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Regular sleep habits in toddlers are associated with social development and brain coherence

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ABSTRACT

Objective: Although sleep habits are associated with the development of toddlers, factors affecting social development and brain function remain unclear. We aimed to elucidate the relationship between sleep habits and social development as well as brain coherence in toddlers.

Methods: We used the data set at 1.5–2 years old, in the longitudinal study until 6 years old. We evaluated sleep parameters, such as average wake-up time, bedtime, nighttime sleep duration, total sleep duration, and the standard deviation (SD) of sleep habits. We also examined the development, including the social stimuli fixation percentage using Gazefinder® and electroencephalography (EEG) coherence between brain regions.

Results: Seventy-two children (37 boys and 35 girls) were included. The fixation percentage for the human face was negatively correlated with the SD of the total sleep duration, nighttime sleep duration, nap duration, and bedtime ($r = -0.516$, $p = 0.000$; $r = -0.331$, $p = 0.005$; $r = -0.330$, $p = 0.005$; and $r = -0.324$, $p = 0.005$, respectively). The EEG analysis indicated that α-band coherence in the right centro-parietal area was negatively correlated with the total sleep duration ($r = -0.283$, $p = 0.016$). The path diagram demonstrated a direct significant effect of sleep duration irregularity on development including social communication and fixation percentage for human faces. Additionally, total sleep duration exhibited a direct effect on α cortical coherence in the right centro-parietal area.

Conclusions: In this study, we found an association between sleep irregularity and the development of social communication, preference for humans, and brain coherence in toddlers. We suggest that regular sleep plays an important role in promoting the development of social communication.

1. Introduction

Sleep has a restorative effect on the brain and is thus essential for survival [1,2]. Furthermore, it plays a pivotal role in consolidating learning and memory by pruning excess synapses during sleep [2–5]. Consequently, sleep deprivation has been associated with detrimental effects on performance and language acquisition [6].

Worldwide birth cohort studies have demonstrated that short sleep duration, frequent awakening after sleep onset, and late bedtime in early childhood were associated with high scores for attention deficit hyperactivity disorder and lower language acquisition at 5–6 years old, along with depression, and psychotic symptoms in adolescence [7–11]. However, a previous systematic review demonstrated that the association between short night sleep duration, long sleep-onset latency, frequent night-waking, and less prosocial behavior remains controversial [12]. In addition, the duration of night sleep was positively related to the receptive vocabulary ability in children aged 36–60 months [13, 14]; however, in another cross-sectional study of children aged 51–67

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months, no significant association was reported [15]. In toddlers, while shorter nap duration and higher nighttime sleep ratios were reported to be associated with cognition, nighttime/total sleep duration and nighttime sleep midpoint were related to gross motor development [16].

In summary, the relationship between average sleep-related time and cognitive function or developmental profiles remains unclear.

Newborns show interest in human faces from birth [17]. Children with autism spectrum disorders (ASD) have been reported to prefer repetitive images (geometric patterns) rather than social images (such as humans) and pay less attention to the human eye than children with typical development do [17–21]. Therefore, eye tracking is expected to be a biomarker for individuals with ASD, with gaze patterns being considered indicators of social development. Specifically, less fixation on the eyes is correlated with greater social disability [20]. Using an eye-tracking machine, infantile sleep problems were negatively associated with a later preference for human faces [22]; however, there have been only a few reports about the relationship between sleep habits and social attention using objective tools.

The brain networks associated with attention to social images involve the area of perceptual decoding and integration of social cues (face, gaze, action, and voice), which is related to the posterior superior temporal sulcus, adjacent lateral occipitotemporal cortex, fusiform gyrus, intraparietal sulcus, and premotor cortex [23–26]. These corresponded to central and parietal regions on electroencephalography (EEG). In a resting-state functional magnetic resonance imaging study, children with ASD had decreased functional connectivity in the action observational network, particularly in the lateral occipital cortex and fusiform gyrus [27].

This study aimed to investigate the relationship between sleep habits and development, especially social development, using an eye tracker and brain coherence EEG in toddlers.

2. Methods

2.1. Participants

Eighty-six young children, aged 1.5–2 years (range 18–25 months), were enrolled between March 2021 and January 2023 through web advertising and leaflet distribution around Osaka University. This study used the data set at the first time point in the longitudinal study, from toddlers until 6 years old. There has not been enough research on the relationship between sleep and brain functional development using objective tools such as EEG or eye tracking. Therefore, in this study, we evaluated the data set at the first time point as the cross-sectional exploratory study examining the sleep-related factors influencing brain functions. We will confirm its validity in a longitudinal follow-up study where improvement of these sleep-related indices may make a significant influence in brain functional development in the future study.

The inclusion criterion was healthy, full-term children aged 18–35 months. The exclusion criteria were as follows: 1) the children were suspected of being abused, 2) the caregiver could not cooperate with this study because of their mental disease, and 3) the children had received interventions for their mental and motor developmental problems.

