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RESEARCH ARTICLE

Validation of manually scored multichannel frontal electroencephalography against polysomnography in a paediatric cohort

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Summary

Polysomnography is the only internationally recognized method to diagnose paediatric obstructive sleep apnea, thus, simpler and more cost-effective diagnostic tools are urgently needed. This study aimed to validate the manual scoring of frontal self-applicable electroencephalography against polysomnography in a paediatric cohort. The polysomnography and the frontal electroencephalography were simultaneously recorded for 1 night ($n = 102$) in 10–13-year-old children. Scoring was performed according to the American Academy of Sleep Medicine rules, with minor adjustments to the frontal electroencephalography. Manual scorings of sleep stages were compared in an epoch-by-epoch manner using Cohen's kappa (κ) and confusion matrices using three different models: the three-stage (wake/non-rapid eye movement/rapid eye movement), the four-stage (wake/sleep stage 1 + sleep stage 2/deep sleep Stage 3/rapid eye movement) and the five-stage model (wake/sleep stage 1/sleep stage 2/deep sleep Stage 3/rapid eye movement). The inter-scorer agreements were assessed, and the intraclass correlation coefficient was used for common sleep

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variables: total sleep time, wake after sleep onset, sleep efficiency, sleep-onset latency and arousal index. Cohen's κ values for the three-stage, four-stage and five-stage models were 0.85, 0.73 and 0.70, respectively. The agreement for the sleep variables studied ranged from 0.87 to 0.99. The inter-rater agreement ($n = 10$) was $\kappa = 0.78$ for the polysomnography and $\kappa = 0.70$ for the frontal electroencephalography. Sleep staging from the frontal electroencephalography was comparable to that of a standard polysomnography in a paediatric cohort, and showed promising results in estimating sleep time and sleep architecture.

KEYWORDS
electroencephalography, manual sleep staging, paediatric sleep-disordered breathing, self-applied polysomnography

1 | INTRODUCTION

Sleep-disordered breathing (SDB) can range from primary snoring, being its mildest form, to severe obstructive sleep apnea (OSA; Sheldon et al., 2014). OSA in the adult and paediatric populations is characterized by a partial or complete obstruction of the airway disrupting normal breathing and interrupting normal sleep architecture (American Academy of Sleep Medicine, 2014). The prevalence of paediatric OSA has been estimated to be 1.2%–5.7%, while the prevalence of primary snoring, as reported by questionnaires, ranges between 1.5% and 27.6% (Marcus et al., 2012). This wide range is caused by the large variety of methodologies and diagnostic criteria utilized in different studies (Marcus et al., 2012).

It has been shown that SDB in children is linked to decreased academic performance (Galland et al., 2015) and cognitive dysfunction (Brockmann et al., 2012), with more severe SDB leading to greater cognitive impairment (Hunter et al., 2016). Other negative effects of SDB include, but are not limited to, hyperactivity and behavioural problems (Sedky et al., 2014), excessive daytime sleepiness (Brockmann et al., 2012), and hypertension (Ai et al., 2022). These adverse consequences of SDB highlight the importance of diagnosing and treating the affected children timely and effectively, both for primary snoring and OSA. The gold-standard method for the diagnosis of OSA in children is an in-laboratory polysomnography (PSG; Sheldon et al., 2014), commonly referred to as a type I sleep study. It, however, has several limitations: the setup is laborious and requires well-trained sleep technologists to hook-up the equipment and monitor the patient overnight (Fischer et al., 2012). In-laboratory PSG is also expensive (Masa et al., 2013), access is limited in many countries (Flemons et al., 2004), and the unfamiliar sleeping environment can cause anxiety and negatively affect sleep quality (Bruyneel et al., 2011). In such cases, the home setting may be a more desirable option. PSG in the home setting, commonly referred to as a type II sleep study or an ambulatory PSG, is also available but shares many of the same disadvantages as the in-lab PSG. Today the only internationally accepted method to diagnose paediatric OSA is an in-laboratory PSG (American Academy of Sleep Medicine, 2014; Berry et al., 2018).

In recent years, the use of single-channel frontal electroencephalography (EEG), often to supplement simpler sleep studies like respiratory polygraphy (type III sleep study), has been introduced. The benefits of a single-channel EEG include the possibility of sleep staging and total sleep time (TST) evaluation, and that the frontal placement of electrodes is easily accessible to the patient/participant for self-administration. Several studies (Light et al., 2018; Lucey et al., 2016; Sabil et al., 2019; Shambroom et al., 2012) have found good agreement between the single-channel frontal EEG and PSG in regard to sleep staging and/or sleep time. Studies also indicate that using frontal derivations is comparable to the more conventional montage (Fu et al., 2021; Korkalainen et al., 2019; Lee et al., 2019; Wang et al., 2021) in sleep staging with automatic algorithms, both for adults and children. The main limitation of a single-channel frontal EEG is the possibility of misplacement or detachment, lowering the reliability of sleep staging and sleep structure estimation (Lucey et al., 2016; Shambroom et al., 2012).

To overcome the limitations of the single-channel EEG, simple and easy-to-use new solutions with multi-channel frontal EEG are being developed, one of which is the self-applied somnography (SAS) system (Nox Medical, Reykjavik, Iceland) used in this study. The setup is done by the patient or their parent at home after watching an online instructional video, substantially lowering the workload on healthcare professionals and thereby potentially lowering the costs of the study. The relevance of the frontal EEG has been further emphasized by the COVID-19 pandemic as sleep diagnostics in many countries have shifted more towards home sleep recordings as in-laboratory PSGs were not available (Grote et al., 2020).

The aim of this study was to validate manual sleep staging of the frontal EEG against the standard EEG of a traditional PSG setup in a paediatric cohort. The primary hypothesis was that manual sleep staging of the frontal EEG, with adjusted scoring rules, is comparable to the manual sleep staging of the PSG. A secondary hypothesis was that other sleep variables, like TST, wake after sleep onset (WASO), sleep efficiency (SE), sleep-onset latency (SOL) and arousal index (ArI), are comparable between the two methods.

