Predictors for achieving optimal sleep in healthy children: Exploring sleep patterns in a sleep extension trial

Barbara C. Galland, PhD⁎, Jillian J. Haszard, PhD, Rosie Jackson, MDiet, Silke Morrison, PhD, Kim Meredith-Jones, PhD, Dawn E. Elder, FRACP, PhD, Dean Beebe, PhD, Rachael W. Taylor, PhD

⁎Corresponding author: Barbara Galland, PhD, Department of Women’s & Children’s Health, Dunedin School of Medicine, University of Otago, Dunedin, New Zealand.

E-mail address: barbara.galland@otago.ac.nz (B.C. Galland).

© 2023 The Author(s). Published by Elsevier Inc. on behalf of National Sleep Foundation. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

A R T I C L E   I N F O

Article history:
Received 10 January 2023
Received in revised form 19 July 2023
Accepted 24 September 2023

Keywords:
Actigraphy
Bedtime
Sleep health
Sleep guidelines
Sleep manipulation
Sleep need

A B S T R A C T

Study objectives: Earlier bedtimes can help some children get more sleep, but we don’t know which children, or what features of their usual sleep patterns could predict success with this approach. Using data from a randomized crossover trial of sleep manipulation, we sought to determine this.

Methods: Participants were 99 children aged 8-12 years (49.5% female) with no sleep disturbances. Sleep was measured by actigraphy at baseline and over a restriction or extension week (1 hour later or earlier bedtime respectively), randomly allocated and separated by a washout week. Data were compared between baseline (week 1) and extension weeks only (week 3 or 5), using linear or logistic regression analyses as appropriate, controlling for randomization order.

Results: One hour less total sleep time than average at baseline predicted 29.7 minutes (95% CI: 19.4, 40.1) of sleep gained and 3.45 (95% CI: 1.74, 6.81) times higher odds of successfully extending sleep by > 30 minutes. Per standardized variable, less total sleep time and a shorter sleep period time were the strongest predictors (significant odds ratios (ORs) of 2.51 and 2.28, respectively). Later sleep offset, more variability in sleep timing and lower sleep efficiency also predicted sleep gains. The sleep period time cut-point that optimized prediction of successful sleep gains was < 8 hours 28 minutes with 75% of children’s baseline sleep in that range.

Conclusions: Children with a baseline sleep period time < 8½ hours a night obtained the most sleep from earlier bedtimes maintained over a week, demonstrating experimentally the value of earlier bedtimes to improve sleep.


© 2023 The Author(s). Published by Elsevier Inc. on behalf of National Sleep Foundation. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Introduction

It is well documented that many children do not get as much sleep as public health guidelines recommend, with data from several epidemiological studies reporting that up to 50% do not meet the recommended sleep duration for their age.1-4 Most countries, including Aotearoa New Zealand follow the American National Sleep Foundation or American Academy of Sleep Medicine guidelines that recommend children aged 6-13 years obtain between 9 and 11 hours of sleep per night for optimal performance and health.5,6 Undeniably, longer sleep or regularly meeting sleep duration recommendations is associated with better outcomes including improved attention, behavior, learning, memory, emotional regulation, quality of life, and mental and physical health.6-8 In contrast, shorter sleep or regularly sleeping fewer than the number of recommended hours is associated with attention, behavior, and learning problems, a higher risk of obesity and many other factors.6-8 Whilst sleep...
duration is most commonly measured in relation to these outcomes, healthy sleep in children also requires appropriate timing, good quality, regularity (in sleep schedules and consistent bedtime routines), and the absence of sleep disturbances and disorders.9

Children receiving less than their optimal amount of sleep during the school week may accumulate a sleep debt or deficit (the cumulative effect of not getting enough sleep), as estimated through their ability to catch up sleep when given the opportunity to do so.10

In a research setting, this can involve experimental manipulation of sleep through extending time in bed, but most children still need to get up to go to school, meaning manipulations are more difficult at the wake end of sleep. Therefore, earlier bedtimes with consistent wake-up times11-14 are strategies used to extend sleep. The few sleep manipulation studies involving healthy children used randomized crossover trial designs with both a restriction and an extension (a.k.a. optimized sleep15 condition (3-7 days of each) separated by a washout period.11-14

Sleep manipulation studies have been used successfully to inform important areas of child and adolescent cognition, behavior and health, including seminal research on the neurocognitive consequences of sleep loss in children,14 and contributions of sleep loss to emotional health14 academic performance,12 and eating behaviors.15 As far as we are aware, no studies have exploited these datasets to focus specifically on what features of a child’s sleep patterns predict success with sleep extension. As a result, there is little empirical guidance on who might benefit the most from earlier bedtimes to attain greater sleep quantity with an extension condition. Such information would provide pragmatic guidance to both public health guidelines around good sleep health and treatment approaches to circadian rhythm issues that use phase shifting at bedtime.16