This study was approved by the Institutional Review Board of Osaka University Hospital (20260-3) prior to the start of the study and conformed to the tenets of the Declaration of Helsinki. The parents of all children provided written informed consent before enrollment.

2.2. Sleep parameters

Data for sleep parameters were collected for 8 consecutive days using the Nenne Navi app, as previously described [28]. Previous studies have demonstrated the app's sufficient usability and acceptability, and the reported data were sufficiently reliable in comparison with those obtained using actigraphy [28,29]. We obtained representative sleep parameters, such as average wake-up time, bedtime, nighttime sleep duration, total sleep duration, nap duration, and sleep onset latency. The mean sleep parameters in each child were averaged over 7 days. The standard deviations (SD) of these parameters for 7 days in each child were calculated and used as indices of sleep irregularity. We analyzed the children who have entered sleep factors on at least 3 consecutive weekdays and weekends.

2.3. Measure of Children's development

To assess global development, we used the Kinder Infant Development Scale (KIDS), which is a parent-rated questionnaire developed and validated in Japan [30], and the Bayley Scales of Infant and Toddler Development, Third Edition, Japanese version [31], which was used by psychologists to assess five domains: cognition, receptive communication, expressive communication, fine motor, and gross motor. To evaluate the ASD characteristics, the Japanese version of the Modified Checklist for Toddlers with Autism (M-CHAT) was administered [32]. The children who failed three or more items were suspected of having features of ASD.

2.4. Acquisition of eye-tracking data and EEG

To evaluate the association between a lack of orientation toward humans and brain connectivity during visual attention, we simultaneously measured eye tracking while watching a video monitor and recorded EEG.

The eye-tracking measurement was performed using Gazefinder® (JVC KENWOOD Co, Yokohama, Japan).

Children were placed on their caregivers' laps and fitted with a stretch cap (Waveguard; Eemagine Medical Imaging Solutions GmbH, Berlin, Germany) with 19 electrodes in a 10/20 system pattern (Fig. 1a). The children watched a 19-inch monitor with 1280 × 1024 pixels, which was set approximately 60 cm away from them. Eye position was recorded at a sampling rate of 50 Hz. After calibration of the eye position was performed using a five-point method, a series of short movies lasting approximately 2 min were displayed to calculate the fixation time in the relevant area.

One of the presented images is shown in Fig. 1b. The movie included several types of videos of a human face, biological motion, pointing objects, and human and geometric figures.

The percentage of fixation times for defined areas in each movie was automatically calculated. In the movies with human and geometric figures, the target areas were set as human or geometric figures, and the target areas were set as the eyes and mouth in a movie of a talking human. We analyzed only the fixation times with a whole viewpoint acquisition rate of 60 % or higher. The mean percentage of fixation times in movies similar to those used in previous reports documenting ASD characteristics was analyzed [21,33].

Simultaneously, EEG, which is a noninvasive and readily available tool for toddlers, was recorded using the TruScan 32 system (DeyMed Diagnostic, Kudrnáčova, Czech Republic) with a sampling rate of 1000 Hz, and a CPz electrode was used as a system reference. The hardware filter setting was 0.1–100 Hz.

Coherence analysis was performed using the EMSE Suit (Corthch Solutions, NC, USA). Artifacts were visually removed by experienced researchers (Y.I. and S.N.). EEG coherence between pairs of scalp locations can provide information on the intrahemispheric and interhemispheric networks. The frequency bands were divided into delta (1.96–3.92 Hz), theta (4.9–7.84 Hz), alpha (8.83–13.72 Hz), beta (14.7–24.5 Hz), and gamma (35.28–44.1 Hz). Coherence values were derived for each band.

2.5. Statistical analysis

We conducted a correlation analysis of the variables after testing for normality. Spearman's rank correlation test in non-normal distribution or the Pearson correlation test in normal distribution was performed to

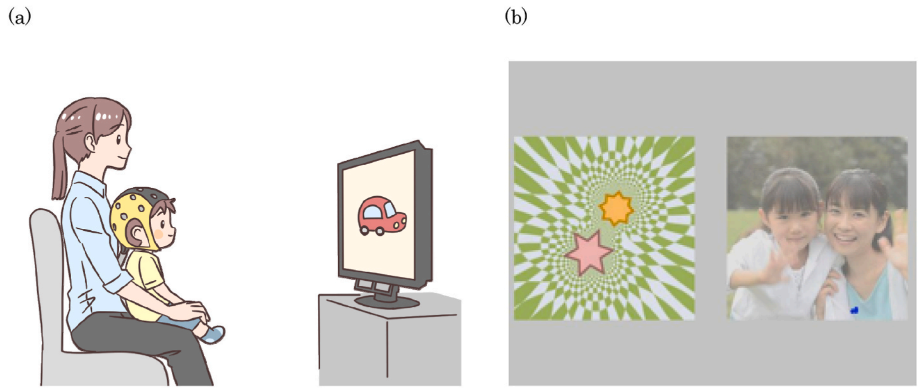

Fig. 1. Schematic diagram of the experiment (a) The child sitting on the mother's lap and watching a movie with an electrode cap (b) One of the presented images in the movie on the screen. Left, geometric figure; Right, human face.