2 | METHODS

2.1 | Participants

The study consisted of 118 Icelandic children, aged 10–13 years. The children were participants in the Icelandic EuroPrevall/iFAAM (Integrated Approaches to Food Allergen and Allergy Risk Management) birth cohort study (European Commission, 2017; Keil et al., 2010). As a part of the EuroPrevall study in Iceland (Clausen et al., 2018), parents answered a questionnaire 2 years prior to the current study, including whether their children snored or if they had witnessed their children experiencing apneic episodes. All children with reported snoring, at least three times a week and/or witnessed apneas at least once a week ($n = 109$), were invited to take part in the present study; from which 55% ($n = 60$) agreed to participate. Children with no reported snoring or witnessed apneas were invited to participate as a control group. In the present study, however, these groups were pooled together and studied as a whole. The final study population consisted of 102 participants (girls $n = 35$; Figure 1; Table 1). The study was approved by the Ethical Committee of Landspitali (the National University Hospital of Iceland) and the National Bioethics Committee of Iceland (VSN 18-206). An informed written consent was obtained from a parent and/or legal guardian of all participants as well as oral consent from the participants themselves.

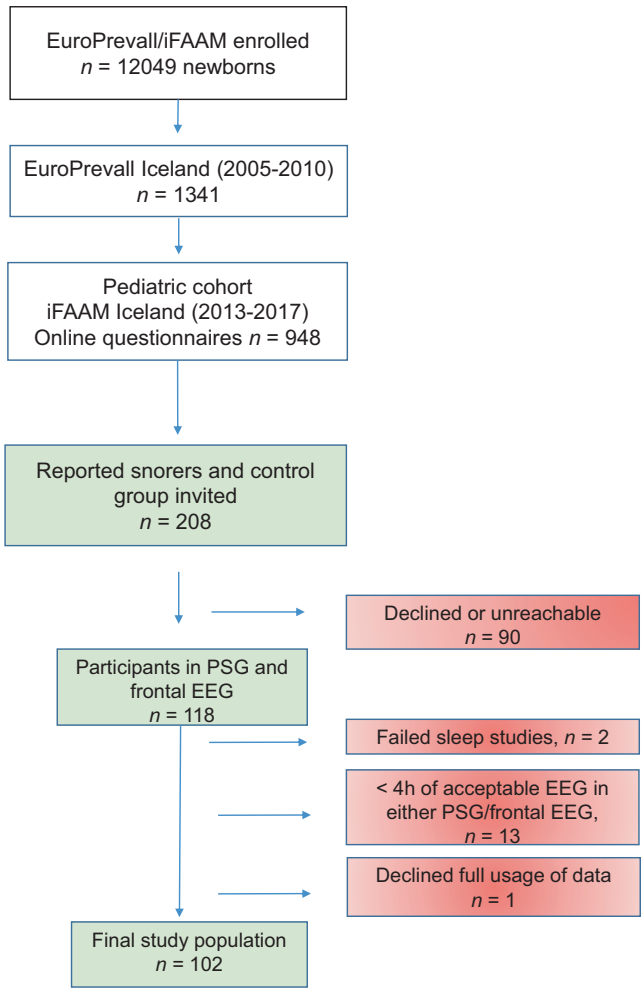

FIGURE 1 The flowchart of the study participant inclusion. EEG, electroencephalogram; iFAAM, integrated approaches to food allergen and allergy risk management; PSG, polysomnography.

TABLE 1 The demographics of the study population, shown as mean ± standard deviation except otherwise indicated.

Number of participants (boys *n*)	102 (67)
Age (years)	11.7 ± 0.8
BMI (kg m^{-2})	20.6 ± 3.6
AHI (events per hr)	0.8 ± 0.9
Children with AHI ≥ 1[a]	23.5%
Sat O_2	97.1 ± 0.6
Snoring (%)	2.4 ± 6.2
TST (min)	479.3 ± 55.9
SE (%)	93.1 ± 4.3
ArI (events per hr)	7.3 ± 2.5
SOL (min)	5.9 ± 5.0
WASO (min)	29.9 ± 21.2

Abbreviations: AHI, apnea–hypopnea index; ArI, arousal index; BMI, body mass index; sat O_2, oxygen saturation; SE, sleep efficiency; SOL, sleep-onset latency; TST, total sleep time; WASO, wake after sleep onset.
[a]Presented as percentage of children with AHI ≥ 1, not a mean value.

2.2 | Data collection

The data collection was conducted at the Icelandic Children's Hospital (Reykjavik, Iceland). Prior to the visit, the parent/legal guardian answered online questionnaires. Heights and weights were measured in a standardized manner, and neuropsychological tests were performed at the beginning of the children's visit. The latter part of the visit was the sleep study setup of the PSG and the frontal EEG. The equipment was hooked-up by experienced sleep technologists. The children slept with the equipment at home for 1 night.

The PSG study (Nox A1, Nox Medical) included the following sensors: EEG, electrooculogram (EOG), chin and leg electromyogram (EMG), electrocardiogram, nasal and oral pressure transducer (PureFlow® Duo oronasal cannula, Braebon, Kanata, Canada), thorax and abdomen respiratory inductance plethysmography belts, finger probe oximeter, microphone, electrodermal activity sensor, and an accelerometer. The placement of the electrodes was in accordance with the AASM Scoring Manual recommendations: F4-M1, C4-M1 and O2-M1 (F3-M2, C3-M2 and O1-M2 for backup) for EEG, and E1-M2 and E2-M1 for EOG (Berry et al., 2018). An additional Nox A1 device was placed on participants to measure the frontal EEG. The oral pressure transducer was connected to the second Nox A1 device as there is only one pressure channel on each device. The frontal EEG was recorded with a 10-electrode cable from the following locations: AF4, AF3, AF8 and AF7 (Figure 2). An EOG was also recorded with