Intuitively, we might expect that children with the least amount of sleep for their age, would benefit the most from sleep extension. However, the amount children sleep is highly variable,17,18 and not every child is able to extend their sleep even if compliant to a protocol, because they may have sleep onset issues due to behavioral sleep disorders, already have optimal sleep, or need far less sleep than their peers to function well.10 In a recent randomized crossover trial,20 we induced a sleep difference in 8- to 12-year-old children (n = 105) by manipulating their bedtime (1 hour earlier and 1 hour later than measured during a baseline week) over 7 days for each condition (sleep extension and sleep restriction, respectively), with 1 week of washout in between. Over the extension week, 63% of children were able to extend their sleep from normal by an average of 38 minutes per night, with some children not being able to extend at all (37%). Examining that dataset further, the current study aims to determine which characteristics of children’s baseline sleep patterns predict the best sleep gains in the sleep extension week, including beneficial gains of more than 30 minutes per night, hypothesizing that metrics related to shorter sleep quantity, poorer sleep quality and timing, and more variability will be implicated, although the strongest predictor is unknown. Sleep gains are referred to throughout as increases in total sleep time (TST; ie, the true amount of sleep attained between going to sleep at night and waking in the morning, and thus excludes any periods of waking overnight).

Methods

The study was conducted between October 2018 until March 2020. The full study (DREAM study) used a randomized crossover trial design. The protocol and primary outcomes and secondary outcomes (eating behaviors) for the full study are published14,15,17,20 and comply with the Consolidated Standards of Reporting (CONSORT) requirements for extension to randomized crossover trials.21 Primary caregivers provided written informed consent, and the child gave written assent. Participants and caregivers received gift vouchers (NZS100 and $50, respectively) on completion of the full study. Ethical approval was granted from the University of Otago Ethics Committee (reference #18/146).

Participant recruitment

Participants (children aged 8-12 years) and their families were recruited by targeted advertisements on social media and via parent community networks. Parents completed an online questionnaire via a link on the web-based platform REDCap (Vanderbilt University, Nashville, TN) that screened for their child’s eligibility. Inclusion criteria were children aged 8-12 years of age, living in the greater Dunedin area with a parent-reported time in bed of 8-11 hours per night. Excluding children who were usually in bed for <8 hours/night was a safety consideration for the restriction week of the full study. Exclusion criteria were any medical condition or medication that affects sleep or eating behavior; presence of a diagnosed sleep disorder, or determined by a total score >39 on the Sleep Disturbance Scale for Children (SDSC)22 with borderline scores reviewed by a Pediatric Sleep Specialist (DEE). The SDSC is a 26-item scale developed to assess the presence of sleep difficulties in children (aged 6-15 years) within the previous 6 months.

Procedures

The full study followed a 5-week protocol: a baseline week (week 1); randomization and study instruction week (week 2); first intervention week (week 3); washout week (week 4); second intervention week (week 5). For logistical reasons, accommodating family schedules and illness, some had more than 1 week following the baseline week before the first intervention, but the majority followed this 5-week schedule continuously. Here, we focus on the methods relevant to additional analyses of the sleep data, and only utilizing data from the baseline (week 1) and extension weeks (week 3 or 5) of the trial.

Baseline week

During a child and parent clinic visit, children’s height and weight were measured and instructions for completing a sleep diary (parent help if required) and wearing the actigraph for 1 week (see Measures and contributing authors for details) were given. Sleep diaries recorded lights off and wake times and any discrepancies from normal (eg, sleepover with a friend). Questionnaires described below were also completed at this visit.

Randomization and sleep instructions

Children were randomized to one of two groups (sleep extension or sleep restriction) stratified by age group (8-10 and 11-12 years) and gender using the randomization module in REDCap.23 Randomization tables were generated by the study biostatistician (JJH) using random blocks lengths (Stata 15.1; StataCorp) in a 1:1 allocation.