evaluate the correlation between sleep habits and development, the percentage of fixation times for eyes and mouths in a face or preference for human and geometric figures, and EEG coherence. All the children were classified into group T with less than three failed M-CHAT items and group M with three or more failed items. The Mann–Whitney *U* test was used to detect the differences between these two groups to examine the effects of autistic features on communicative development and eye-tracking traits. Otherwise, children were classified into a group (group H) in which the father and mother are highly educated (university or graduate school graduates) and another group (group L) in which the father and mother are not highly educated. The comparison between sexes and, high and low parental education was performed using a Mann–Whitney *U* test or a *t*-test. Regarding family income, children were classified into four groups (1; 3,000,000–5,000,000 yen, 2; 5,000,000–7,000,000 yen, 3; 7,000,000–10,000,000 yen, 4; >10,000,000 yen). The Kruskal-Wallis test was used for the analysis.

All analyses were performed using the Statistical Package for Social Sciences (SPSS), version 26.0 (SPSS Inc. Chicago, Illinois, United States).

Structural equation modeling (SEM) was used to elucidate the factors that are correlated with the development and coherence of toddlers based on the following hypothesis: We hypothesized that sleep habits, including average sleep duration, bedtime, awakening frequency after sleep onset, and the SD of these parameters influenced social and communication development and brain function. Moreover, we considered age, sex, parental education, and family income as potential confounding variables, performed correlation analysis, and added the factors correlated with the development and coherence. We ascertained that the models, consistent with the hypothesis, were either accepted or rejected. The goodness-of-fit index (GFI), adjusted goodness-of-fit index (AGFI), comparative fit index (CFI), and root mean square error of approximation (RMSEA) were used to evaluate the model fit. The SEM analysis was performed using AMOS version 29 (IBM Japan Ltd.).

3. Results

3.1. Overall results of clinical characteristics

A total of 72 children (37 boys and 35 girls) were included in the

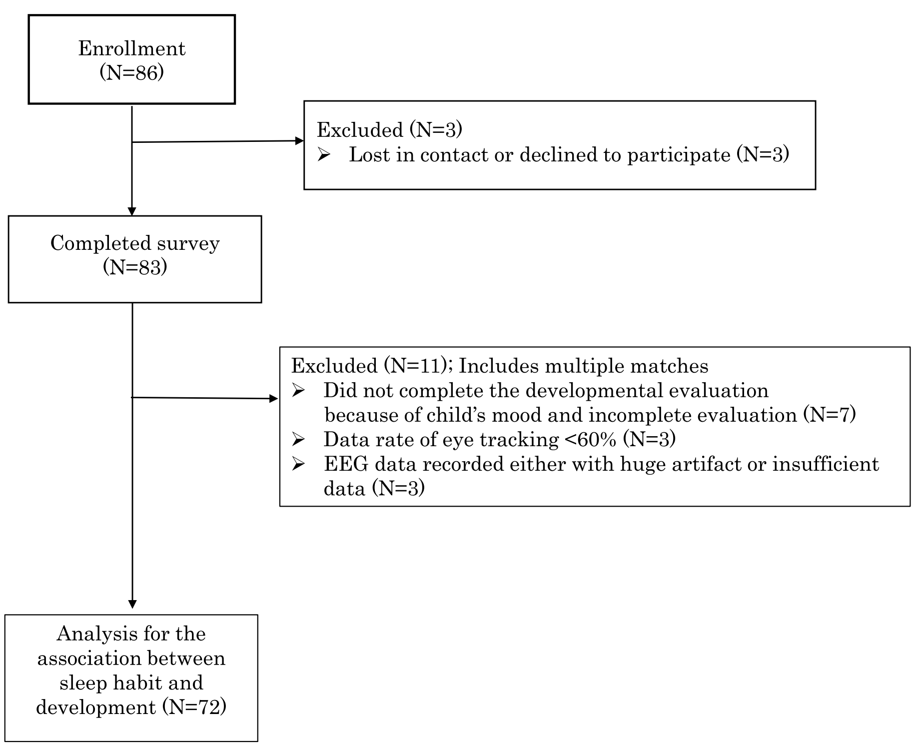

Fig. 2. Flow diagram of the study EEG, electroencephalography.

analysis after excluding 14 children (Fig. 2). Notably, all the children except three had sleep parameters for 7 days and the remaining three children had 6-days consecutive data.

The developmental quotient (DQ; mean ± SD) of the KIDS in 72 children was 107 ± 13 (Table 1). Eight children (11 %) had three or more failed items of M-CHAT. The number of failed items was not associated with development on the Bayley Scales (data not shown). Moreover, there were no significant differences in cognition, receptive communication, expressive communication ability, or fixation percentage for humans between groups M and T ($p = 0.462$, $p = 0.107$, $p = 0.680$, and $p = 0.936$, respectively).

