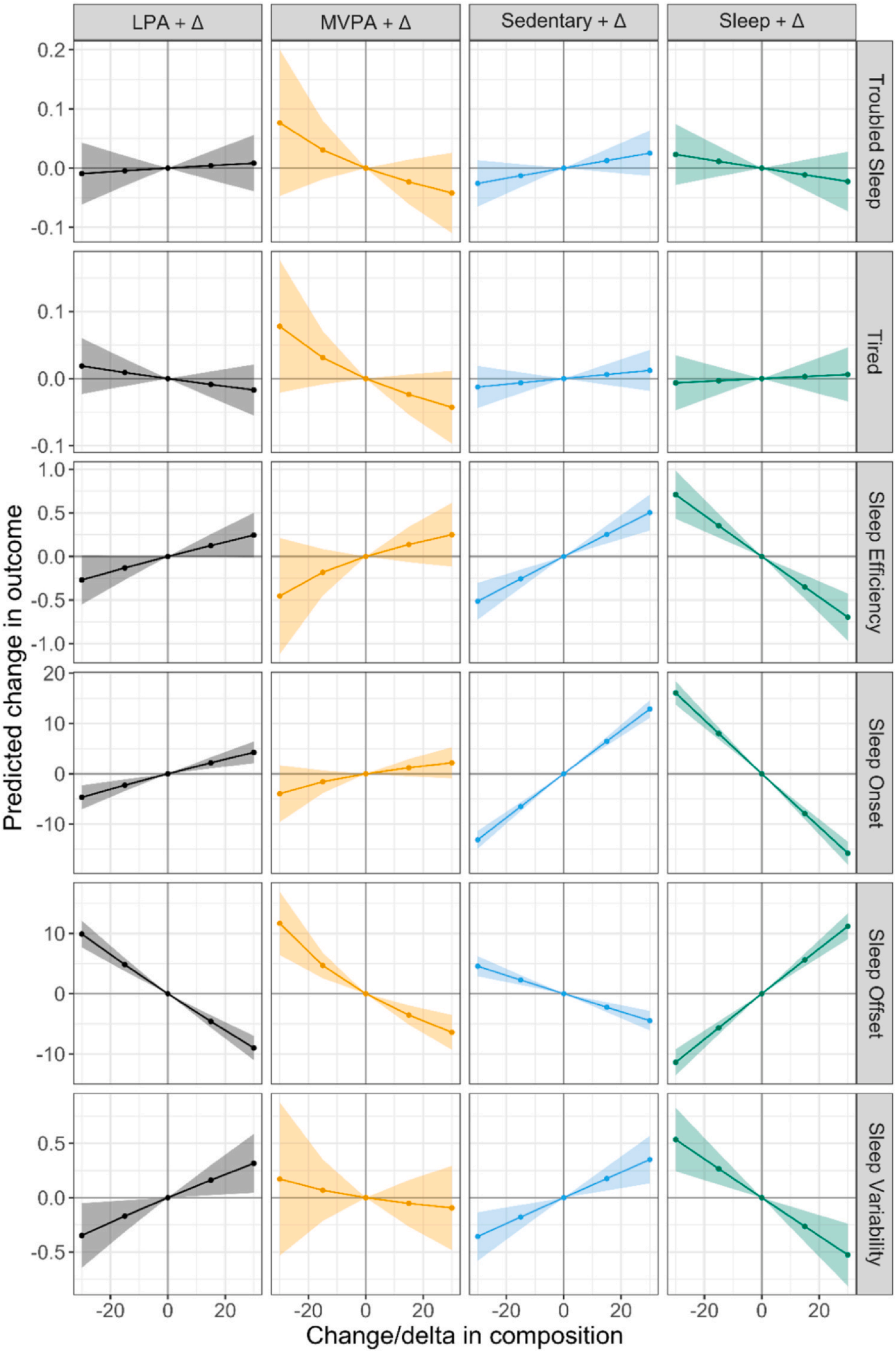

Fig. 1. One-for-remaining time reallocations for children, adjusted model predicted changes for each sleep dimension outcome (confidence intervals are Bonferroni adjusted). LPA, light physical activity; MVPA, moderate-vigorous physical activity; sedentary, sedentary time; sleep, sleep duration, measured in terms of sleep period, the difference between sleep onset and offset

Clinical implications

This study suggests that the 24-hour activity composition is associated with dimensions of healthy sleep in both children and adults. These findings seem to highlight the importance of considering specific activity trade-offs. In the same way that activity trade-offs are being examined to optimize health, the 24-hour day may be constructed in a way to optimize sleep. For practitioners working with children and families, these findings could offer valuable insights into tailoring interventions aimed at improving sleep. It underscores the significance of adopting both age-specific strategies, especially for children, and more holistic 24-hour activity strategies when addressing sleep-related issues. Future efforts that consider different time-use trade-offs (eg, one-for-one instead of one-for-all reallocations) may shed further insight. This may have important clinical implications and offer a novel solution for individuals prone to experiencing poor sleep, which may in turn have additional effects on improving health.