The sleep diary was used to determine each child’s usual bedtime/“lights off” and wake time during weekdays and weekend days, calculating median values for each and checking against the actigraphy data collected during the baseline week. The researcher confirmed the times with the parent in the face-face visit, to ensure median times reflected the “usual” lights off and wake-time routines for their child. For example, if the child did not turn the lights off until 11:30 PM during a sleepover on a weekend night during the baseline week, but usual lights off was 10:00 PM at the weekend, the child’s bedtime was adjusted for 10:00 PM. Based on their randomization group, each child was instructed to go to bed 1 hour later or earlier than their usual week and weekend bedtime for seven nights (week 3), while maintaining their usual wake-up time during the week and weekend. Personalized daily bedtime text reminders were sent via the MightyText (https://mightytext.net/) service approximately 2 hours before “lights off” time to encourage adherence. Following a week of...
no intervention and no measurements (week 4; washout) the child then underwent the opposite intervention (week 5).

**Sleep extension week**

Sleep diary and actigraphy data were collected over 7 days as for the baseline week. At the end of the sleep extension week, the child and caregiver returned for a clinic visit and returned the actigraphy and diaries and completed measures related to the full study.20

**Measures**

**Questionnaires**

Caregivers completed an online questionnaire at the baseline visit covering child and caregiver demographic information. Household address was also obtained to calculate the New Zealand Deprivation Index (2018)24; a deprivation score as a proxy for SES. Scores range between 1 and 10, where 1 indicates an area is one of the 10% least deprived, and 10 indicates an area is one of the 10% most deprived.

The Children’s Sleep Hygiene Scale (CSHS),25 a 22-item parent-report measure assessing sleep-facilitating and sleep-inhibiting practices of children aged 2–12 years was completed. Parents report how often sleep-related behaviors have occurred during the past month along a six-point scale assessing good sleep hygiene practices. The CSHS provides scores in six domains that include physiological, cognitive emotional, environmental, bedtime routine, and sleep stability, as well as a total scale score. While higher scores indicate better sleep hygiene there are no cut-off scores to indicate clinically significant poor sleep hygiene. The scale has been good internal reliability yielding a total Cronbach’s α of 0.72.

**Anthropometry**

Body mass index (BMI) z-scores were calculated using WHO growth standards for children aged 5–19 years with underweight defined as ≤−2 SD, normal weight as > −2 SD to +1 SD, overweight as > +1 SD to 2 SD, and children with obesity as > +2 SD.26

**Sleep measured at baseline and extension weeks**

An actigraph (the ActiGraph wGT3X-BT) was worn on the right hip 24 hours/day for each week. The hip, rather than the wrist was chosen because in our previous validation study against gold standard polysomnography, this device worn at the hip had very accurate sleep onset timing and better wake timing than when worn at the wrist, and therefore sleep period time (SPT) was also more accurate27; factors important for this study’s protocol focused on sleep and wake timing. Actigraphy data were processed in the automated mode using our count-scaled algorithm developed in MATLAB (MathWorks, Natick, MA), described in greater detail elsewhere.28 Sleep variables defined below included those related to dimensions of (a) sleep timing: sleep onset and sleep offset, (b) sleep quantity; SPT and TST and, (c) sleep quality; waking after sleep onset (WASO), number of awakenings and sleep efficiency.

- **SPT:** the elapsed time between sleep onset and sleep offset
- **TST:** represents true sleep time and is calculated as SPT minus WASO
- **Sleep efficiency:** the percent of time asleep between sleep onset and offset and thus excludes sleep latency
- **WASO:** number of minutes scored as awake between sleep onset and offset
- **Sleep onset:** clock time of first consecutive minutes scored as evening sleep
- **Sleep offset:** clock time of first consecutive minutes scored as morning wake
- **Number of awakenings:** number of awakenings between sleep onset and offset

- **Sleep timing variability:** summed standard deviations of sleep onsets and offsets

**Statistical analysis**

All statistical analysis was undertaken in Stata 17.0 (StataCorp, TX). Demographic predictors of length of sleep extension were assessed using linear regression models adjusted for randomized order. Baseline sleep predictors of length of sleep extension were also assessed using linear regression models adjusted for randomized order and reported using both standardized and unstandardized predictors. Estimates were also determined with adjustment for age, sex, BMI z-score, and area level of deprivation. Residuals of models were plotted and visually assessed for homoskedasticity and normality.

Predictors of a “successful” sleep extension, that is, more than 30 minutes (a binary outcome), were estimated as for continuous sleep extension but using logistic regression models and calculating odds ratios and 95% CI.