The number of group H in parental education or maternal education was 57 (79 %) and 51 (71 %), respectively. However, the number groups 1, 2, 3 and 4 in the family income were 11 (15 %), 14 (19 %), 27 (38 %), and 17 (24 %).

3.2. Development and sleep habits

The correlations between sleep habits and developmental and behavioral indices are shown in Table 2. The DQ of the cognitive domain was negatively correlated with the SD of bedtime ($r = -0.242$, $p = 0.041$) and SD of nighttime sleep duration ($r = -0.261$, $p = 0.027$) (Fig. 3a). Moreover, the DQ of the receptive communication domain was negatively correlated with the SD of bedtime ($r = -0.397$, $p = 0.001$), SD of total sleep duration ($r = -0.252$, $p = 0.032$), and SD of nighttime sleep duration ($r = -0.245$, $p = 0.038$). The DQ of the expressive communication domain correlated with the SD of bedtime ($r = -0.317$, $p = 0.007$) and nighttime sleep duration ($r = -0.263$, $p = 0.026$) (Fig. 3b). The DQ of the gross motor domain was correlated with the SD of sleep-onset latency and SD of total sleep duration ($r = -0.233$, $p = 0.048$; $r = -0.241$, $p = 0.041$). However, fine motor development was

Table 1
Characteristics and sleep habits of participants in this study.

	Mean ± SD
Age (month)	22 ± 2
Sex (male/female)	37/35
Bayley Scales of Infant and Toddler Development	
Cognition	108 ± 15
Receptive communication	99 ± 24
Expressive communication	93 ± 24
Gross motor	99 ± 16
Fine motor	105 ± 12
Kinder Infant Development Scale	
Total developmental quotient	107 ± 13
Sleep habits	
Wake-up time (time, min)	7:13 ± 0:48
SD of wake-up time (min)	29.9 ± 15.1
Bedtime (time, min)	20:53 ± 0:52
SD of bedtime (min)	30.3 ± 25.1
Sleep-onset latency (min)	32.7 ± 21.4
SD of sleep-onset latency (min)	18.8 ± 13.6
Total sleep duration (min)	691.1 ± 38.9
SD of total sleep duration (min)	50.4 ± 22.3
Nighttime sleep duration (min)	584.6 ± 43.3
SD of nighttime sleep duration (min)	45.0 ± 24.4
Number of awakenings after sleep onset (per night)	1.4 ± 1.3
Nap duration (min)	106.2 ± 33.2
SD of nap duration (min)	38.7 ± 19.3
Nap starting time (time, min)	13:13 ± 1:15
Nap ending time (time, min)	15:02 ± 1:20
Gazefinder: Mean fixation percentages	
Human (%)	0.578 ± 0.120
Geometric figure (%)	0.140 ± 0.111
Eyes in a talking human face (%)	0.229 ± 0.182
Mouth in a talking human face (%)	0.642 ± 0.233
α-band coherence of the EEG	
C3-C4	0.124 ± 0.070
C3-P3	0.328 ± 0.081
C4-P4	0.307 ± 0.081

SD, Standard deviation; EEG, Electroencephalography.

Table 2
Correlation between sleep habits and developmental/behavioral indices.

Sleep habits	DQ					Human and geometric figure†		Talking human face†		Coherence of the EEG				
	Cog	RC	EC	Fine motor	Gross motor	Human face (%)	Geometric figure (%)	Eyes (%)	Mouth (%)	C3-P3 (α)	C4-P4 (α)	C3-C4 (α)	F3-F4 (θ)	Fp1-Fp2 (γ)
Wake-up time (time, min)	0.041	−0.083	0.103	0.138	−0.100	−0.052	−0.040	−0.011	0.151	0.152	−0.178	0.080	0.177	−0.082
SD of wake-up time (min)	−0.104	−0.191	−0.161	−0.112	0.158	−0.022	0.209	−0.038	0.050	0.216	0.064	0.147	0.107	**−0.247***
Bedtime (time, min)	−0.092	−0.118	−0.016	0.065	−0.072	−0.105	0.001	−0.062	0.052	0.129	−0.059	0.124	0.205	−0.184
SD of bedtime (min)	**−0.242***	**−0.397****	**−0.317****	0.004	−0.110	**−0.324****	0.139	−0.190	**0.283***	0.185	−0.113	0.043	**0.255***	−0.168
Sleep-onset latency (min)	0.016	0.195	0.082	−0.008	−0.148	0.044	0.137	0.024	−0.042	−0.104	0.024	−0.093	0.155	−0.170
SD of sleep-onset latency (min)	−0.179	−0.019	0.023	−0.046	**−0.233***	−0.183	0.211	−0.122	0.074	−0.027	0.042	−0.009	**0.338****	−0.163
Total sleep duration (min)	−0.032	−0.107	−0.013	0.032	0.092	0.129	−0.212	0.130	0.037	0.019	**−0.283***	−0.096	−0.073	**0.274***
SD of total sleep duration (min)	0.038	**−0.252***	−0.197	−0.010	**−0.241***	**−0.516****	**0.385****	−0.133	0.111	**0.243***	0.121	0.101	0.189	−0.200
Nighttime sleep duration (min)	0.084	−0.052	0.051	0.035	−0.018	0.132	−0.169	0.074	0.078	0.043	−0.144	−0.105	−0.149	**0.263***
SD of nighttime sleep duration (min)	**−0.261***	**−0.245***	**−0.263***	0.023	−0.073	**−0.331****	0.199	**−0.270***	0.231	0.080	−0.097	0.084	**0.337****	**−0.295***
Number of awakenings after sleep onset	−0.016	−0.059	−0.055	0.018	0.025	−0.030	−0.078	**−0.289***	0.204	−0.123	−0.033	−0.095	0.040	0.036
Nap duration (min)	−0.143	−0.060	−0.086	−0.006	0.115	−0.004	−0.062	0.115	−0.074	−0.031	−0.140	0.026	0.113	−0.010
SD of nap duration (min)	0.037	−0.232	−0.111	−0.175	−0.102	**−0.330****	**0.354****	−0.019	−0.003	0.208	0.135	0.048	**0.336****	−0.082
Nap starting time (time, min)	−0.023	0.086	0.009	0.040	−0.051	−0.147	0.070	0.021	0.058	0.039	−0.007	−0.006	0.014	−0.163
Nap ending time (time, min)	−0.077	0.091	−0.009	−0.009	−0.019	−0.163	0.085	0.182	−0.068	0.017	−0.028	−0.003	0.047	−0.181