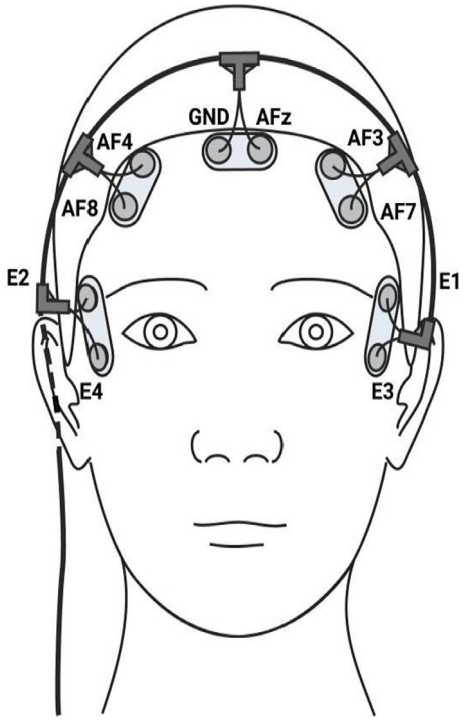

FIGURE 2 The frontal electrode setup used in the self-applied somnography (SAS). Figure courtesy of Nox Medical, Reykjavik, Iceland.

placements at approximately 1 cm above and below each eye (Figure 2). The AF leads were referenced to the average value from both eyes (E3 and E4) to minimize eye movement artefacts in the EEG. GND was the ground electrode and AFz was used for referencing the EOG (E2-AFz and E3-AFz). The muscle component of the EOG, named EMG temporalis, was used as a substitute for chin EMG.

As two different EEG recordings were collected from each participant, a total of 204 (2 × 102) recordings were used for analysis. The total number of 30-s epochs during the 102 recorded nights was 103,742, which yielded a total of 207,484 (2 × 103,742) epochs for comparison.

2.3 | Data analysis

The PSG studies were scored in a blinded fashion by two European Sleep Research Society-certified sleep technologists in conformity with the AASM paediatric scoring rules, version 2.5, the newest available at the time (Berry et al., 2018). One exception to these rules was applied: respiratory events after all large body movements (e.g. changing positions) were not scored unless they were part of a series of events, or occurred more than 20 s after the body movement.

The frontal EEG recordings were scored by the same sleep technologists in the same manner as the PSGs, except for the following modifications.

a. The low-pass filter of the EEG was changed from 0.3 to 0.5 Hz to get a more stable baseline for scoring, due to common baseline fluctuations.
b. The peak-to-peak amplitude criteria for the slow-wave activity was changed from 75 to 45 μV. Our previous work showed that the frontal EEG used in the present study has consistently lower amplitude and less power within the analysed frequency range (Kainulainen et al., 2021), making this change necessary to achieve scoring corresponding to PSG.
c. The low chin EMG rule was removed as there was no chin EMG in the frontal EEG setup. The EMG temporalis was used to substitute the chin EMG when scoring arousals in rapid eye movement (R) sleep, as an increase in EMG for at least 1 s is required to be able to score an arousal in that sleep stage (Berry et al., 2018).

The PSG and frontal EEG scorings were performed blindly with more than 6 months apart. Scorers were blinded to the order of recordings but not the study type (i.e. PSG or frontal EEG). It was not considered doable to blind scorers to the different types of studies, due to the differences between the signals and amplitude criteria used. Analyses were performed using Noxturnal (version 5.1.3.20388, Nox Medical, Reykjavik, Iceland) for the PSGs and Noxturnal Research (version 6.1.0.30257, Nox Medical, Reykjavik, Iceland) for the frontal EEGs. The same analysis periods (the same "lights off" and "lights on" time) were used in both the PSG and the frontal EEG recordings. All recordings with ≥ 4 hr of recorded EEG for both the frontal EEG and PSG were used in the comparison.

A set of 10 recording pairs (i.e. the PSG and the frontal EEG) were blindly scored by three certified sleep technologists twice (Scorer 1 and 2 for PSG and Scorer 2 and 3 for frontal EEG), with at least 2 weeks between the scorings, to assess the inter- and intra-scorer agreement.

2.4 | Statistical analysis

The manual sleep staging of PSGs and frontal EEGs was compared in an epoch-by-epoch manner. The agreement between scorings of PSGs and frontal EEGs was assessed using Cohen's kappa coefficient (κ; Cohen, 1960). The levels of agreement for the kappa statistics were categorized the following way: 0–0.20 = slight agreement; 0.21–0.40 = fair agreement; 0.41–0.60 = moderate agreement; 0.61–0.80 substantial agreement; and 0.81–1.00 as almost perfect agreement (Landis & Koch, 1977). Confusion matrices were made to illustrate the accuracy of the sleep staging, and three different models were used for this: a three-stage classification of sleep (wake [W], non-rapid eye movement sleep (NR), and sleep stage R); a four-stage classification where stage NR sleep was classified into light sleep (sleep stages 1 [N1] and 2 [N2] combined) and deep sleep (N3); and a five-stage classification. In the five-stage classification, NR sleep was further classified into N1, N2 and N3. Average time for each sleep stage and averages for the sleep variables (i.e. TST, WASO, SE, SOL and ArI) were also compared between the two methods using bivariate analysis, after testing the normality of the data using the Shapiro–Wilk test. The relationship of sleep stages, as well as the above-

mentioned sleep variables, between the PSG and frontal EEG recordings was further evaluated by using an intraclass correlation coefficient (ICC), and described graphically with scatter plots (SE and WASO) and Bland–Altman plots. The levels of agreement for the ICCs were categorized the following way: 0.00–0.25 = little; 0.26–0.49 = low; 0.50–0.69 = moderate; 0.70–0.89 = strong; and 0.90–1.00 = very strong (Munro, 2005). Statistical analysis was done in SPSS (version 28.0.1.1; Lucey et al., 2016) and Python (version 3.10.6), with additional panda (2.0.3) and scikit-learn (1.1.2) packages. Statistical significance was set at $p < 0.05$, with Bonferroni correction applied for multiple comparisons.

The overall inter- and intra-scorer agreements were assessed with Cohen's kappa coefficient and score match percentage (percent accuracy), for both methods, on a subset of the data ($n = 10$). Sleep stage-specific agreements were also calculated. These were computed by separately treating each manual scoring set as a reference, with the final sleep stage-specific percentage representing the average of the two values obtained from these calculations.