Receiver operating characteristic (ROC) analyses were undertaken for SPT at baseline predicting a successful sleep extension greater than 30 minutes. A ROC curve was generated and AUC calculated with 95% CI. An optimal cut-point for predicting those who successfully extended their sleep was determined using the Liu method.29

**Results**

For the full study, 399 children were assessed for eligibility with 293 not reaching inclusion criteria, 272 (56.9%) of whom had SDSC scores ≥39. Thirty-two (8.0%) were excluded because their parents reported their child regularly slept <8 hours. Of the 105 children who completed the full study, 99 had complete data suitable for this analysis meeting criteria for matching valid actigraphy sleep data (minimum 3 days) at both baseline and extension weeks. The median (25th, 75th percentile) number of valid days of actigraphy at baseline was 6 (5, 6), and exactly the same at extension.

**Participant characteristics**

The mean age was 10.3 years and 49 (49.5%) were female (Table 1). The majority identified as New Zealand European ethnicity (74.8%), and 38.5% resided in areas of low deprivation (New Zealand Deprivation Index levels 1-3). Twenty-four (24.2%) children were overweight and 15 (15.2%) were obese. The mean (SD) Sleep Disturbance Scale for Children scores for all children was 34.3 (3.5).

**Baseline sleep**

A descriptive summary of actigraphy-derived sleep measures related to sleep quantity, quality, timing, and variability at baseline are given in Supplementary Table 1. The mean (SD) number of hours slept between sleep onset and offset (SPT) was 9 hours 39 minutes (37 minutes) with 74% having between 9 and 11 hours, with a true/total sleep time (TST) of 9 hours (33 minutes) yielding a sleep efficiency of 95.8% (4.3%). For sleep quality, 80.8% of children had 0 or 1 waking per night that by actigraphy variable definition met the guideline definition30 of ≥5 minutes duration, and 97.0% with recommended sleep efficiencies ≥85%.

Sleep hygiene scores at baseline are also given in Supplementary Table 1 demonstrating overall good sleep hygiene for all scales. Mean scores in subscales ranged from 4.5 to 5.3 with a total mean score of 5 out of a possible 6. A score of 4 reflects a mean response of “quite often” to a good sleep hygiene practice, and for a score of 5, “frequently if not always.”
Effects of the sleep extension

A descripti ve summary of actigraphy-derived sleep measures related to sleep quantity, quality, timing, and variability during the sleep extension week are given in Supplementary Table 1. An overall mean (SD) increase of 15.5 (39.8) minutes/night TST was achieved with a sleep difference between baseline and extension ranging from −75 to 203 minutes. This comprised 33 participants (33.3%) who successfully extended their sleep by >30 minutes/night, of which 30 (90.9%) had baseline less than this at baseline, of which 30 (40.5%) successfully extended their sleep. Over all, 33 (33.3%) participants successfully extended their sleep. For sleep timing, earlier sleep offset (morning waking) was significantly predicted sleep gains, that is, for each 1 hour earlier waking at baseline, 16.2 minutes (95% CI: 19.4, 40.1) extra sleep was gained during the extension week, and variability in sleep timing overall (summed standard deviations of onset and offsets) predicted sleep gains, whereas sleep onset time per se did not. Adjusting for relevant demographic factors, sleep hygiene scores and school term time (4 terms across a year) made little difference to the outcomes (Supplementary Table 2).

Participant characteristics: associations with sleep gains

Table 1 also reports the associations between participant characteristics and sleep gains (ie, TST increases) made during the extension week. Each measure is analyzed relative to the reference group and effect sizes reported as mean differences (for minutes of TST), or odds ratios (able to successfully extend their sleep or not).

There were no significant associations with any demographic characteristics. The order of randomization for the sleep intervention week also did not significantly influence a child's ability to increase their sleep.

Sleep variables predicting sleep gains

Table 2 reports actigraphy sleep variables and sleep hygiene factors at baseline as potential predictors of sleep gains (TST) made during the extension week. Estimates are presented in the direction indicative of less/poorer sleep at baseline and adjusted for randomization order. For example, in relation to sleep quantity, for each 1 hour less sleep per night at baseline (unstandardized TST), 29.7 minutes (95% CI: 19.4, 40.1) of nightly sleep was gained with sleep extension and the odds of successfully extending their sleep was 3.45 (95% CI: 1.74, 6.81) times higher. A shorter SPT at baseline also significantly predicted sleep gains as did all sleep quality variables, that is, lower sleep efficiency, more wakeups or more WASO were predictive of sleep gains and odds of being able to successfully extend sleep. For sleep timing, earlier sleep offset (morning waking) significantly predicted sleep gains, that is, for each 1 hour earlier waking at baseline, 16.2 minutes (95% CI: 19.4, 40.1) extra sleep was gained during the extension week, and variability in sleep timing overall (summed standard deviations of onset and offsets) predicted sleep gains, whereas sleep onset time per se did not. Adjusting for relevant demographic factors, sleep hygiene scores and school term time (4 terms across a year) made little difference to the outcomes (Supplementary Table 2).