†; Mean fixation percentages measured using Gazefinder®. *; $p < 0.05$; **; $p < 0.01$, Cog; Cognition, RC; Receptive communication; EC; Expressive, SD; Standard deviation.

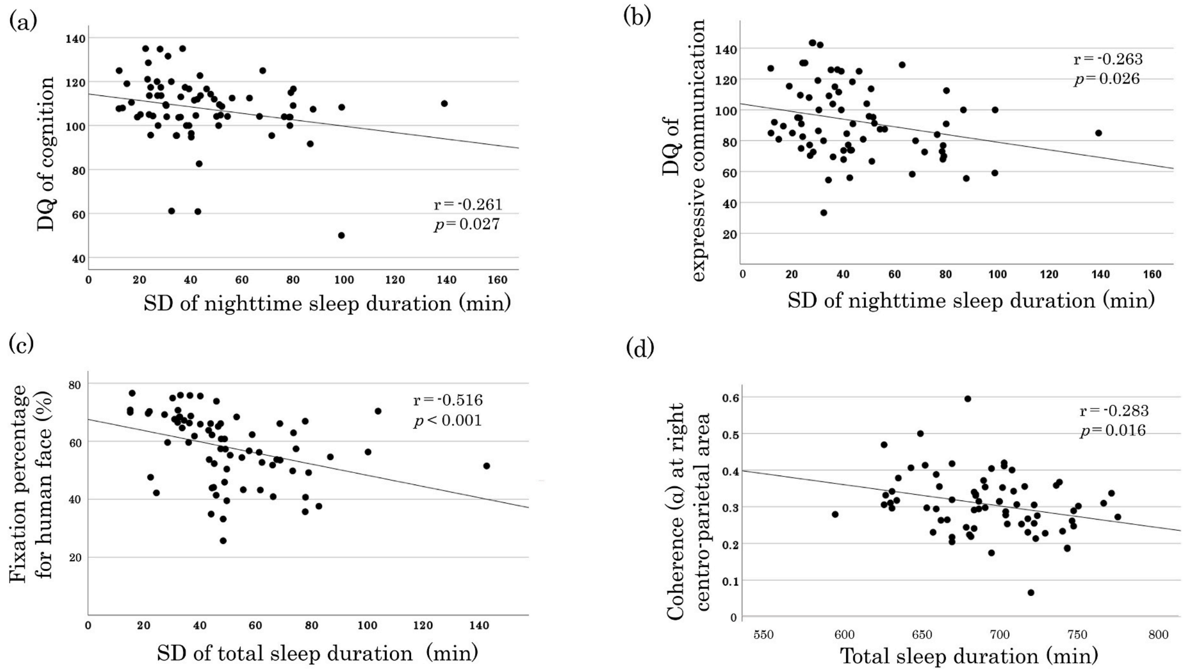

Fig. 3. Correlation between social development, brain function, and sleep habits (a) Scattered plots of correlation between cognition and the SD of nighttime sleep duration (b) Scattered plots of correlation between expressive communication and the SD of nighttime sleep duration (c) Scattered plots of association between the fixation percentage for the human face (%) and SD of total sleep duration (d) Scattered plots of correlation between coherence (α) at the right centro-parietal area and the total sleep duration.

not associated with any of these sleep habits.

3.3. Eye-tracking fixation time percentage and sleep habits

The average percentage of fixation was 93.4 ± 5.8 % in all series of movies. The fixation percentage for the human face was negatively correlated with the SD of the total sleep duration (Fig. 3c), nighttime sleep duration, nap duration, and bedtime (Table 2; $r = -0.516$, $p < 0.001$; $r = -0.331$, $p = 0.005$; $r = -0.330$, $p = 0.005$; and $r = -0.324$, $p = 0.005$, respectively). Only in group T and not in group M, the fixation percentage for the human face was negatively correlated with the SD of the total sleep duration ($r = -0.530$, $p < 0.001$) (Supplementary Fig. 1).