3 | RESULTS

3.1 | Scoring concordance between PSG and frontal EEG

In the three-stage classification model (W/NR/R), the epoch-by-epoch accuracy was 93.6%, corresponding to Cohen's κ of 0.85 (Figure 3). The accuracies of NR, stage W and stage R were 95.5%, 78.1% and 92.1%, respectively. In the four-stage model (W/N1 + N2/N3/R), the epoch-by-epoch accuracy was 81.8%, corresponding to Cohen's κ of 0.73 (Figure 4). In the five-stage model (W/N1/N2/N3/R), the epoch-by-epoch accuracy was 79.5%, corresponding to Cohen's κ of 0.70 (Figure 5). In the five-stage model, the misclassifications of NR sleep stages were most prominent. N1 epochs were only correctly classified 54.4% of the time, and most often classified as stage R and N2. N2 was correctly classified 65.3% of the time, and most often misclassified as N3. N3 was accurately classified 83.1% of the time.

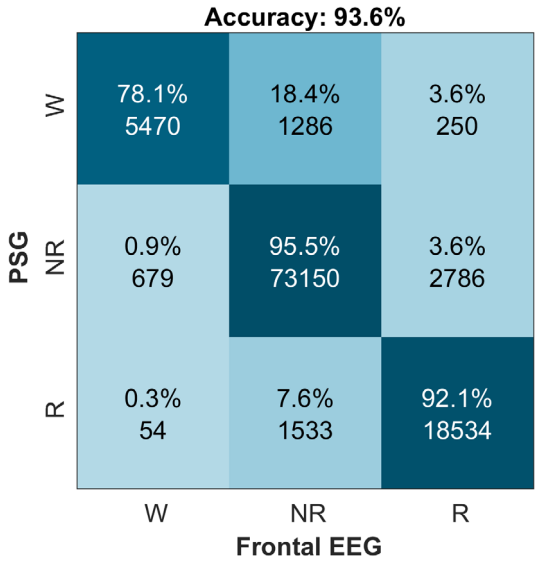

FIGURE 3 Confusion matrix of the sleep staging accuracies for wake (W), non-rapid eye movement sleep (NR) and rapid eye movement sleep (R) in a paediatric population ($n = 102$). EEG, electroencephalogram; PSG, polysomnography.

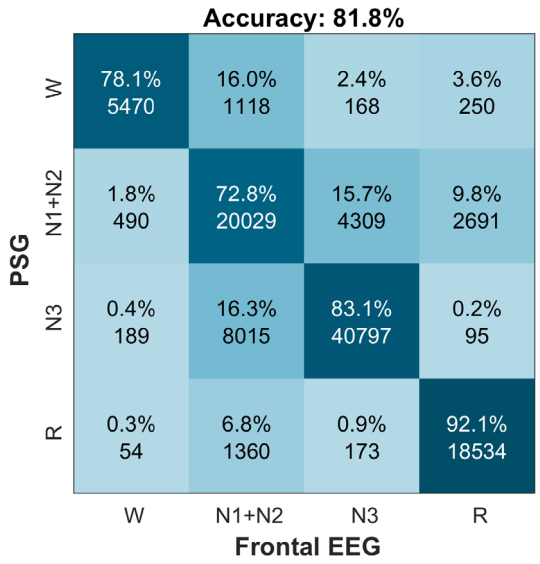

FIGURE 4 Confusion matrix of the sleep staging accuracies for wake (W), light sleep (N1 + N2), deep sleep (N3) and rapid eye movement sleep (R) in a paediatric population ($n = 102$). EEG, electroencephalogram; PSG, polysomnography.

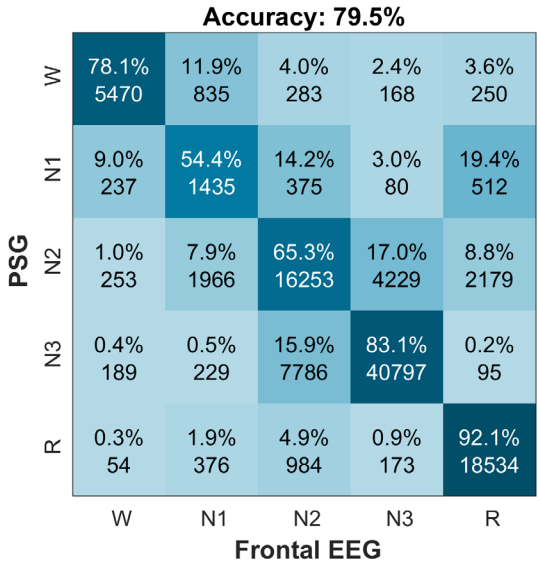

FIGURE 5 Confusion matrix of the sleep staging accuracies for wake (W), sleep stage N1, sleep stage N2, sleep stage N3 and rapid eye movement sleep (R) in a paediatric population ($n = 102$). EEG, electroencephalogram; PSG, polysomnography.

3.2 | Agreement of sleep variables

For the total duration of the sleep stages, the lowest correlation was for N1 (ICC of 0.51), but the others had an ICC > 0.78 with the highest value for stage R (0.93; Table 2). The intraclass correlation for all the sleep variables assessed (TST, WASO, SE and SOL) was >0.90, except for the ArI (ICC = 0.87; Figure 6; Table 2).

No statistically significant difference was found for the average amount of sleep stage N2 between the PSG and the frontal EEG (Table 2). However, the amount of stage N1 and stage R was significantly higher (by 10.7 ± 15.4 and 7.2 ± 14.9 min on average), and stage N3 was significantly lower in the frontal EEG than in the PSG (by −18.8 ± 51.4 min on average). In addition, the sleep variables examined differed significantly between the two methods, SOL being the only exception, even though the absolute difference was small. The bias was slightly positive for TST, SE and ArI. It was, however, slightly negative for WASO and close to zero for SOL (Figures 7–11; Table 2).