For standardized analyses, all variables excluding sleep onset significantly predicted sleep gains (Table 2). Less TST at baseline had the greatest influence on sleep gains followed by lower sleep efficiency and a shorter SPT and longer WASO, with earlier sleep offset having the least influence. Less TST, a shorter SPT and lower sleep efficiency were also significantly associated with higher odds of children successfully extending their sleep.

Optimal SPT for a successful sleep extension of > 30 minutes/night

Having demonstrated with logistic regression models that a shorter sleep period significantly predicted children being able to successfully extend their sleep, ROC curves were generated to determine the optimal cut point for this; calculated at 8 hours 28 minutes with an acceptable degree of accuracy (AUC, 0.726; 95% CI 0.617, 0.834). Seventy-four (74.8%) participants had sleep periods less than this at baseline, of which 30 (40.5%) successfully extended their sleep. Overall, 33 (33.3%) participants successfully extended their sleep by >30 minutes/night, of which 30 (90.9%) had baseline SPTs <8 hours 28 minutes.

### Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean difference (95% CI)</th>
<th>Odds ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, mean (SD) years</td>
<td>10.3 (1.4)</td>
<td>0.5 (-5.8, 6.9)</td>
</tr>
<tr>
<td>Sex, n (%)</td>
<td></td>
<td>1.09 (0.81, 1.47)</td>
</tr>
<tr>
<td>Female</td>
<td>49 (49.5)</td>
<td>Reference</td>
</tr>
<tr>
<td>Male</td>
<td>50 (50.5)</td>
<td>-0.3 (-18.7, 16.9)</td>
</tr>
<tr>
<td>Ethnicity, n (%)</td>
<td></td>
<td>Reference</td>
</tr>
<tr>
<td>New Zealand European</td>
<td>74 (74.8)</td>
<td>Reference</td>
</tr>
<tr>
<td>Mori</td>
<td>16 (16.2)</td>
<td>9.0 (-15.8, 33.9)</td>
</tr>
<tr>
<td>Others</td>
<td>9 (9.1)</td>
<td>17.4 (-15.1, 49.8)</td>
</tr>
<tr>
<td>Area-level deprivation, n (%)</td>
<td></td>
<td>Reference</td>
</tr>
<tr>
<td>Low (1-3)</td>
<td>38 (38.4)</td>
<td>Reference</td>
</tr>
<tr>
<td>Medium (4-7)</td>
<td>41 (41.4)</td>
<td>-16.2 (-35.9, 3.5)</td>
</tr>
<tr>
<td>High (8-10)</td>
<td>20 (20.2)</td>
<td>2.5 (-21.7, 26.6)</td>
</tr>
<tr>
<td>Maternal education, n (%)</td>
<td></td>
<td>Reference</td>
</tr>
<tr>
<td>Secondary school</td>
<td>22 (22.9)</td>
<td>Reference</td>
</tr>
<tr>
<td>Post-secondary</td>
<td>26 (27.1)</td>
<td>-3.9 (-28.8, 21.1)</td>
</tr>
<tr>
<td>University degree</td>
<td>48 (50.5)</td>
<td>-19.5 (-41.7, 2.7)</td>
</tr>
<tr>
<td>Child BMI z-score, mean (SD)</td>
<td>0.72 (1.17)</td>
<td>2.6 (-5.1, 10.2)</td>
</tr>
<tr>
<td>Child weight status, n (%)</td>
<td></td>
<td>Reference</td>
</tr>
<tr>
<td>Normal weight</td>
<td>60 (60.6)</td>
<td>Reference</td>
</tr>
<tr>
<td>Overweight</td>
<td>24 (24.2)</td>
<td>0.2 (-21.3, 21.7)</td>
</tr>
<tr>
<td>Obese</td>
<td>15 (15.2)</td>
<td>2.0 (-23.7, 27.8)</td>
</tr>
<tr>
<td>Randomized order, n (%)</td>
<td></td>
<td>Reference</td>
</tr>
<tr>
<td>Restriction first</td>
<td>49 (49.5)</td>
<td>Reference</td>
</tr>
<tr>
<td>Extension first</td>
<td>50 (50.5)</td>
<td>0.0 (-17.7, 17.7)</td>
</tr>
</tbody>
</table>

* Mean (SD) sleep extension = 15.5 (39.8) min, ranging from -75 min to 203 min. Mean differences (95% CI) determined using regression models adjusted for randomized order.