The fixation percentage for geometric figures showed a positive correlation with the SD of total sleep duration and SD of nap duration ($r = 0.385$, $p = 0.001$; and $r = 0.354$, $p = 0.002$, respectively) (Table 2). Children with a shorter SD of nighttime sleep duration and fewer awakenings tended to look at the eyes of a talking human for a longer time ($r = -0.270$, $p = 0.022$; $r = -0.289$, $p = 0.014$, respectively). The averages of wake-up time, bedtime, sleep-onset latency, total sleep duration, nighttime sleep duration, and nap duration were not associated with any eye-tracking trait in human and geometric figures or talking human movies.

3.4. EEG coherence and sleep habits

The correlation between EEG coherence and sleep habits is presented in Table 2. The α-band coherence in the left centro-parietal area (C3-P3) was correlated with the SD of total sleep duration ($r = 0.243$, $p = 0.040$), while that in the right centro-parietal area (C4-P4) was negatively related with total sleep duration ($r = -0.283$, $p = 0.016$) (Fig. 3d). Moreover, there was a positive correlation between the fixation time percentage for geometry and α-band coherence in the leftand right centro-parietal areas ($r = 0.302$, $p = 0.010$; $r = 0.240$, $p = 0.042$) (Table 3, Fig. 4-ab).

3.5. Directional association between sleep habits and development

As each sleep parameter may be associated with the others, we created a path diagram to examine which sleep habits influenced social and communication development and brain function most strongly. Age was neither correlated with the DQ, nor with the percentage of fixation times for preference for human and geometric figures or coherence (Supplementary Table). Regarding the sex, the Fp1-Fp2 coherence and DQ of expressive communication were significantly higher in girls than in boys ($p = 0.012$, $p = 0.031$). There was no relationship between the DQ, the percentage of fixation times and coherence and parental education and family income (Supplementary Table). Therefore, we created a suitable model according to the results of the correlational analysis. The previous model of the relationship among sleep habits, development, and frontal and centro-parietal coherence proposed that irregular sleep habits influence the connection of different brain regions and development. This model demonstrated that the direct effect of nighttime sleep duration irregularity on development, consisting of receptive/expressive communication, cognition, and fixation time for humans, was statistically significant. Moreover, we identified the direct effect of total sleep duration on α cortical coherence in the C4-P4 area while watching the movies, irregular nighttime sleep duration on γ coherence at Fp1-Fp2, and irregular nap duration on θ coherence at F3-F4 (GFI = 0.890, AGFI = 0.828, CFI = 0.946, and RMSEA = 0.050; Fig. 5). There was no significant direct link between development and

Table 3
Correlation between eye tracking results and centro-parietal coherence indices.

	Human and geometric figures		Talking human face	
	Human figure (%)	Geometric figure (%)	Eyes (%)	Mouth (%)
α-band coherence of EEG				
C3-C4	0.089	0.215	0.089	0.044
C3-P3	−0.108	0.302**	0.211	−0.125
C4-P4	−0.034	0.240*	0.005	−0.111

*:p < 0.05, **: p < 0.01.

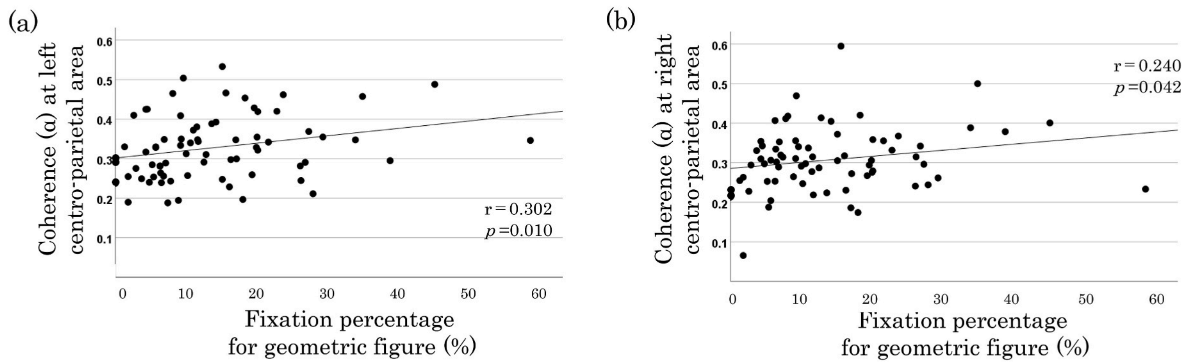

Fig. 4. Scatter plots of correlation between the alpha band coherence in the centro-parietal area and fixation percentage for geometric figures (a) Left, (b) Right.

brain coherence. However, sex was associated with expressive communication. Another model was created based on the hypothesis that sex was associated with Fp1-Fp2 coherence and DQ of expressive communication (GFI = 0.887, AGFI = 0.827, CFI = 0.966, and RMSEA = 0.037). In the model, the SD of nighttime sleep duration on Fp1-Fp2 coherence tends to be significant ($p = 0.055$), and sex on DQ of expressive communication was not significant. Therefore, the former of these two models was judged to be a fit when considering suitability.

