

Big-data Evaluation of Infant Sleep Pattern and Health Indicators  
Using a User-Oriented Smartphone Application: A Longitudinal Analysis

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## Abstract

**Introduction.** Infant sleep is important for growth and development as well as parental well-being. Researchers have placed efforts in developing optimal measurement tools for capturing infant sleep patterns, including both subjective and objective means. User-oriented strategies for collecting infant data in real-time through smartphone application has been recently explored. Considering the diversity in normative sleep pattern across countries, there is a need to examine optimal sleep durations and its determinants in Japanese infants, a population for which evidence is currently limited.

**Methods.** Utilizing the data from free, publicly-available digital lifelog smartphone application for caregivers to record the life of infants, sleep pattern and growth of infants in their first year of life were analyzed.

**Results.** Total number of participants was 4164, and 52.4% were male. In total, 2,785,529 sleep sessions were included in the analysis. The median length of night time sleep was 3.0 and 0.9 for daytime sleep. The mean and standard deviation of total sleep hours per day during the one year after birth was  $11.8 \pm 1.8$  hours. Mixed effects regression model with repeated measures showed duration of total sleep hours per day was associated with infant height depending on age.

**Conclusion.** Normative Japanese infant sleep pattern was evaluated with access to user-oriented big-data. Infant sleep hours might influence the growth of infants during the first year of life, and the influence may vary depending on age. Data collection strategy through smartphone application might be useful for more efficient accessibility by researchers to a wide range of population data at a large scale.

*Keywords:* Infant, Sleep, Growth, Longitudinal Studies, Smartphone, Mobile application

## Big-data Evaluation of Infant Sleep Pattern and Health Indicators Using a User Oriented Smartphone Application: A Longitudinal Analysis

### Introduction

#### Infant Sleep and Health Outcome

Sleep is important for infants. Infant sleep patterns dramatically change in the first year of life with considerable variability across individuals where, generally, fragmented sleep at birth gradually becomes consolidated mainly at night with a few bouts of daytime naps (Galland, Taylor, Elder, & Herbison, 2012; Henderson, France, & Blampied, 2011). This change in pattern is largely driven by biological mechanisms, but it is also highly influenced by other factors, such as environmental and social circumstances (Sadeh, Tikotzky, & Scher, 2010). A recent systematic review described evidence showing that adequate sleep duration was associated with preferable outcomes regarding a wide range of health indicators; adiposity, emotional regulation, and growth; however, the collective epidemiological evidence supporting the relationship is still limited (Chaput et al., 2017). Previous studies suggested sleep problems could have an effect on a child's physical, cognitive and social development as well (Burnham, Goodlin-Jones, Gaylor, & Anders, 2002). Healthy infant sleep is also considered important in the context of health management of caregivers especially mothers, with infant sleep problems being one of the well-known risk factors of postpartum depression (Hiscock & Wake, 2001; Lam, Hiscock, & Wake, 2003). Since problematic infant sleep can impact infant development as well as family well-being, several behavioral intervention have been examined and showed efficacy on infant sleep improvement and maternal mood (Kempler, Sharpe, Miller, & Bartlett, 2016).

#### Infant Sleep and Growth

Compared with the relationship between infant sleep and weight, the scientific evidence of the relationship between infant sleep and linear growth (height) is still limited (El

Halal & Nunes, 2018). The previous literature evaluating the association between sleep duration and height in Singaporean children reported that short sleepers grew less at 24 months of age (Zhou et al., 2015). A cross-sectional study in Israel observed a positive association between infant night-time sleep and linear growth among children less than 6 months of age (Tikotzky et al., 2010). In addition, a longitudinal study identified that longer sleep duration at night or increased naps preceded growth spurt by 0 to 4 days (Lampl & Johnson, 2011). In contrast, there were several studies showing no association between sleep duration and growth among children aged over one year (Gulliford, Price, Rona, & Chinn, 1990; Jenni, Molinari, Caflisch, & Largo, 2007). Considering the inconsistent results of those previous literatures, it appears appropriate to hypothesize that the association between sleep and growth may vary by age group.

### **Measurement of Infant Sleep**

With recognition that early detection of infant sleep problem might lead to effective treatment (Sadeh, 2004), researchers have placed efforts in developing optimal measurement tools for observing infant sleep pattern for epidemiological study. Conventional data collection strategies have included videotaping, caregiver interviews, parent questionnaire and sleep-logs.

Actigraphy, which is an ambulatory device to detect infant activity to estimate sleep pattern, is considered a more reliable objective assessment tool than subjective records (Meltzer, Montgomery-Downs, Insana, & Walsh, 2012; So, Adamson, & Horne, 2007). Actigraphy has the advantage of being able to assess the sleep and wake patterns that might not be observed by parents, but it might interfere with the usual sleep resulting in underestimating the sleep duration. Alternatively, Sadeh developed a subjective assessment tool called, brief screening questionnaire (BISQ), to screen for infant sleep problems and validated it with actigraphy (Sadeh, 2004). His team also demonstrated its ability in obtaining

reliable assessment even through the internet, thus enabling obtainment of infant sleep measurements at a large-scale.

In addition to conventional methodology, more user-oriented strategies for collecting infant data in real-time has been recently explored. Mindell et al. collected infant sleep data through a smartphone application and reported sleep patterns based on the analysis of more than 150,000 sessions derived from 841 children (Mindell et al., 2016). This user-oriented approach may lead to more measurement error than studies utilizing direct measurement approaches, but this approach could be a strategy for more efficient accessibility by researchers to a wide range of population data at a large scale. Sleep logging through a smartphone application in real-time fashion would be preferable to avoid recall bias, a limitation that subjective data collection methods are prone to, such as parent interviews and questionnaires.

### **Normal Infant Sleep Pattern**

Identification of normative sleep pattern have also been eagerly explored (Dias, Figueiredo, Rocha, & Field, 2018; Galland et al., 2012). Galland et al. reported the mean sleep duration per day of infants to be 14.6 hours from birth to two months of age, which decreased to 12.9 hours at 6 months of age and remained similar afterwards until about two years of age. In 2015, an expert panel of the National Sleep Foundation (NSF) in the USA developed recommendations on infant sleep duration; 14 to 17 hours per day for newborns (0 to 3 month age) and 12 to 15 hours for infants (4 to 11 month age) (Hirshkowitz et al., 2015). The American Academy of Sleep Medicine also published consensus statement about optimal infant sleep duration which was similar to the NSF recommendation (Paruthi et al., 2016).

Although those recommendations were based on systematic reviews of recent studies and may be a reliable consensus by experts in sleep medicine, generalizing this standard across different populations may warrant some care. Mindell et al. conducted large-scale research on infant and toddler sleep patterns in a multi-cultural setting and concluded that

infant and toddler sleep patterns were significantly different across countries (Mindell, Sadeh, Wiegand, How, & Goh, 2010). Owing to later bedtime, Asian predominant countries had less total sleep hours per day than Caucasian predominant countries by more than one hour; the total sleep hours ranged from 11.6 hours in Japan to 13.3 hours in New Zealand. The authors also argued there were substantial difference in the sleep setting across countries as babies were more likely to sleep in their parents' room and sleep in their parents' bed in Asian countries than in non-Asian countries. Since infant sleep is inevitably affected by environment and social factors, we have to take country or cultural background into consideration when we discuss the normative values of infant sleep pattern.

### **The Aim of This Study**

Currently, the evidence is limited in determining what may be the optimal sleep duration for Japanese infants. Shimada et al. described Japanese infant sleep pattern with a daily plot for a consecutive 2 to 52 weeks among 208 mothers (Shimada et al., 1999). This study showed a mean total sleep hours per day of Japanese newborn babies (0 month age) to be 14.1 hours, which gradually decreased with age with 10.9 hours observed at 1 year of age. The mean sleep duration per day was one to two hours shorter than that described in previous research in Japan. Kohyama et al. observed sleep patterns in 872 Japanese participants through using the internet approach and reported infant sleep pattern compared to patterns in other Asian countries (Kohyama, Mindell, & Sadeh, 2011). Mean total sleep hours in Japanese was 14.7 hours for newborns (0-2 months) and 12.0 hours for infants (3-11 months), values which lie close to the lower value range for sleep duration recommended by the NSF in the USA.