1 Thirty-three participants (33.3%) extended their sleep by more than 30 min. Odds ratios (95% CI) determined using logistic regression models adjusted for randomized order.

2 New Zealand Deprivation Index.

3 Three participants had unknown maternal education.

4 BMI z-score determined using WHO growth charts; overweight classified as BMI z-score > 1 & ≤ 2 and obese classified as BMI z-score > 2.
bed 1 hour earlier than baseline (sleep extension week). We found all four dimensions of sleep – quantity, quality, timing (waking), and sleep variability (sleep timing variability) – significantly predicted sleep gains. All changes were in the expected direction: less sleep, shorter sleep period, poorer quality and earlier waking at baseline predicted more sleep gains. Per standardized variable, less sleep and a shorter sleep period were the strongest predictors of successful sleep gains (>30 minutes/night), followed by longer WASO and lower sleep efficiency. The intervention did not target WASO, but the fact that longer WASO at baseline predicted more sleep gains when children were given more sleep opportunities (sleep extension), provides further support that many children’s sleep at baseline was not optimal, and they were likely carrying a sleep debt.

A third of our sample were able to extend their sleep by more than 30 minutes per night, a level that in previous sleep manipulation studies has been shown to significantly improve children’s performance on executive function measures of working memory and attention. Not surprisingly, restricting sleep by this amount has deleterious effects on children’s cognitive processing. Whilst it could be argued that the financial incentive offered may have increased adherence to the protocol for children that attained extra sleep (63%), but even with additional time in bed, some children could not extend their sleep. This is perhaps not surprising since children with sleep disturbance and those usually spending less than 8 hours in bed were not included in this study. It also likely reflects that some children’s sleep is already sufficient and/or an inability to comply with the experimental conditions of sleep extension with some receiving less than at baseline during the extension week. Anecdotally, and related to the full study, parents found the extension week the most difficult to comply with, compared to the restriction week.

Children’s ability to lengthen their sleep when given the opportunity to do so likely reflects a very real sleep debt many children experience on a regular basis, and suggests their baseline sleep was not meeting their sleep needs, despite those who regularly slept <8 hours (parent report) having been screened out. The recommended guidelines for sleep duration are between 9 and 11 hours for this age group. A quarter of our sample slept <9 hours at baseline as measured by actigraphy, operationalized as sleep onset to offset to more closely align with parent report of sleep duration. It is however important to note that, although actigraphy studies have been used amongst the relevant literature guiding recommendations, the majority are parent report that overestimate sleep duration compared to actigraphy, hence likely more of our children did not meet sleep duration recommendations. However, we can confirm that many did reach sleep quality recommendations that are objectively based (polysomnography and actigraphy), and could reflect the screening that ruled out those with disturbed sleep.

The ability of many children to extend their sleep likely represents a typical homeostatic sleep rebound to sleep loss. As children reach the age of onset of puberty and typical phase delays, there could be a turning point where earlier bedtimes no longer allow children to extend their sleep, but we did not find that age influenced the sleep gains made, despite some children approaching the teenage years. Interestingly, a recent experimental study demonstrates that sleep gains can still be made by earlier bedtimes in adolescents, suggesting that adolescents can behaviorally overcome these phase delays.

We can estimate that 75% of our participants had a high chance of having a sleep debt because their baseline sleep period, at less than 8½ hours, significantly predicted that they could extend their sleep by at least 30 minutes/night. The 8½ hours cut-point may therefore be useful as a threshold for actigraphy-derived sleep entry criteria to research/clinical studies concerned with extending children’s sleep. Unexpectedly, later sleep onset time at baseline predicted only small, nonsignificant sleep gains, and of all sleep factors, 

Discussion

In this sleep intervention study of 8–to 12-year-old children, we used 7-day actigraphy to examine the baseline sleep patterns that predicted which children were able to extend their sleep by going to

Fig. 1. Plots of individual total sleep times (TSTs) at baseline and extension weeks illustrating sleep gains made in those who achieved >30 minutes per night (A) or ≤30 minutes per night (B), and those who made no sleep gains (C). The plot order is for illustrative purposes from the longest to shortest baseline TSTs (extending vertically)
was the weakest predictor. Further research is needed to confirm this finding. Whilst there are no universal sleep timing guidelines to follow (although they are in development\textsuperscript{33}), our study provides direct experimental evidence that one-third of our children benefitted from a 1 hour earlier bedtime than usual in terms of obtaining more sleep.