4. Discussion

This is the first study to demonstrate that nighttime sleep duration irregularity in toddlers is associated with the development of cognition and social communication. In addition, we found a correlation between total sleep duration, irregularities in night sleep/nap duration, and coherence in the centro-parietal and frontal regions.

4.1. Sleep habits and child early development

Since the average bedtime and nighttime sleep duration for Japanese children at less than 3 years old were 21:11 ± 1:04 and 565.2 ± 65.4 min, respectively [34], the sleep habits in this study were representative of the population in Japan.

Our study revealed no significant correlations between the developmental profiles and any average values of sleep parameters. The discrepancies in our results compared to those of these previous studies may be attributed to the age group included in our study, which is younger than that in previous studies. Alternatively, many previous longitudinal reports have evaluated language and behavioral difficulties, including inattention, at a later stage [7,9,11,35]; however, our study is a cross-sectional one where the present developmental profile may reflect the preceding sleep habits of toddlers and brain function. Notably, no previous study has evaluated the relationship between the sleep habits of toddlers and functional evaluation using EEG and eye-tracking.

Recently, the association between irregular bedtime and aggression or inattention in children aged 2–5 years [36] and that between irregular wake time and poor cognitive development in preterm toddlers [37] were demonstrated. Moreover, in a longitudinal study of children aged 3–7 years, irregular bedtimes led to problematic behavior, which improved with consistent bedtimes [38]. Our study added to the evidence that the irregularity of sleep habits, but not their average time, may have a larger impact on the development of toddlers.

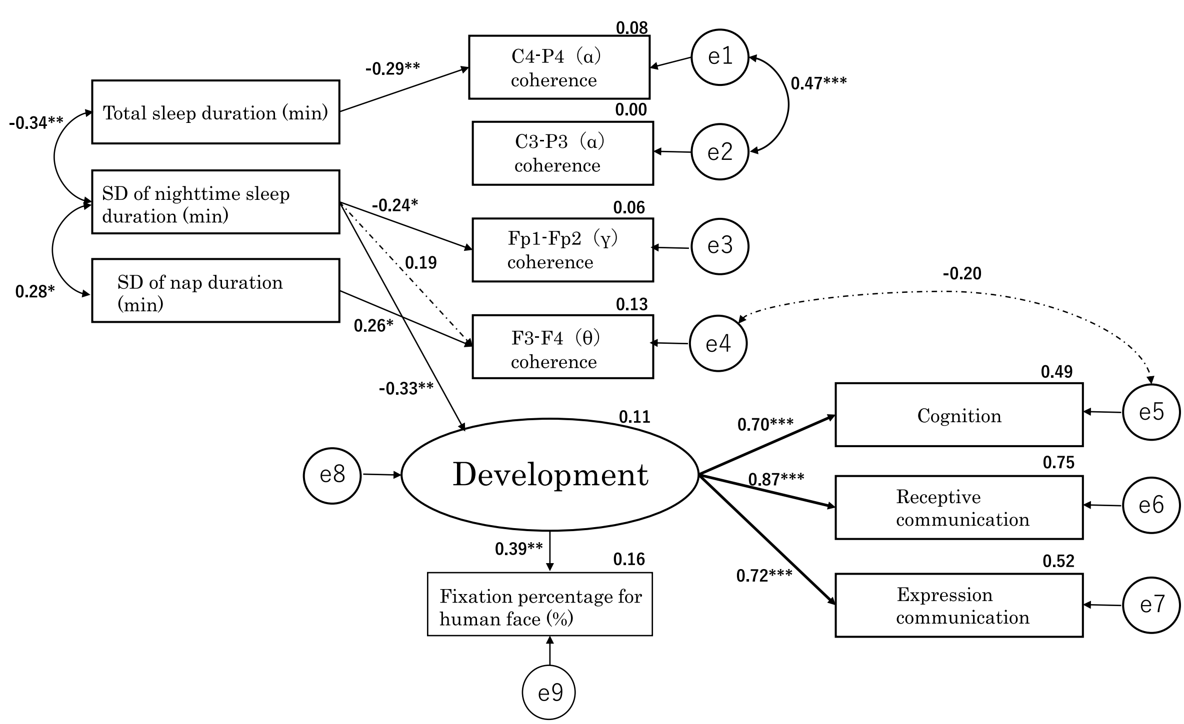

Fig. 5. Path diagram of a multi and mediated model for associations between sleep habits and development *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

4.2. Sleep habits, visual preference for human and geometric images, and brain coherence

It may be argued that sleep irregularity, a feature of ASD, led to decreased attention to the faces in this study. However, although 11 % of children had M-CHAT scores of more than 3, M-CHAT scores at baseline were not related to sleep habits or development. In addition, as described, only in group T and not in group M, the fixation percentage for the human face was negatively correlated with the SD of the total sleep duration ($r = -0.530$, $p < 0.001$). This correlation might indicate that the correlation of non-preference for humans with irregular sleep duration was not a direct result of the autistic traits among children. Whereas the M-CHAT score at this young age does not precisely predict later ASD diagnosis, this result may indicate that irregular sleep habits distort social development towards autism even in children without inborn ASD traits.