To our knowledge, no Japanese studies have examined the association between infant sleep pattern and health indicators, especially height. Utilizing a unique strategy for large-scale longitudinal population data collection through a smartphone application that allowed for real-time recording, the objectives of the current study were to (1) explore the normative

sleep patterns of modern Japanese infant in the first year of life, and (2) investigate the relationship between total sleep hours and linear growth as one health indicator in infants as a way to inform a discussion on optimal sleep hours for infants. We also examine the hypothesis that this relationship might change across children's age in month.

## **Methods**

### **Participants**

Data source was a free, publicly-available digital lifelog Android® and iOS® application for caregivers to record the life of infants, Papatto-Ikuji® (developed by First Ascent, Inc., Tokyo, Japan). A retrospective cohort study was conducted using data accumulated by this application during a study period of 46 months from January 2014 to October 2017. Through this application installed on a smartphone, caregivers are able to record childrearing features that have taken place in real-time, such as frequency and characteristics of breastfeeding and formula feeding practices, sleep patterns, change of diapers, defecation, bathing as well as growth or developmental indicators and milestones with date.

Data for infants recorded from date of birth to one year of age (360 days) were used in this analysis of sleep patterns and growth measurements. Inclusion criteria were subjects who recorded any childrearing features in the application at least 100 times (active users), recorded sleep sessions for at least 25 times, and with at least two height measurements. Active users received pop-up notices to ask whether they were willing to have their data be used for research purposes. Among those included based on these criteria, no subject exclusion were performed for the analysis of sleep sessions.

## **Ethical Statement**

This study was conducted under the approval of the ethics committee of National Center for Child Health and Development (NCCHD). All users provided consent to the usage of their lifelog data not specific for this study but in general anonymously and were able to opt out of the study easily from the notice page in the application.

## **Data management**

Data were provided by FirstAscent Inc. FirstAscent was primarily responsible for development and release of the software, data storage and security, extracting the data, and assembling a de-identified dataset for analysis. Variables for data extraction was determined based on the discussion of study hypotheses and analytical plan by the study team (investigators at NCCHD and FirstAscent, Inc.)

## **Data collection**

**Sleep sessions.** Within the mobile application, a new sleep session was initiated when a user pressed the ‘start sleep’ button and ended when the user subsequently pressed the ‘awake’ button. Users were able to modify the recorded start and end time of each sleep session at any time. On initial check of the distribution of sleep session length, outliers were observed; for example, records of either very short durations (less than 10 minutes) or very long durations (16 hours or more) were observed. Outliers in the lower end were assumed to be trial usage of the application by caregivers, and those in the upper end were likely records where caregivers may have forgotten to stop recording the sleep session. Exclusions of those outlier observations, whose duration was less than 10 minutes and longer than 16 hours were performed similar to criteria used in previous research (Mindell et al., 2016; Sadeh, Mindell, Luedtke, & Wiegand, 2009). Night-time sleep was defined as any sleep session starting between the hours of 18:00 and 7:00 the following day. Daytime sleep included all other



sessions. Total sleep hours per day (TSH) was defined as the sum of sleep duration for sessions starting from 7:00 in the morning on a particular day and included the following 24 hours. The TSH variable was also assessed for outliers, and we excluded observations located greater than two standard deviations (SD) away from the mean by age category (newborn, 0-3 month; infant, 4-11 month according to the definition of the NSF in the USA).

**Height.** Users could input the infant's growth measurement (height and weight) and corresponding date. There were no restriction on number of input records. Height measurement were recorded in the form of integer with units in centimeters.

**Other covariates.** Child's age was considered as number of days since birth, as well as age in months. As nutrition is a factor affecting both sleep and growth, the main type of feeding (breastfeeding and/or formula) was included. Subjects were categorized into three groups according to a breastfeeding index defined as the number of breastfeeding records divided by the number of total feeding records (breastfeeding and formula). Mainly breastfeeding, mainly formula, or mixed was defined at index cut-points of 0.90 or greater, 0.50 to 0.89, and 0.50 or less, respectively. Other covariates included child's sex, season of birth and height measurement. Seasons were defined according to the standard Japanese Meteorological Agency; Spring (March to May), Summer (June to August), Autumn (September to November) and Winter (December to February). Although the BISQ, the most well-known subjective questionnaire for infant sleep included additional data regarding the child's relationship to the responder, sleep environment (room sharing status with parents or siblings) and caregivers' judgement on infants' sleep problem, this application did not contain those questions as it was not designed originally for research purposes. Parents' physiological and social information were also not available.

## Statistical Analysis and Tests

**Dataset for regression.** The final aim of this study was to assemble a regression model to examine the relationship between TSH and height. In this process, we created a dataset including both TSH and height measured on the same day; however, there were imbalanced observations between the numbers of measures of TSH and height. To address this issue, the statistical analysis was pursued in two stages. First, we regressed each individuals TSH data as a function of age, sex and nutrition; and generated TSH estimates for each subject with the mixed effects model. Next, we used these estimates to fill in TSH measures for the corresponding height measure available, and we evaluated the relationship between TSH and height.

**Mixed effects model.** To accommodate the data structure of repeated measures, we used the mixed effects regression model in the analysis (Bates, Mächler, Bolker, & Walker, 2014; Laird & Ware, 1982). The random effects component of the model allowed for within-infant random heterogeneity. The model of the analysis was theoretically expressed as follows;

$$Y_i = X_i\beta + Z_ib_i + \epsilon_i$$

where  $Y_i$  was the response, TSH in the first model and height in the second model of the  $i$  th subject across time.  $X_i$  is the matrix of fixed effect and  $\beta$  is the constant slope for the fixed effect terms. In the sleep estimation,  $X$  consisted of age, sex, and nutrition, while in the final model,  $X$  consisted of age, age-squared, estimated TSH on the day, sex, and nutrition, and season of height measurement.  $Z_ib_i$  is the random effects term of the  $i$  th subject, where  $Z_i$ , represents the within-infant variance and  $b_i$  is the slope for random effects.  $\epsilon$  is an error term. We assumed a random intercept for each subject and common slope across age. We introduced an interaction term into the model representing the product of TSH and age to

examine the hypothesis that the effect of sleep on height could vary depending on age.

Statistical analyses were performed using R version 3.5.1(R Foundation for Statistical Computing, Vienna, Austria ) (R-Core-Team, 2018).

## Results

### Characteristics of Children

Total number of participants with sufficient data available (at least 100 activity logs without withdrawal of study participation, 25 sleep sessions and multiple measures of height) was 4,164 during the study period. Males comprised 52.4% (n=2,184) of the study subjects, and 53.7% (n = 2,236) mainly breastfed. The characteristics of the children are shown in Table 1.

Table 1. Characteristics of children included in the analysis

Characteristic	Categories	n	(%)
Total children		4,164	(100%)
Sex, n (%)	Male	2,184	(52.4%)
	Female	1,980	(47.6%)
Nutrition, n (%)	Breastfeeding	2,236	(53.7%)
	Mixed	832	(20.0%)
	Formula	1,088	(26.1%)
Season of birth, n (%)	Winter	825	(19.8%)
	Spring	1,136	(27.3%)
	Summer	1,189	(28.6%)
	Autumn	1,014	(24.4%)

## Sleep Sessions

In total, 2,785,529 sleep sessions were included after exclusion of potentially erroneous records during the study period. The number of sleep session records for an individual ranged from 25 to 2,561 during the first year of each subject's life. The number of subjects and observed sleep sessions by age are shown in Table 2. The mean (SD) length of each sleep session was 2.6 (2.7) hours. The number of sleep sessions by sleep session length across age (Figure 1) showed that the lengths of each sleep session were mostly short, and the range of sleep session length was small at 0 months of age, and median sleep session length gradually increased with age. A small peak was observed at around 9 hours from about 5- to 6-months age, and finally formed a peak around 10 hours at 11-months age. Figure 2 shows the relationship between start time and length of each sleep session. The sleep sessions which started during night-time hours were longer in length than sleep session starting in the daytime.