The reasons for several children in this study apparently having less than their optimal amount of sleep at baseline is unknown, despite being apparently healthy sleepers with sleep hygiene scores averaging at the higher end of the rating scales. Insufficient sleep among children may be due to many things, including weekday scheduling constraints (eg, school start times),\textsuperscript{34} low priority of sleep relative to other commitments (eg, responsiveness to family, sociocultural factors),\textsuperscript{35} time displacement (eg, screen time),\textsuperscript{36} lack of parental awareness or knowledge of sleep's role in optimizing health,\textsuperscript{37} or even genuine fears of the dark.\textsuperscript{38} Although we screened out children with sleep disorders that disrupt their sleep,\textsuperscript{39} some children may have been naturally short sleepers, genetically wired to have a lifelong reduction in nightly sleep duration, apparently without any daytime or long-term consequences.\textsuperscript{40} Although a caregiver was always present when advice on adhering to the extension protocol was given, parent's sleep-promoting directives likely varied and some children may simply have had more autonomy over their own bedtimes, than others.

Unfortunately, this study cannot determine how much more children actually need for optimal health and performance (sleep need), although the full study has shown that differences in sleep of 40-60 minutes each night influences dietary intake and eating behaviors in children,\textsuperscript{41} as well as several facets of children's health-related quality of life.\textsuperscript{42} “Sleep need” is subject to continual debate, and even deciding on what the best outcome measure might be (eg, performance in a running race vs. a math test), or whether it should be based on immediate or long-term consequences is fraught with many unknowns.\textsuperscript{43} There is certainly no magic “number of sleep hours” that works for everybody of the same age, and large individual differences undoubtedly exist, prompting one researcher to suggest that “the search for sleep need may be in vain.”\textsuperscript{44}

Although this study has several strengths, it also has limitations. Primarily, the study was not designed to measure sleep gains as a primary outcome, rather it was focused and powered on eating behavior as a potential mechanistic pathway in the sleep-obesity relationship.\textsuperscript{14,15} For that reason, aside from participant demographics and sleep hygiene factors being assessed, many other determinants of sleep health, including social determinants were not included as possible predictors of children being able to extend their sleep, or not. For example, level of family chaos, household crowding, parental knowledge and value placed on sleep and its relation to health, and parenting practices including conflict and anxieties surrounding children's sleep.\textsuperscript{45} In addition the physical sleep location in proximity to others and their feelings of safety in the sleep environment, could have impacted a child's ability to extend their sleep (or not), as well as their levels of self-control. A useful adjunct to the study would be to understand, from the perspectives of both the parent/s and child, issues related to adherence to the protocol and the experience of the sleep manipulation trial that could have contributed to whether or not a child could extend their sleep. Finally, this is an experimental trial over 1 week, and we don't know if the sleep gains demonstrated here, could be sustained over the longer term.

Sleep latency could not be included because this relied on subjective reporting and not all data were reliable due to missing days or unreliable entries. In addition, the accuracy of the baseline sleep as representing the child’s usual sleep, is uncertain, and the potential for sleep gains to be made during the sleep extension week relied on this representation. The baseline bed and wake times may also have been more variable than during the extension week, since there were no directives for bed and wake times at this time. The placement of the actigraph on the hip rather than the wrist (convention for sleep) has potential limitations in that it has been shown to underestimate WASO and overestimate sleep efficiency.\textsuperscript{27} but on the other hand, had better accuracy for determining sleep onset and

---

**Table 2** Associations of sleep factors (unstandardized and standardized) at baseline with sleep extension minutes gained (n=99)