3.3 | Inter- and intra-scorer reliabilities

The overall intra-scorer agreements for the PSGs were 87.5% (κ = 0.82) and 89.3% (κ = 0.85) for the expert scorers S1 and S2, respectively, using a subset ($n = 10$) of the data. Similar agreements, albeit slightly lower, were found for the frontal EEGs, 83.8% (κ = 0.78) and 88.2% (κ = 0.84) for scorers S3 and S2, respectively (Table 3). Furthermore, the score match percentage for each sleep stage was calculated (Table 4). The agreement between the two methods was very similar for wake, for both intra- and inter-scoring reliability. For N1 and N2, the intra- and inter-scoring agreements were somewhat higher for the frontal EEG. The agreement for stages N3 and R was very similar for both methods' intra-scoring reliability, but slightly lower for the frontal EEGs inter-scoring reliability.

4 | DISCUSSION

In this study, the aim was to validate manual sleep staging of a frontal EEG against the standard PSG in a paediatric cohort. Sleep staging was found to be comparable between PSG and a multi-channel frontal

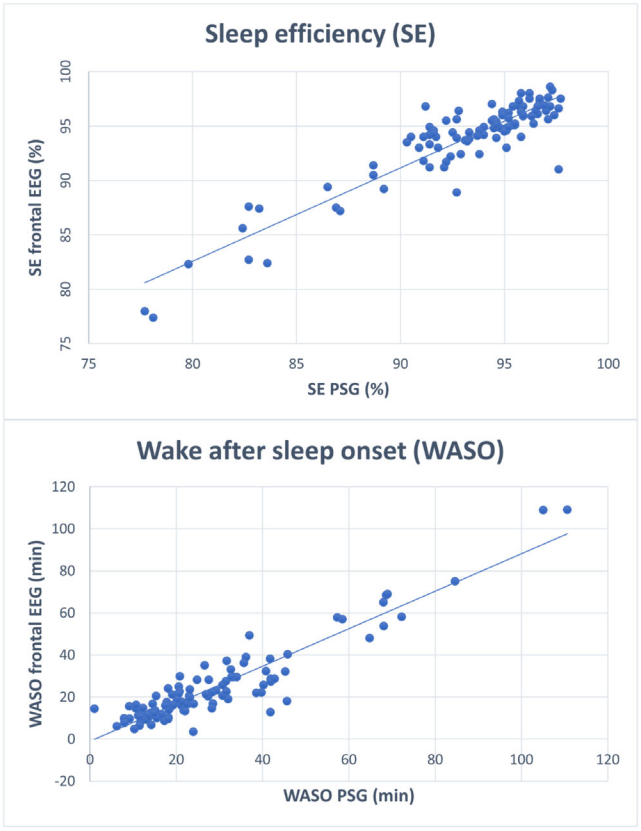

FIGURE 6 Scatterplots of the agreement between frontal electroencephalogram (EEG) versus polysomnography (PSG) for sleep efficiency (SE) and wake after sleep onset (WASO) in a paediatric population ($n = 102$).

TABLE 2 Comparison of sleep parameters between manually scored PSG and frontal EEG recordings ($n = 102$).

	PSG Mean ± SD	Frontal EEG Mean ± SD	Difference Mean ± SD	*p*-Value	PSG versus frontal EEG ICC
N1 (min)	13.0 ± 10.4	23.7 ± 15.8	10.7 ± 15.4	< *0.001*	0.512
N2 (min)	121.2 ± 50.2	125.9 ± 54.6	4.7 ± 44.5	0.493	0.780
N3 (min)	241.6 ± 61.9	222.8 ± 62.3	−18.8 ± 51.4	< *0.001*	0.793
R (min)	98.7 ± 26.9	105.7 ± 31.1	7.2 ± 14.9	< *0.001*	0.930
WASO (min)	29.1 ± 20.0	25.1 ± 19.1	−4.0 ± 7.2	< *0.001*	0.964
TST (min)	474.3 ± 63.4	478.1 ± 62.8	3.9 ± 7.4	< *0.001*	0.997
SE (%)	93.1 ± 4.2	93.8 ± 4.0	0.7 ± 1.5	< *0.001*	0.965
ArI (events per hr)	7.3 ± 2.5	7.6 ± 2.6	0.3 ± 1.7	0.024	0.873
SOL (min)	5.9 ± 5.0	5.6 ± 5.1	−0.3 ± 2.9	0.064	0.907

Note: The *p*-values were obtained with Wilcoxon Signed Rank Test. Italic values indicate a statistical significance ($p < 0.006$). The difference was calculated by subtracting PSG-based values from frontal EEG-based values.

Abbreviations: ArI, arousal index; EEG, electroencephalogram; ICC, intraclass correlation coefficient; N1, sleep stage 1; N2, sleep stage 2; N3, sleep Stage 3; PSG, polysomnography; R, rapid eye movement sleep; SD, standard deviation; SE, sleep efficiency; SOL, sleep-onset latency; TST, total sleep time; WASO, wake after sleep onset.

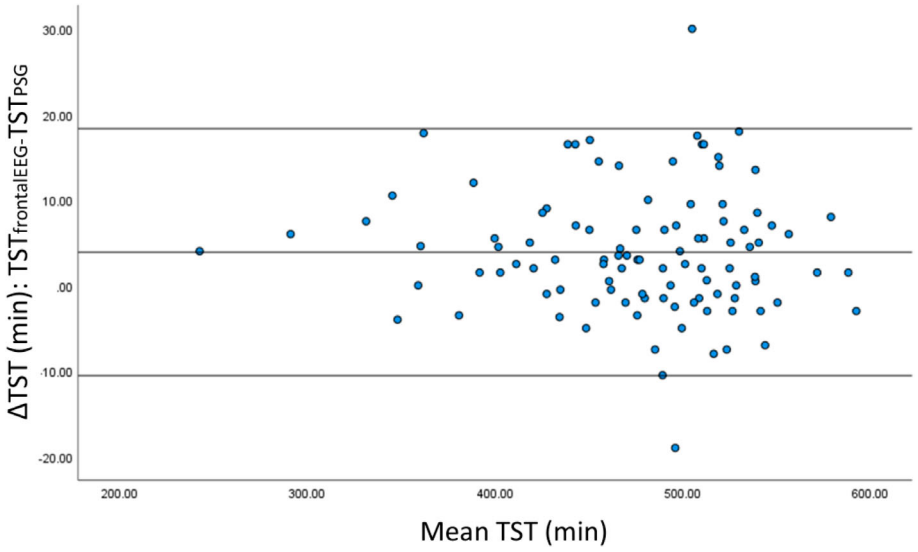

FIGURE 7 Bland–Altman plot of the agreement between total sleep time (TST), in minutes, determined from polysomnography (PSG) and frontal electroencephalogram (EEG) recordings. The centre line presents the mean difference, and the outer lines indicate the mean difference ± 1.96 SD.