In many reports, individuals with ASD have shown differences in coherence based on EEG, because of the age differences, the types of presented tasks, and conditions (e.g., eyes open or eyes closed) [39–42]. A previous systematic review using EEG and magnetoencephalography demonstrated under-connectivity between long-distance regions, including the interhemispheric and interlobar distances, in the lower frequencies (delta to beta bands) in ASD. However, local (short-distance) underconnectivity at lower frequency ranges or over-connectivity at lower and higher frequencies have also been reported in ASD. These inconsistent results indicate that local connectivity remains controversial [43].

Direct gaze elicits a gamma burst over the right prefrontal area in 4-month-old infants [44]. Increased or decreased coherence in the frontal area is associated with later ASD symptoms and diagnosis [45,46]. The decreased gamma coherence with increased theta coherence in the frontal region in this study might be associated with later symptoms of ASD. The centro-parietal area is associated with visual attention and the execution of actions when observing other people's actions [47]. This area plays an important role in higher brain functions, such as execution and social behavior.

Irregular sleep directly affects the circadian rhythm, which interacts with a homeostatic process [48]. In a study assessing motor skill and visual skill tasks, correlations were observed between improvements in daytime performance and a higher percentage of slow wave sleep (SWS) in the first quarter of the night, as well as stage 2 rapid eye movement (REM) and non-REM (NREM) sleep in the last quarter of the night [6]. Therefore, maintaining regular sleep-wake rhythms is crucial, as they influence the pattern of the sleep stage. On the other hand, under normal conditions, synaptic strength increases during wakefulness and decreases during sleep [49]. This downscaling of synaptic strength is beneficial for learning and memory consolidation. Notably, SWS and REM sleep are thought to contribute to the consolidation of complex memory [6]. Irregular sleep might thus affect the downscaling of synaptic strength and gamma oscillation emerging from the coordinated interaction of excitation and inhibition, which might be reflected in EEG coherence. Our results suggest a concerning implication: sleep irregularity during early childhood disrupts brain coherence, potentially impairing social development or possibly reinforcing existing impairments. In this study, we performed SEM by dividing the data based on sex, which is considered a covariate. However, the number of cases was small; therefore, we were unable to analyze it. Thus, considering the suitability of SEM, we thought that a model that did not include sex would be better. Given that previous studies have indicated significant long-term effects of sleep habits on developmental outcomes, it is imperative to conduct a longitudinal cohort study to track the children from this study and validate our findings.

4.3. Strengths and limitations

In this study, we analyzed children's development as evaluated by a psychologist and objective tools, such as eye-tracking devices and EEG. However, this study has some limitations. First, this study analyzed data from the first time point in the longitudinal study, from toddlers until 6 years old with a relatively small sample size. Therefore, to mitigate this limitation, we used the Bayley Scales of Infant and Toddler Development and the report of sleep habits over consecutive 8 days to estimate the SD. Although EEGs and eye-tracking measurements can be challenging in many uncooperative toddlers, we provided the results based on exact and objective data with only a small number of dropouts. Second, the sleep habits were exclusively based on the parental reports. However, the used app requiring daily inputs made the recall bias insignificant. Third, in this study, the number of children with three or more failed items of the M-CHAT was small; therefore, we could not completely deny the association between sleep habits and social development with eye tracking in children with innate ASD.

5. Conclusion

The development of social communication may be associated with sleep irregularity in toddlers. Regular sleep plays an important role in promoting socio-communicational development, which is the basis of well-being. In the future, we should confirm the association between sleep habits, development, and brain connectivity in a longitudinal study to determine whether improvement in sleep habits could facilitate social communication skills in each child.

CRediT authorship contribution statement

Yoshiko Iwatani: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Kuriko Kagitani-Shimono:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Azusa Ono:** Writing – review & editing, Investigation, Formal analysis, Data curation, Conceptualization. **Tomoka Yamamoto:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Ikuko Mohri:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Arika Yoshizaki:** Writing – review & editing, Validation, Methodology, Funding acquisition, Data curation, Conceptualization. **Masako Taniike:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Masako Taniike reports financial support was provided by Japan Science and Technology Agency. Masako Taniike reports financial support was provided by Japan Society for the Promotion of Science. Kuriko Kagitani-Shimono reports financial support was provided by Japan Society for the Promotion of Science. Arika Yoshizaki reports financial support was provided by Japan Society for the Promotion of Science. Yoshiko Iwatani reports financial support was provided by the Japan Foundation for Pediatric Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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