Table 2. The number of unique subjects and sleep sessions by age (months)  
of contribution of longitudinal data.

Age (months)	Unique subjects*	Number of sleep sessions
0	1,289	110,556
1	1,970	227,989
2	2,470	292,033
3	2,832	314,509
4	2,833	313,620
5	2,796	301,697
6	2,719	281,782
7	2,511	256,456
8	2,302	222,145
9	2,078	187,599
10	1,862	153,563
11	1,583	123,580

\*Subjects may be included in multiple age categories as sleep data was available longitudinally. For example, 1,289 unique subjects contributed a total of 110,556 sleep sessions at 0 months of age.

Figure 1. The number of sleep sessions by sleep session length across age (month)

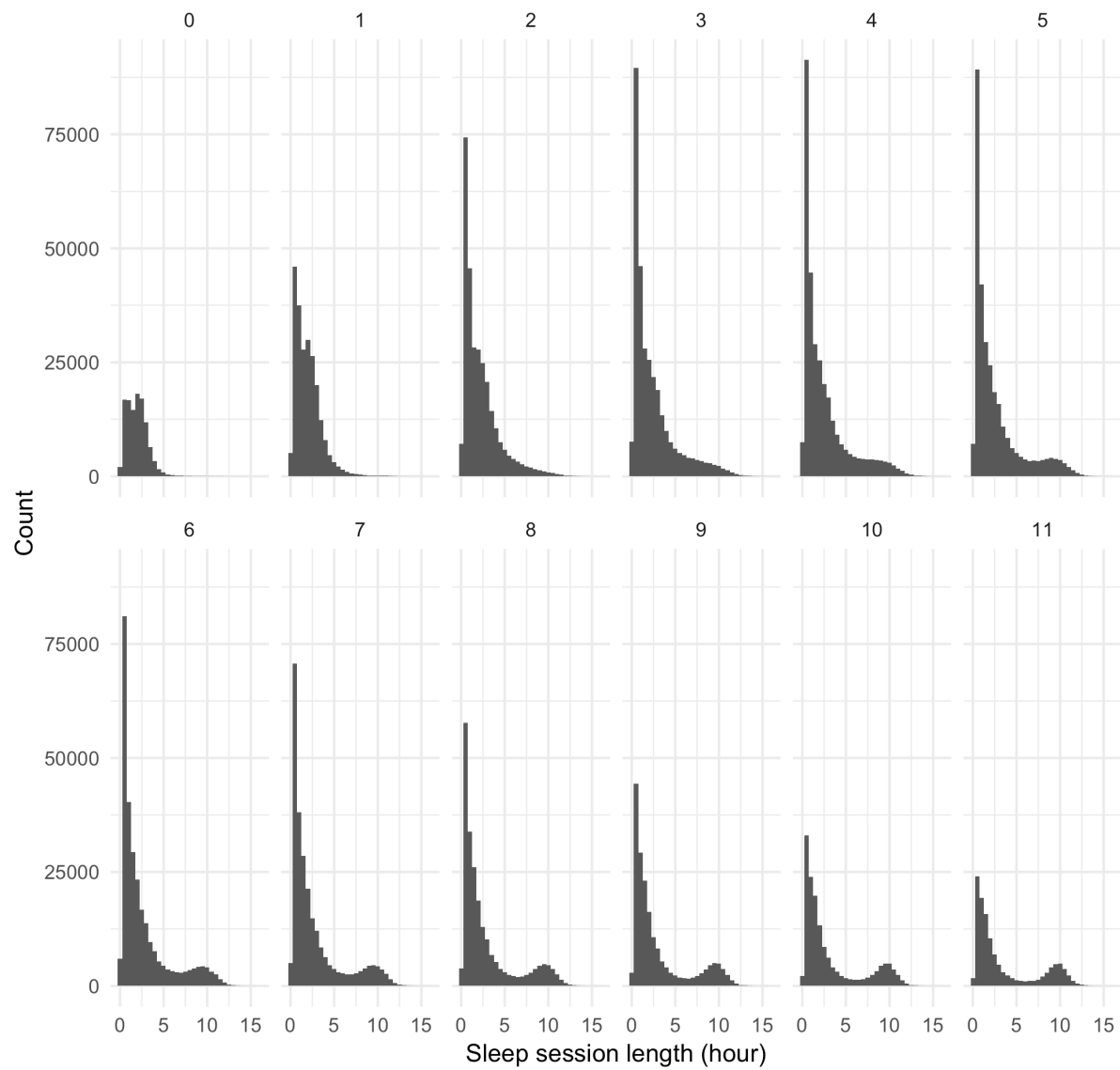
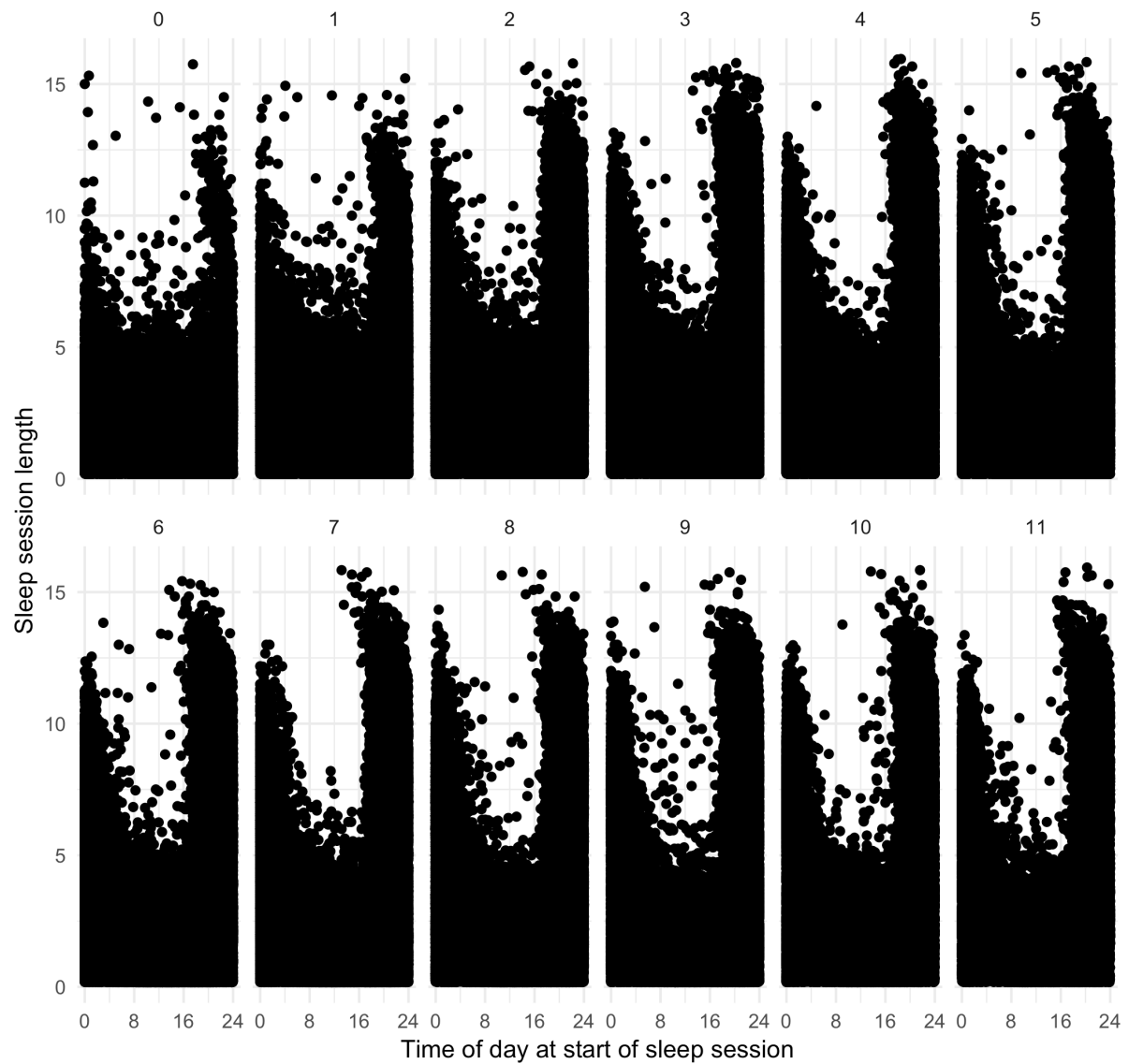