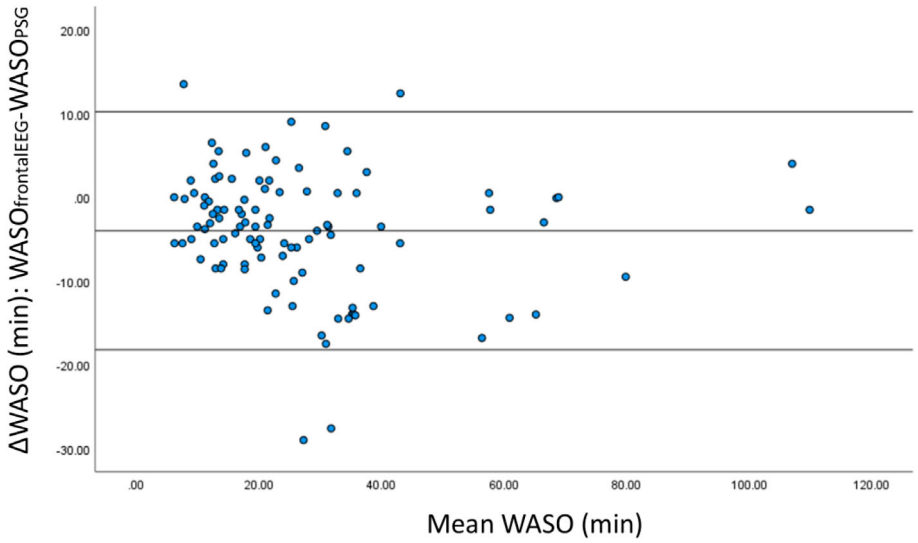

FIGURE 8 Bland–Altman plot of the agreement between wake after sleep onset (WASO), in minutes, determined from polysomnography (PSG) and frontal electroencephalogram (EEG) recordings. The centre line presents the mean difference, and the outer lines indicate the mean difference ± 1.96 SD.

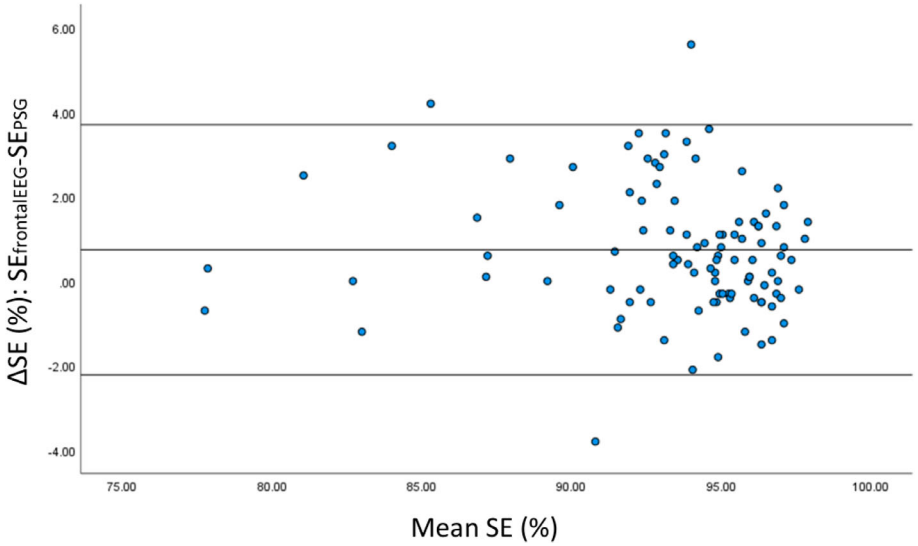

FIGURE 9 Bland–Altman plot of the agreement between sleep efficiency (SE), as percentages, determined from polysomnography (PSG) and frontal electroencephalogram (EEG) recordings. The centre line presents the mean difference, and the outer lines indicate the mean difference ± 1.96 SD.

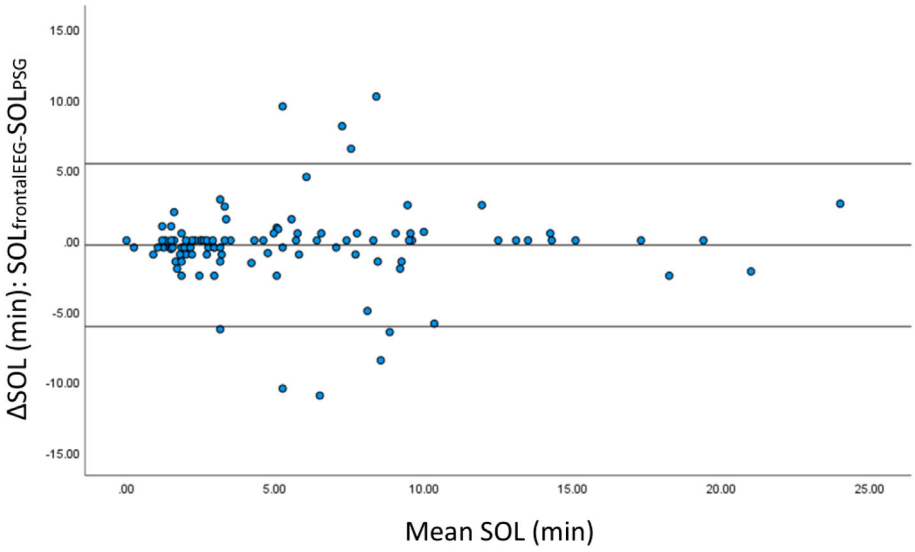

FIGURE 10 Bland–Altman plot of the agreement between sleep-onset latency (SOL), in minutes, determined from polysomnography (PSG) and frontal electroencephalogram (EEG) recordings. The centre line presents the mean difference, and the outer lines indicate the mean difference ± 1.96 SD.