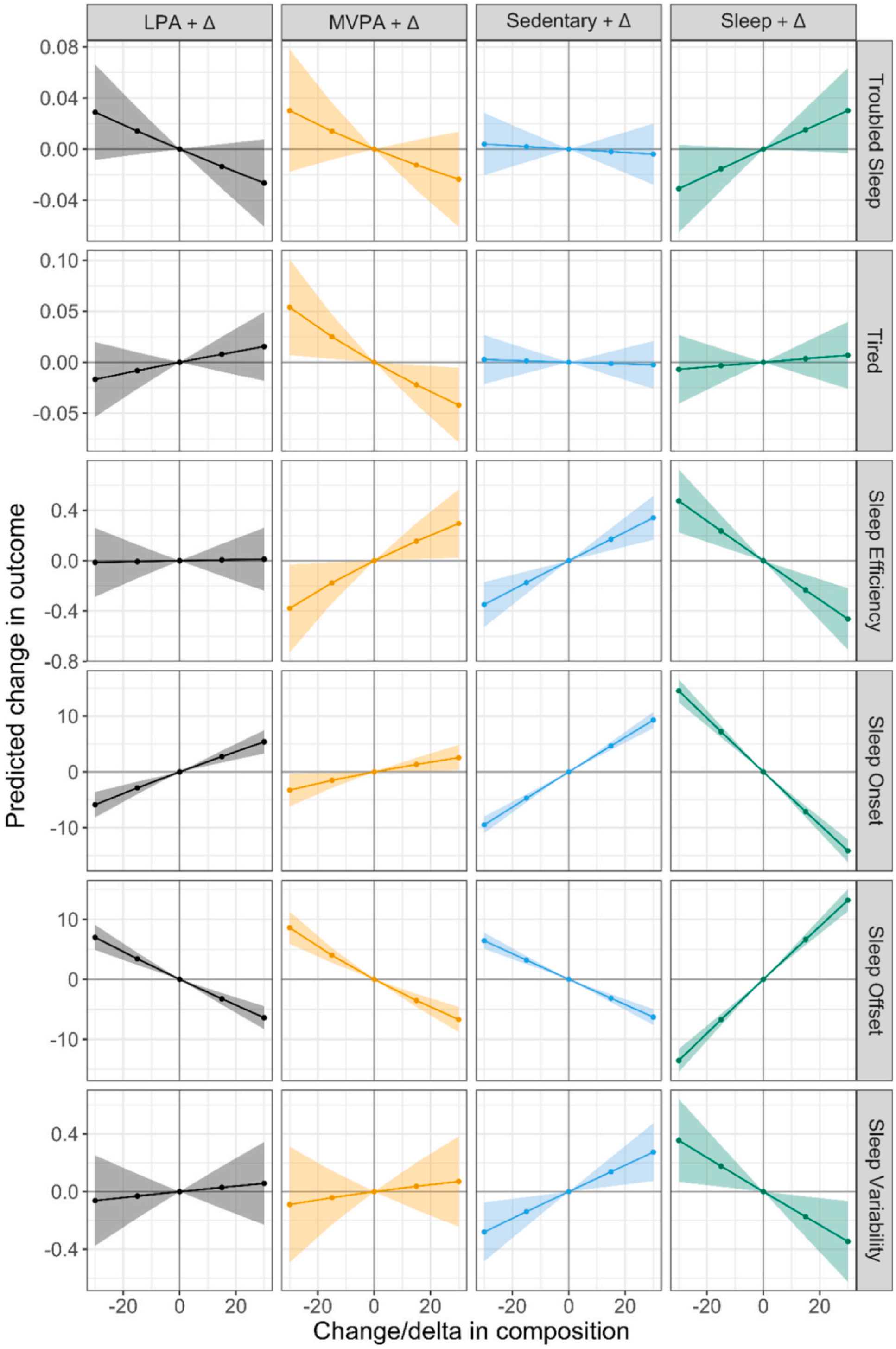

Fig. 2. One-for-remaining time reallocations for adults, adjusted model predicted changes for each sleep dimension outcome (confidence intervals are Bonferroni adjusted). LPA, light physical activity; MVPA, moderate-vigorous physical activity; sedentary, sedentary time; sleep, sleep duration, measured in terms of sleep period, the difference between sleep onset and offset

Conclusion

Sleep is often viewed as a separate entity from the 24-hour day. However, our study highlights the integral relationship between sleep and daily activities. Our findings suggest that the composition of our daily activities may have a significant impact on the multiple dimensions of sleep, emphasizing the importance of considering the integrated effects of time use. This new knowledge warrants further investigations into whether the structure of our days can help achieve healthy sleep, to enhance physical and mental wellbeing.

Author contributions

LM conceived and conceptualized the study, prepared the initial draft, participated in the writing and preparation of the manuscript and the analysis and interpretation of data; DD, TS, CM, PB, LB participated in the writing and preparation of the manuscript and the analysis and interpretation of the data; TO helped conceptualize the study, participated in the writing and preparation of the manuscript and the analysis and interpretation of the data.

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Declaration of conflict of interest

The authors have no conflicts to declare.

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