Figure 2. Relationship between start time and length of sleep sessions across age (month)



### Night-time and Daytime Sleep Sessions

A total of 1,400,094 sleep sessions (50.3% of all sessions) were observed as night-time sleep. The overall median and interquartile range (IQR) of night-time and daytime sleep lengths were 3.0 (4.3) and 0.9 (1.0) hours, respectively (Figure 3). Changes in distribution of night-time and daytime sleep across age are shown in Figure 4, which illustrated that night-time sleep became longer and more variable with increasing age while daytime sleep appeared similar across age.

Figure 3. Distribution of night-time and daytime sleep session length

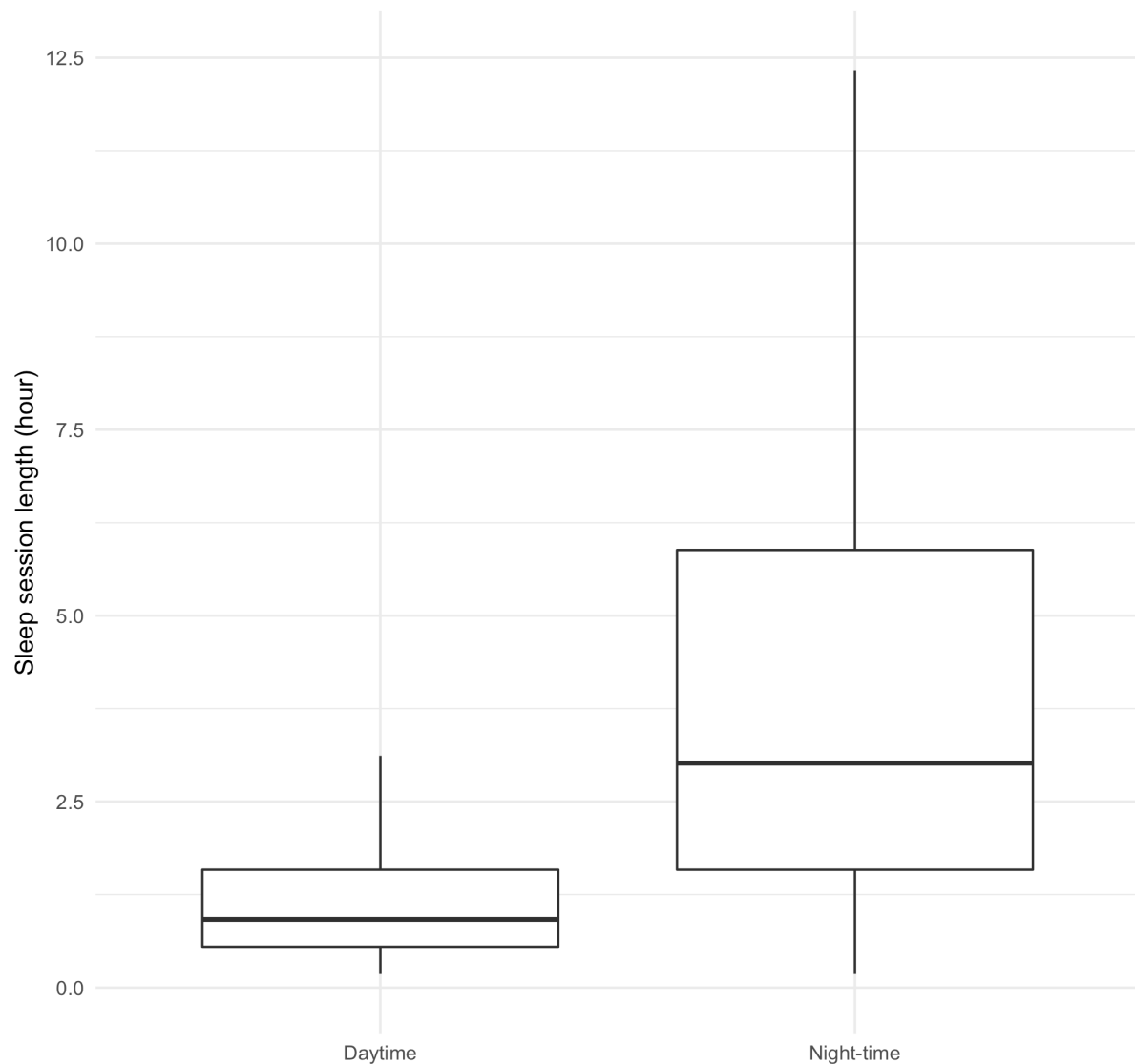
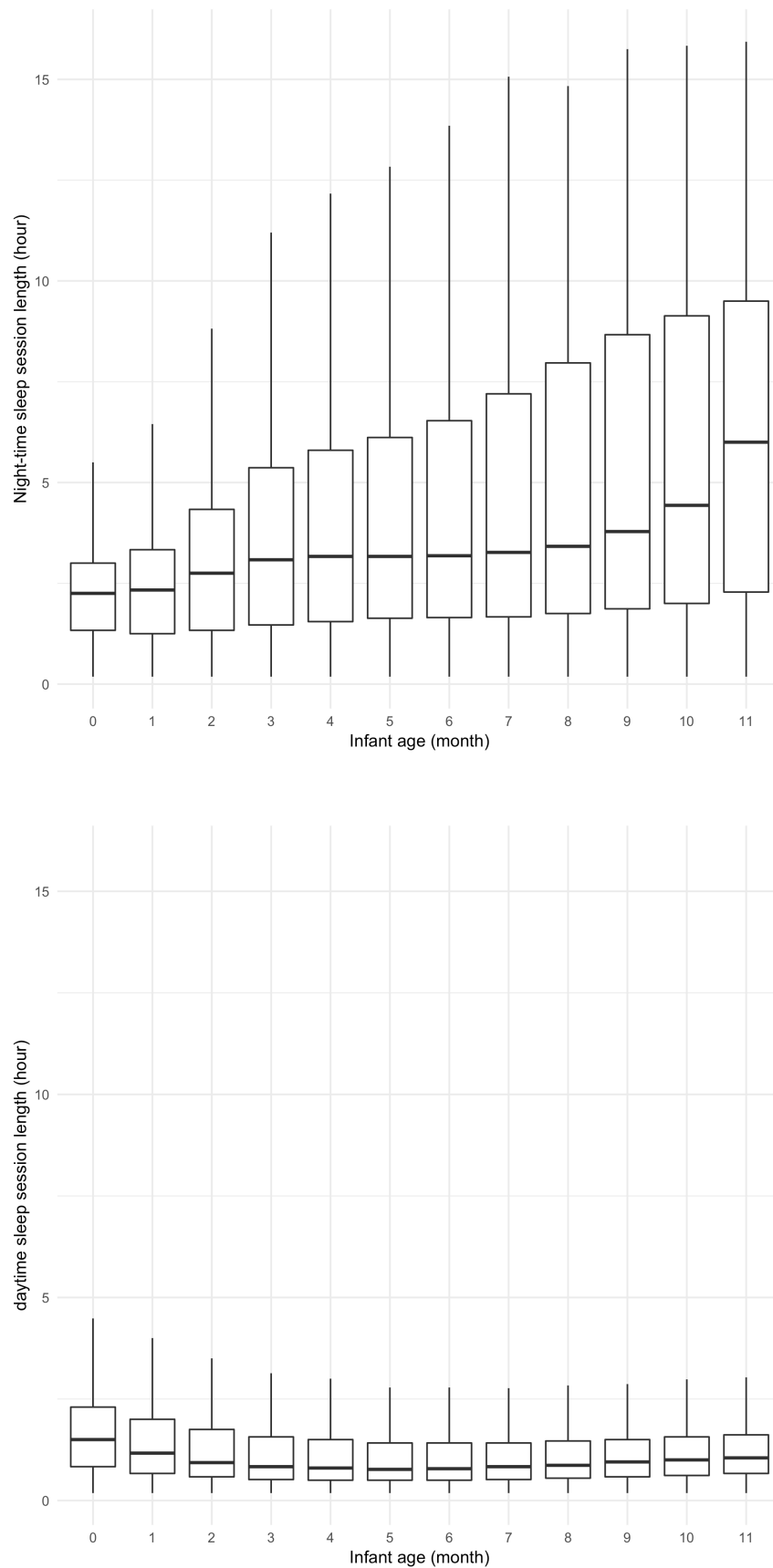