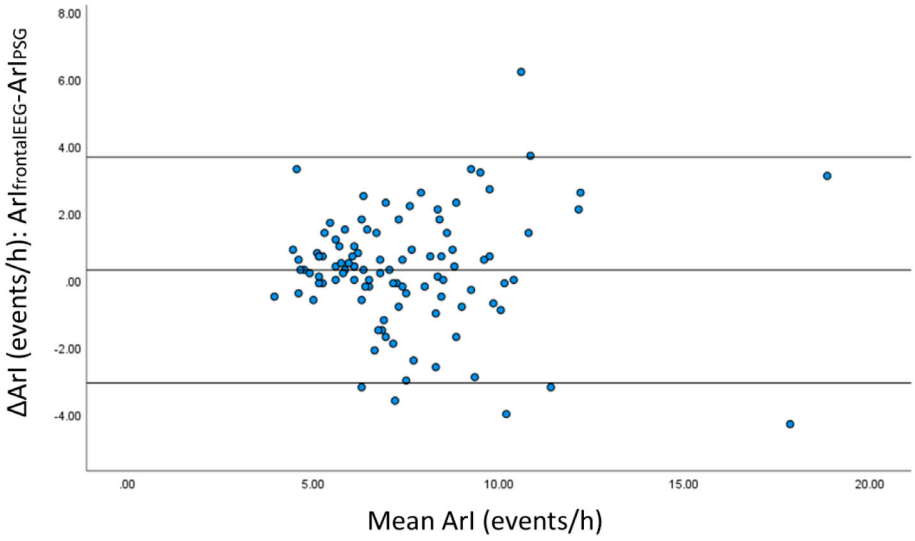

FIGURE 11 Bland–Altman plot of the agreement between arousal index (ArI), as events per hour, determined from polysomnography (PSG) and frontal electroencephalogram (EEG) recordings. The centre line presents the mean difference, and the outer lines indicate the mean difference ± 1.96 SD.

TABLE 3 Overall intra- and inter-scorer agreements for manual scorings of the PSG and the frontal EEG for Scorers S1–S3.

	S1/S3 intra-scorer agreement	S2 intra-scorer agreement	Inter-scorer agreement
Cohen's kappa (PSG)	0.82 (S1)	0.85	0.78
Cohen's kappa (frontal EEG)	0.78 (S3)	0.84	0.70
Score match % (PSG)	87.5 (S1)	89.3	84.6
Score match % (frontal EEG)	83.8 (S3)	88.2	78.0

Note: A subset of 10 PSG and 10 frontal EEG recording pairs were double scored by three scorers used for agreement analyses. Scorer 1 double blindly scored the PSGs; scorer 2 double blindly scored both the PSGs and the frontal EEGs; and scorer 3 double blindly scored the frontal EEGs.
Abbreviations: EEG, electroencephalogram; PSG, polysomnography; S1, scorer 1; S2, scorer 2; S3, scorer 3.

EEG, after applying minor changes to the frontal EEG scoring rules due to frequency and amplitude differences. Overall, the agreement in sleep staging between frontal EEG and PSG was high. Based on measures of agreement, the agreement ranged from almost perfect agreement for the three-stage model to substantial agreement for the five-stage model. Moreover, the correlations for all the sleep variables assessed (TST, WASO, SE, SOL and ArI) were again either strong or very strong. These results are promising, despite the small but significant difference for some of the sleep parameters between the two methods. Our main focus was on the epoch-by-epoch agreement, but we also assessed important derived sleep parameters. The literature on how error propagates from sleep stage classification to sleep parameters in manually scored PSG studies is unfortunately scarce to none. A meta-analysis of inter-rater reliability of manual scoring

TABLE 4 Sleep stage-specific intra- and interscorer agreements between the PSG and the frontal EEG for Scorers S1–S3.

	S1/S3 Intra-scorer agreement (%)		S2 Intra-scorer agreement (%)		Inter-scorer agreement (%)	
Stage	PSG (S1)	Frontal EEG (S3)	PSG	Frontal EEG	PSG (S1 versus S2)	Frontal EEG (S3 versus S2)
Wake	88.6	89.7	89.6	88.2	83.6	84.7
N1	44.3	59.1	61.3	65.8	32.6	50.5
N2	77.3	84.1	81.4	87.0	72.7	74.8
N3	91.5	93.0	92.5	94.2	91.5	85.8
R	92.7	82.6	93.0	89.5	90.7	83.8

Note: A subset of 10 PSG and 10 frontal EEG recording pairs were double scored by three scorers used for the intra- and interscorer agreement measures. Scorer 1 double blindly scored the PSGs; scorer 2 double blindly scored both the PSGs and the frontal EEGs; and scorer 3 double blindly scored the frontal EEGs.

Abbreviations: EEG, electroencephalogram; N1, sleep stage 1; N2, sleep stage 2; N3, sleep Stage 3; PSG, polysomnography; R, rapid eye movement sleep; S1, scorer 1; S2, scorer 2; S3, scorer 3.

showed an overall κ value of 0.76 (Lee et al., 2022), and a recent multicentre scoring agreement study showed a similar overall agreement of $\kappa = 0.71$ (Nikkonen et al., 2024). It is therefore clinically accepted today to have an approximately 20% disagreement is sleep stage classification without exactly knowing how that affects derived parameters. It is, however, known that these parameters are highly sensitive to sleep staging errors (Hardarson et al., 2023). That is why it is not possible to put much emphasis on the statistically significant differences for the sleep parameters between the two methods seen here, as the same is very possibly evident in today's clinical practice.