<table>
<thead>
<tr>
<th>Sleep factor at baseline</th>
<th>Unstandardized predictors\textsuperscript{a}</th>
<th>Standardized predictors\textsuperscript{a}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean diff. (95% CI)\textsuperscript{b} for sleep extension &gt; 30 min</td>
<td>Mean diff. (95% CI)\textsuperscript{b} for sleep extension &gt; 30 min</td>
</tr>
<tr>
<td>Total sleep time, h</td>
<td>29.7 (20.3, 38.7) 3.48 (1.75, 6.91) 21.8 (15.0, 28.6) 2.51 (1.51, 4.17)</td>
<td></td>
</tr>
<tr>
<td>Sleep period time, h</td>
<td>25.5 (13.4, 37.6) 3.80 (1.63, 8.86) 15.8 (8.3, 23.3) 2.28 (1.35, 3.86)</td>
<td></td>
</tr>
<tr>
<td>Sleep efficiency, %</td>
<td>3.9 (2.2, 5.6) 1.11 (1.01, 2.23) 16.9 (9.6, 24.2) 1.58 (1.03, 2.42)</td>
<td></td>
</tr>
<tr>
<td>Number wakeings, n</td>
<td>21.3 (8.9, 33.6) 1.69 (0.86, 3.31) 131.5 (5.5, 20.7) 1.38 (0.91, 2.09)</td>
<td></td>
</tr>
<tr>
<td>WASO, min</td>
<td>0.7 (0.4, 1.0) 1.02 (0.99, 1.04) 15.8 (8.4, 23.2) 1.50 (0.99, 2.29)</td>
<td></td>
</tr>
<tr>
<td>Sleep onset time, h</td>
<td>11.5 (6.5, 21.5) 1.82 (0.93, 3.57) 7.6 (4.3, 15.6) 1.49 (0.95, 2.32)</td>
<td></td>
</tr>
<tr>
<td>Sleep offset time, h</td>
<td>16.2 (27.2, 97.9) 1.72 (0.83, 3.70) 9.5 (1.6, 17.3) 1.39 (0.89, 2.13)</td>
<td></td>
</tr>
<tr>
<td>Sleep timing variability SD, min</td>
<td>0.4 (0.2, 0.6) 1.01 (1.00, 1.02) 14.5 (6.9, 22.1) 1.56 (1.01, 2.39)</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a} Effects are presented per unit of predictor for unstandardized analyses and per SD of predictor for standardized analyses. Bold indicates statistically significant results (p<0.05).

\textsuperscript{b} Mean differences (95% CI) estimated using linear regression, odds ratios (95% CI) estimated using logistic regression. All adjusted for randomized order.

\textsuperscript{c} Estimates are presented for 1 unit (or 1 SD) lower in the predictor e.g., an hour less total sleep time at baseline was associated with 29.7 min more sleep extension; 1% lower sleep efficiency at baseline was associated with 3.9 minutes more sleep extension.

\textsuperscript{d} Estimates are presented for 1 unit (or 1 SD) higher in the predictor.

\textsuperscript{e} From Le Bourgeois,\textsuperscript{42} on a scale from 1 (never) to 6 (always) or 1 (always) to 6 (never) as appropriate; 5 participants missing some data. Higher scores indicate better sleep hygiene.
offset and hence SPT. Strengths include the objective nature of the data collection through actigraphy, the studies were completed over more than a year (minimizing seasonal effects) and a sensitivity analysis for school term (four terms across the year) did not make any meaningful difference to the results (Supplementary Table 1). In addition, data collection was in the home and restricted to school term time with daylight saving transition weeks avoided. However, all children were healthy without sleep issues, so our findings cannot be generalized to children with sleep problems.

In summary, the study describes the sleep of children with “apparently” healthy sleep, and how they may benefit from earlier bedtimes in terms of the sleep gains that could be made. The findings have implications for clinical practice, as well as research. The method of advancing bedtimes (but keeping the normal wake schedule) fits well with many cultures/countries due to children’s school start time schedules, but caution is necessary here as only one-third were able extend their sleep successfully with this approach. Spending too much time in bed awake, may perpetuate behavioral insomnia in children. It may be that just extending bedtime by half an hour could be beneficial, but would need to be tested. This study, as well as many other studies in the field cannot provide a clear answer to the question of how much sleep is needed for children at different ages. However, our study provides novel use of sleep data emanating from a cross-over trial involving children. The success of our sleep manipulations in 8–12-year-olds may encourage future researchers to explore other or tighter age ranges, and explore more predictors enabling sleep extension. Although we could not accurately determine the amount of sleep debt in the children studied here, we can postulate that a usual sleep period of <8½ hours likely increases the chances of children having a sleep debt as many of these children beneficially extended their sleep when given the opportunity to do so.

Author contributions

Each author contributed substantially to the paper. BCG helped design the study, obtained grant funding and drafted the initial manuscript. RW7 conceptualized and designed the study, and obtained grant funding. JJH helped design the study and carried out the statistical analyses. RJ and SM recruited the study participants and carried out all data collection. KM-J contributed to the study design and sleep data analyses. DEE contributed to data collection methods and screened participant’s data for study entry. DB advised on the design of the study and critically reviewed the manuscript. All authors reviewed and revised the manuscript and approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

Funding

This work was funded by the Marsden fund through the Royal Society of New Zealand (19-UOO-225) University of Otago Research Grant.

Declaration of Competing Interest

The authors have no conflicts of interest to declare.

Acknowledgments

The authors thank the study participants and their families for their contribution to our research. The authors also greatly appreciate the work of the research assistants who helped collect data.