Figure 4. Distribution of night-time and daytime sleep session length across age



**Total Sleep Hours per day (TSH)**

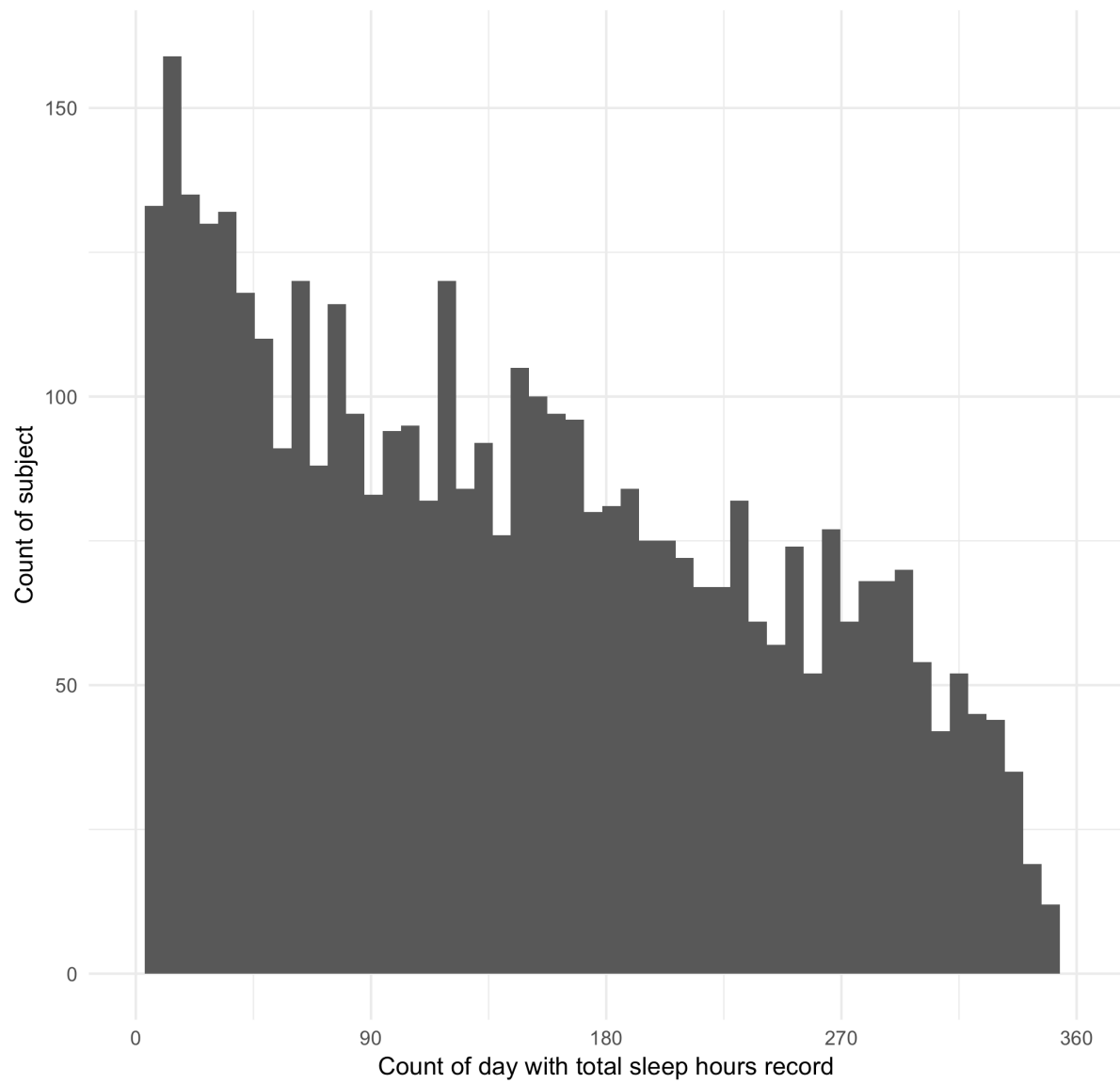
The number of TSH records among 4,134 total subjects was 598,300 after excluding outliers. The number of excluded observations due to the extraordinary length lying above or below two standard deviations from mean for each age categories was 36,315, representing about 5.7% of all TSH records, resulting in exclusion of 30 subjects from the analysis. The numbers of subjects and TSH by age (month) are shown in Table 3. The mode and median number of days with TSH records per subject was 7 and 135 (range, 1 to 353 days). Histogram of the number of days with TSH records available is shown in Figure 5, illustrating that the majority (86.6%) of included subjects recorded sleep data for over 30 days.

Table 3. The number of unique subjects and records of total sleep hours by age (months)

Age (months)	Unique subjects*	Number of records (total sleep hours per day)
0	1,280	15,269
1	1,966	35,586
2	2,456	51,533
3	2,792	61,272
4	2,817	64,585
5	2,777	64,562
6	2,696	62,675
7	2,486	59,338
8	2,279	53,918
9	2,047	48,923
10	1,823	43,087
11	1,561	37,552

\*Subjects may be included in multiple age categories as sleep data was available longitudinally. For example, 1,280 unique subjects contributed a total of 15,269 total sleep hours per day records at 0 months of age.

Figure 5. Number of subjects by counts of days with total sleep hours record



The mean (SD) of TSH during one year since birth was 11.8 (1.8) hours (Figure 6). The descriptive analysis of TSH by age is summarized in Table 4, and the distribution by age is shown in Figure 7. Newborns sleep more than half of the day. TSH slightly decreases with increasing age, and after five months of age, TSH become shorter than half a day. The variance of TSH was greater during younger age.

Figure 6. Distribution of total sleep hours per day (TSH) during the first year after birth

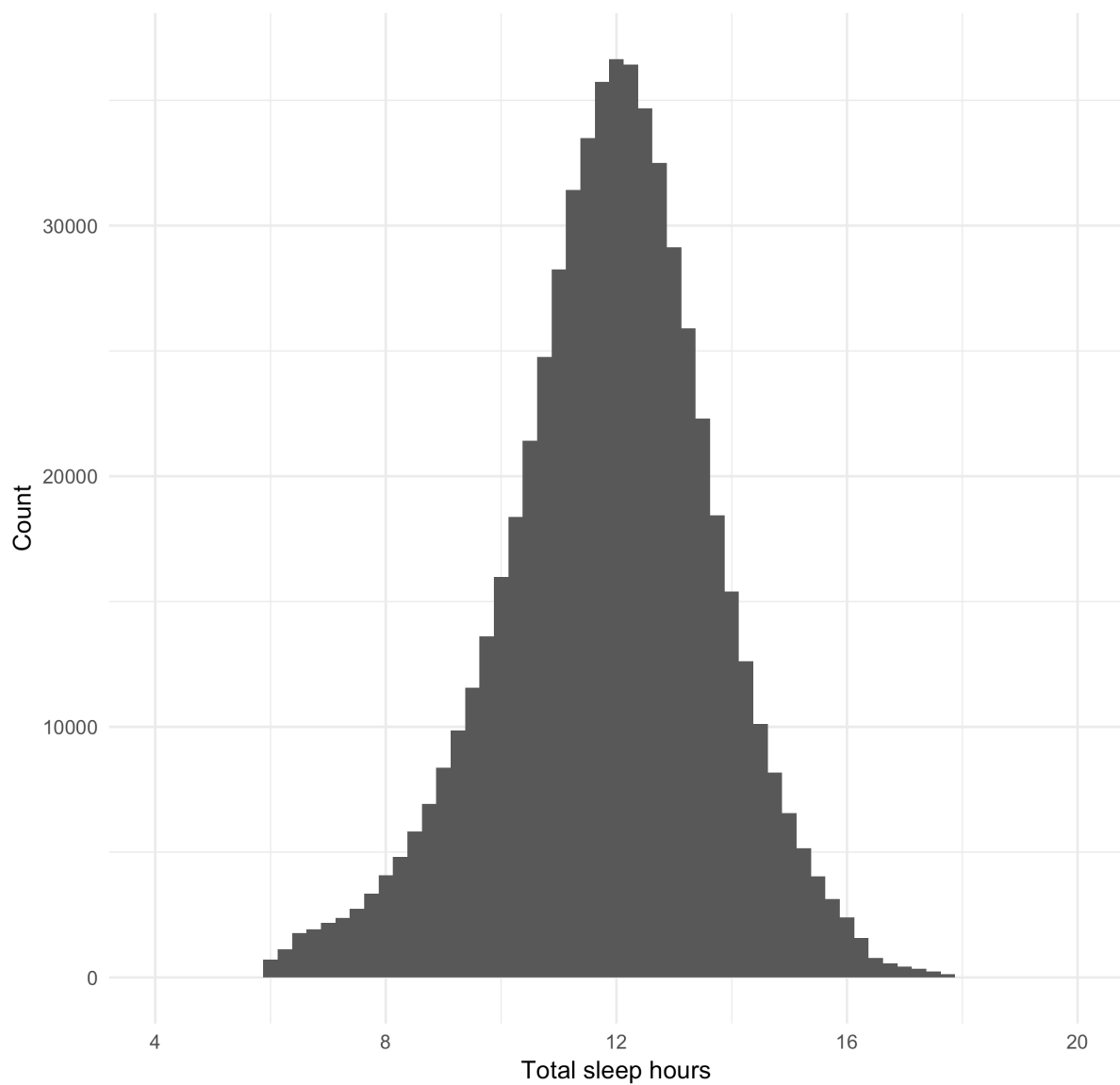
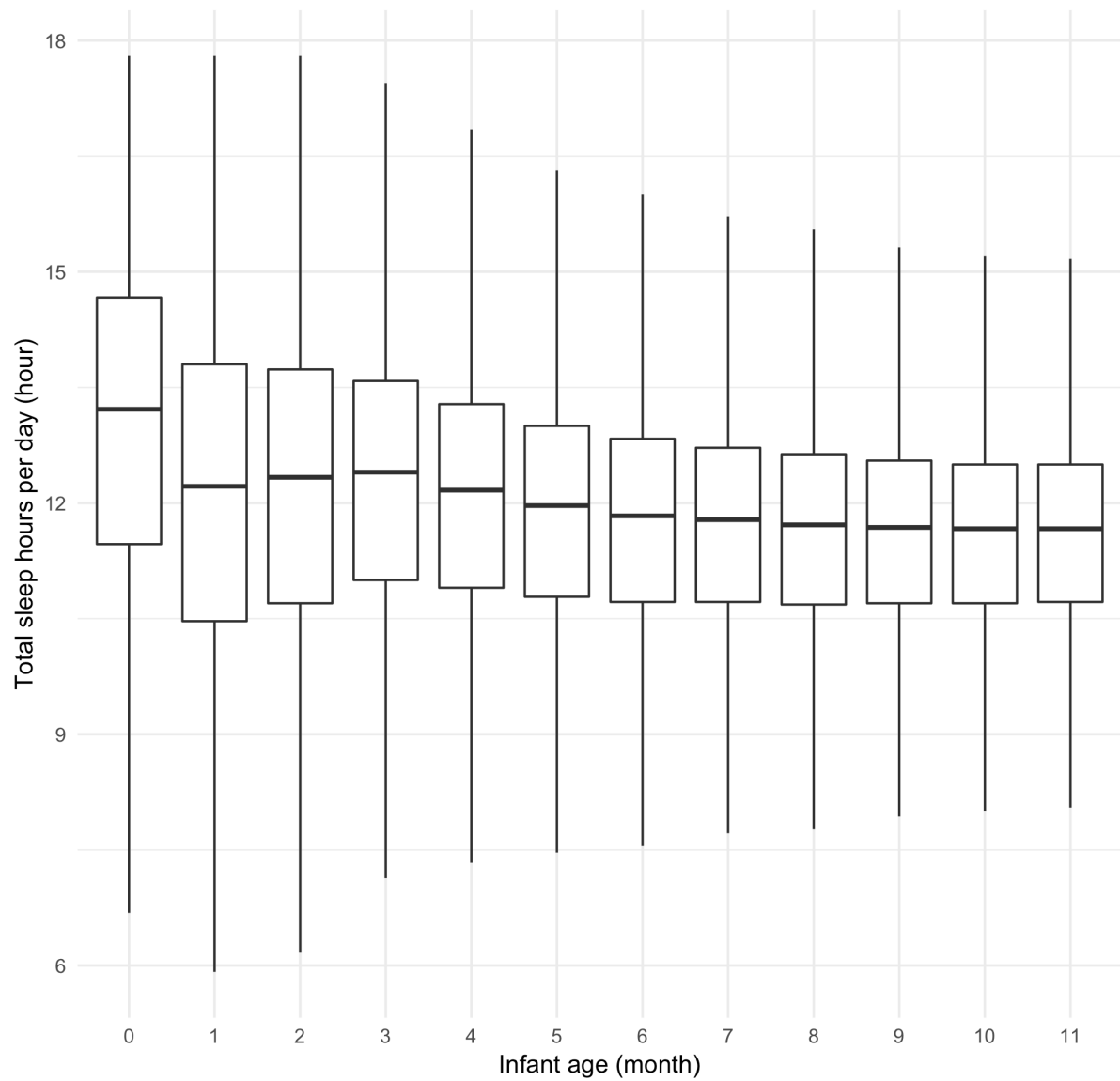


Table 4. Normative total sleep hours per day in Japan across age

Age group	Mean (hour)	SD (hour)
0 month	12.9	2.4
1 month	12.1	2.3
2 month	12.1	2.2
3 month	12.2	2.0
4 month	12.0	1.9
5 month	11.8	1.8
6 month	11.7	1.7
7 month	11.6	1.6
8 month	11.6	1.6
9 month	11.6	1.5
10 month	11.5	1.5
11 month	11.5	1.5
Newborn (0-3 month)	12.2	2.2
Infant (4-11 month)	11.7	1.6
Overall	11.8	1.8

Figure 7. Distribution of total sleep hours per day across age (month)



**Factors associated with sleep duration.**

Mixed effects regression model was used to examine the relationship between TSH and various factors including age (month as continuous variable; day after birth divided by 30), sex and nutrition (breastfeeding as reference) fitted by residual maximum likelihood (REML). In this model, we assumed each subject has a random intercept with a common slope among the study population. The summary of this sleep model was shown in Table 5.

The analysis showed increasing age and feeding practices to be associated with TSH. Holding all other variables constant, on average, each month during the first year of life, infants slept 0.2 hours less than the previous month. Babies with formula feeding slept longer than those mainly breastfed while those infants who had mixed feeding slept less hours.



Table 5. Summary of mixed effects model for variables to predict total sleep hours per day.

		Beta	Standard Error	95% CI	p-value*
<b>Fixed Effects</b>					
(Intercept)		12.43	0.03	12.37 - 12.49	< 0.001
Age (Month)		-0.23	0.00	-0.23 - -0.22	< 0.001
Male sex		-0.05	0.04	-0.12 - 0.02	0.16
Nutrition (ref. Breast Feeding)	Formula	0.15	0.05	0.06 - 0.24	< 0.01
	Mixed	-0.26	0.04	-0.34 - -0.17	< 0.001
<b>Random Effects (Group by Subject)</b>					
		Variance	Standard Deviation		
(intercept)		1.25	1.12		
Residual		2.34	1.53		
Number of groups		4,134			
Observations		598,300			

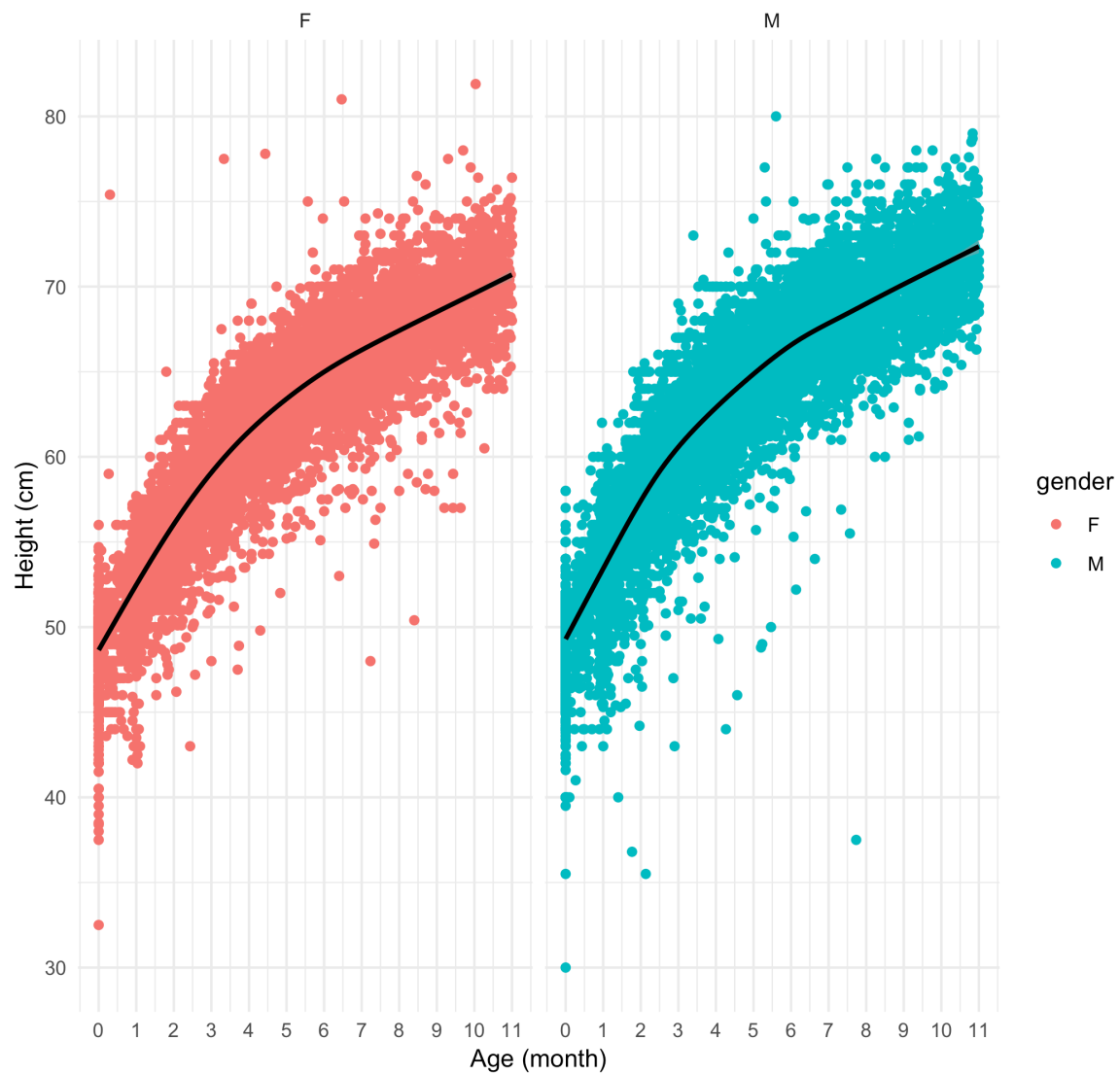
\* p-value was associated with type III tests of fixed effects

**Infant Height**

Height data of those who had TSH data available was analyzed. Among the 4,134 subjects included in this analysis, 22,384 height measures were available. The largest number of height measurements for a single individual was 74 during the first year of life.

Height measures across time by sex were plotted in Figure 8. The height measures may have been prone to measurement error due to home measurement by caregivers which lacked standardization. However, the mean and SD of height in this study was consistent with reports of national survey results (Ministry of Health, 2010).

Figure 8. Height data across age by sex



**Association between child's sleep duration and height**

We used a linear mixed effects regression model for repeated measures of height over time fitted by residual maximum likelihood (REML). This model included a random intercept across subjects, and fixed effects for age (month), age-squared, sex, estimated TSH, nutrition and season of the measurement. The results are shown in Table 6 and indicated that most variables are associated with child height, with the exception of TSH. TSH was not significantly associated with height at the 5% level of significance. The estimated increase of height for everyone month increase in age was 3.8 cm, although the growth rate appeared to decrease as indicated by the age-squared term showing a negative coefficient. As known generally, male infants appeared, on average, to be about 1.2 cm taller than girls holding all other conditions equal. According to the model, breastfed infants were likely to be taller than those with formula feeding or mixed feeding. Interestingly the season of measurement was significantly associated with infant growth.

Table 6. Summary of mixed effects regression model evaluating the association between total sleep hours and height.

		Beta	Standard Error	95% CI	p-value*
<b>Fixed Effects</b>					
(Intercept)		49.18	0.40	48.40 - 49.97	< 0.001
Total Sleep Hours (Estimation)		-0.03	0.03	-0.09 - 0.03	0.32
Age (Month)		3.78	0.01	3.75 - 3.80	< 0.001
Age^2 (Month)		-0.16	0.00	-0.17 - -0.16	< 0.001
Male sex		1.24	0.07	1.10 - 1.38	< 0.001
Nutrition (ref. Breast Feeding)	Formula	-0.53	0.09	-0.71 - -0.36	< 0.001
	Mixed	-0.38	0.08	-0.54 - -0.22	< 0.001
Season (ref. Spring)	Summer	0.27	0.03	0.22 - 0.33	< 0.001
	Autumn	0.38	0.03	0.32 - 0.44	< 0.001
	Winter	0.13	0.03	0.07 - 0.19	< 0.001
<b>Random Effects (Group by Subject)</b>					
		Variance	Standard Deviation		
(intercept)		4.49	2.12		
Residual		1.93	1.39		
Number of groups		4,134			
Observations		22,382			

\* p-value was associated with type III tests of fixed effects

As hypothesized in the methods section, we examined whether the relationship between TSH and height varied depending on age of the infant. The summary table of the mixed effects regression analysis with interaction term is shown in Table 7. In this model, the TSH and the interaction term were both statistically significant. According to this result, TSH was first negatively correlated with height at birth, but at 6-month age, the effect of TSH on height converted to positive. At one year of age, the magnitude of effect of one hour increase of TSH on height was associated with an increase in growth by 0.06 cm.

Table 7. Summary of mixed effects regression model examining interaction by age in the association between total sleep hours and height.

		Beta	Standard Error	95% CI		p-value*
<b>Fixed Parts</b>						
(Intercept)		49.69	0.43	48.86	- 50.53	< 0.001
Total Sleep Hours (Estimation)		-0.07	0.03	-0.14	- -0.01	0.03
Total Sleep Hours * Age (Month)		0.01	0.00	0.00	- 0.02	< 0.001
Age (Month)		3.62	0.05	3.53	- 3.72	< 0.001
Age^2 (Month)		-0.16	0.00	-0.17	- -0.16	< 0.001
Male sex		1.24	0.07	1.10	- 1.38	< 0.001
Nutrition (ref. Breast Feeding)	Formula	-0.53	0.09	-0.71	- -0.36	< 0.001
	Mixed	-0.38	0.08	-0.54	- -0.22	< 0.001
Season (ref. Spring)	Summer	0.27	0.03	0.22	- 0.33	< 0.001
	Autumn	0.38	0.03	0.32	- 0.44	< 0.001
	Winter	0.13	0.03	0.07	- 0.19	< 0.001
<b>Random Parts (Group by Subject)</b>						
		Variance		Standard Deviation		
(intercept)		4.49		2.12		
Residual		1.94		1.39		
Number of groups		4,134				
Observations		22,382				

\* p-value was associated with type III tests of fixed effects

## Discussion

Infant sleep patterns were evaluated with large-scale user-oriented data collected through a novel strategy involving a smartphone application. Over 2.7 million sleep sessions of 4,164 infants were analyzed and normative Japanese infant sleep pattern was identified; the mean of a single sleep session length was 2.6 hours, and there was substantial difference between night-time and daytime sleep. The mean (SD) length were 4.0 (3.2) hours at night-time and 1.2 (0.9) hours at daytime. Tendency for longer sleep hours at night were confirmed even in the newborn babies, which might reflect the effect of mother's circadian rhythm on babies beginning during the fetal period (Shimada et al., 1999).

Descriptive analysis of total sleep hours per day (TSH) was conducted by consolidating the sleep sessions per day. The mean (SD) TSH of newborns (0-3 month age) was 12.2 (2.2) hours; that of infants (4-11 month age) was 11.7 (1.6) hours, which were consistent with the result of the multi-country study conducted in 2010 (Mindell et al., 2010). As discussed in this previous study, Japanese infants had the shortest length of sleep hours among the countries studied (Kohyama et al., 2011). The authors concluded that short total sleep hours per day of young Japanese children were mainly owing to late bedtime compared with non-Asian countries and short duration of daytime sleep. The difference between Japan and other countries should be underscored, when we interpret and apply recommendations formulated in other countries on infant sleep hours.

Since this study was conducted in a retrospective fashion, some covariates which previous literature have identified as being potentially important were not available in this study; namely, sleeping environment such as co-sleeping, room-sharing with siblings or parents, as well as parental behaviors including bedtime interactions and soothing routines and also parents physiological and social factors (Sadeh et al., 2010). Future research should attempt to capture all these features. As demonstrated by this study, researchers may be able



to capitalize on the advantages of this data collection approach and collect the additional information through the smartphone application.

Although there were several studies reporting a significant relationship between increased sleep duration and height during the infancy period (Lampl & Johnson, 2011; Tikotzky et al., 2010), the results of the current study does not fully support these observations. One reason may be due to issues of measurement error in the TSH estimates used in our study which were based on modeled estimates, resulting in the loss of statistical power to detect associations. The GUSTO study showed that the TSH was not associated with growth in the whole population, but only in the subgroup of short sleepers defined as those children with less than 12 hours, there was a positive association between sleep and body length (Zhou et al., 2015). Authors concluded that this result might suggest that infant sleep could have a ceiling effect on height when sufficient sleep was achieved. Considering this research, our study might be focusing on a potentially heterogeneous population. Further subgroup analysis may be needed.

Instead, this analysis suggested that total sleep hours might be associated with height when we consider the interaction of sleep and infant age, even after adjusting for covariates such as age, sex, nutrition and season. The final mixed effects regression model showed that TSH was first negatively associated with height for newborns, but the relationship gradually changed and resulted in a positive association between sleep and height at around 6 months of age. This time dependency in the relationship may reflect influences of biological change in infants regarding linear growth. As the American Academy of Pediatrics recommended exclusive breastfeeding during first 6 month and used the growth chart as the guide for optimal amount of breastfeeding (Eidelman, 2012), nutritional factors might be playing a more important role during early stages of infancy. Considering the previous study discussing that the breastfeeding was associated with more fragmented sleep pattern in infants (DeLeon & Karraker, 2007), TSH might have relatively smaller impact on height in the period of early

infancy. The well-known fact that the pulsatile secretion of growth hormone is observed during the slow-wave sleep after 3 months of age (Hawkes & Grimberg, 2013; Sassin et al., 1969) might support the current study result that TSH had association with linear growth with the maturation of sleep pattern in the first year of life.

Despite the obvious strengths of this study including its size, availability of detailed repeated measures captured at real-time, and use of appropriate statistical modeling of the data, there were also limitations that need to be acknowledged. First, the measurements of sleep likely suffered from a certain degree of misclassification bias. Caregivers were free to use the application as they wished and there was no enforcement in ensuring the accuracy of measures. Cut-off values were implemented to distinguish erroneous and valid records in an attempt to thoroughly address quality control issues of the data. In this study, we adopted the inclusion criteria that more than 25 sessions needed to have been recorded during the infants first year, a threshold used in a previous smartphone application-based study (Mindell et al., 2016), but additional consideration on the appropriateness of this strategy on application-based user-oriented approaches might be needed in the future. This inclusion criteria may have still resulted in sparse data points with sleep session observations spread across the 12-month period for certain infants. A more strict criteria may improve the data quality, but at the cost of reduced sample size and potential influence on generalizability of findings. A very least, this deserves further consideration.

A second limitation as mentioned above, in the final analysis of association between TSH and height, we used estimated total sleep hours on the day that height was measured, instead of actual sleep record. Although the model fit appeared sufficient, this method may have introduced non-differential misclassification in the sleep measure and resulted in reduced statistical power. Third, due to limited data on user profiles and environment, we were not able to ensure the generalizability of our findings. However, our study included a

large number of participants considerably greater than a previous infant sleep study in Japan, and descriptive sleep characteristics appeared to be consistent with national surveys.

In conclusion, this study contributed to identifying the normative infant sleep patterns among the modern Japanese population. Regression analysis showed that infant TSH is associated with height where the effect appears to be differential depending on the age of the infant. This study also serves as a proof of principle for a novel approach to data collection through a smartphone application that might be useful to consider for future epidemiological research strategies.

### **Disclosure of Conflict of Interest**

The authors have no financial conflict of interests to report.

### **Acknowledgement**

The author thanks to all the families who participated in this study through active use of the smartphone application. Also, I would like to express my gratitude to Professor Kevin Urayama as my supervisor, Professor Mahbub Latif for statistical analysis support, Satoshi Narumi for supporting the generation of research ideas and Tomoyuki Hattori for offering access to the dataset and management.

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