Several studies on a single-channel frontal EEG versus PSG have found good agreement between the two methods in regards to sleep staging and/or sleep time in adults (Light et al., 2018; Lucey et al., 2016; Sabil et al., 2019; Shambroom et al., 2012). Various devices or methods of recording frontal EEG with more than one channel have also been introduced, again for adults (Finan et al., 2016; Myllymaa et al., 2016; Younes et al., 2017). These multi-channel methods are promising in measuring sleep variables and sleep architecture, but they all need further validations with larger and more heterogeneous cohorts, including a paediatric cohort. To the best of our knowledge, this is the first study validating the manual scoring of frontal EEG against that of a standard PSG setup in a paediatric population.

For sleep stage agreement, N1 had the highest discrepancy between the PSG and frontal EEG methods. N1 was misclassified as either stage R (19.4%), N2 (14.2%) or wake (9.0%) in the frontal EEG setup. Apart from the N1 misclassification, the combinations of N2/N3 (17.0%), N3/N2 (15.9%) and W/N1 (11.9%) had the most frequent discrepancies. These findings are, apart from the N1/R discrepancy, very well in line with other studies comparing manual sleep staging in adults (Danker-hopfe et al., 2009; Deng et al., 2019; Magalang et al., 2013; Zhang et al., 2015). To the best of our knowledge, there is only one study addressing intra- and inter-scoring reliability of manual sleep staging in a paediatric cohort; however, that study is based on the same paediatric cohort utilized in the present study, making the comparison of the results irrelevant (Somaskandhan et al., 2023). Despite the N1/R discrepancy, the R staging accuracy was high (92.1%), and stage R epochs were very often correctly classified with the frontal EEG, even though some overestimation in the amount of stage R occurred. We hypothesize that the reason for this is the lack of chin EMG that is used in the PSG as an aid in scoring sleep stage R. The frontal EEG system, used in this study, does exploit the muscle component of the EOG to use in scoring instead of the chin EMG, but it does not show the atonia in stage R as the chin EMG does. The lack of occipital electrodes when using the frontal EEG also raised speculations of lower W/N1 scoring reliability because of less alpha activity (Berry et al., 2018). However, the N1 reliability was generally very low in both methods making speculations of this issue difficult. Nevertheless, it is worth noting that both the intra- and inter-scoring agreements for N1 were considerably higher for the frontal EEG than the PSG.

There are some limitations to the present study to address. The age group studied was 10–13 years, which is a relatively small age span. The results can therefore not be generalized to children of all ages because the EEG characteristics of children develop over the years (Berry et al., 2018). The majority of the children studied did not have OSA. Children with OSA have more disturbed sleep with more rapid changes of sleep stages and their sleep may therefore be more difficult to score. Therefore, more studies on the frontal EEG setup are warranted in children with more severe OSA as well as other sleep disorders or comorbidities. Furthermore, the hook-up of the PSG and the frontal EEG was done by experienced sleep technologists, and this study is therefore not evaluating the ease of self-application or failure rate of the frontal EEG setup in the home setting. When it comes to the intra- and interscorer agreement measures, the scorer (S1) that scored the data originally was unavailable for the subset scorings ($n = 10$) of the frontal EEG. Thus, a new scorer (S3) was recruited to score the frontal EEGs to be able to perform inter- and intra-scorer agreement analyses.

The strengths of the study include the large sample size of 102 participants, a considerably larger number than previous studies on frontal multichannel EEG have used (Finan et al., 2016; Myllymaa et al., 2016; Younes et al., 2017). The 102 nights recorded simultaneously with PSG and the frontal EEG setup (204 recordings in total) contain a high number of epochs and events to give the comparison a

statistical strength. Another strength of the study was the no exclusion criteria, and we therefore had a representative general population sample of children.

In conclusion, the manually scored frontal EEG with minor alterations to the scoring rules is comparable to the manually scored standard PSG in a paediatric cohort of 10–13-year-old children in the general population, and provides a fairly good estimation of TST and sleep architecture in this cohort. However, further validations in different age groups and diverse sleep disorders are warranted. Also, future research on the frontal EEG needs to be done on its feasibility of use for children with parental setup. Moreover, further development of automatic scoring algorithms for the frontal EEG is needed to minimize time-consuming manual scoring.

AUTHOR CONTRIBUTIONS

Sigridur Sigurdardottir: Writing – original draft; writing – review and editing; investigation; formal analysis; data curation. **Henna Pitkänen:** Formal analysis; writing – review and editing. **Henri Korkalainen:** Methodology; writing – review and editing. **Samu Kainulainen:** Writing – review and editing. **Marta Serwatko:** Investigation; writing – review and editing; conceptualization. **Kristin A. Olafsdottir:** Funding acquisition; writing – review and editing; investigation. **Sigurveig Þ. Sigurðardóttir:** Writing – review and editing. **Michael Clausen:** Writing – review and editing. **Pranavan Somaskandhan:** Software; writing – review and editing. **Barbara G. Stražišar:** Writing – review and editing; conceptualization. **Timo Leppänen:** Writing – review and editing; validation; conceptualization. **Erna Sif Arnardottir:** Supervision; writing – review and editing; conceptualization.

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CONFLICT OF INTEREST STATEMENT

E.S. Arnardottir reports lecture honoraria from Nox Medical, Philips, ResMed, JazzPharmaceuticals, Linde Healthcare, Wink Sleep, Vistor (NovoNordisk) and Apnimed, as well as participates on the Philips Sleep Medicine and Innovation medical advisory board. However, all these financial disclosures are outside the scope of this work. None of the other authors have financial or non-financial disclosures.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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REFERENCES

Ai, S., Li, Z., Wang, S., Chen, S., Chan, J. W., Au, C. T., Bao, Y., Li, A. M., Zhang, J., Chan, K. C., & Wing, Y. K. (2022). Blood pressure and childhood obstructive sleep apnea: A systematic review and meta-analysis. *Sleep Medicine Reviews*, *65*, 101663. https://doi.org/10.1016/j.smrv.2022.101663

American Academy of Sleep Medicine (Ed.). (2014). *International classification of sleep disorders* (3rd ed.). American Academy of Sleep Medicine. https://learn.aasm.org

Berry, R. B., Albertario, C. L., Harding, S. M., Lloyd, R. M., Plante, D. T., Quan, S. F., Troester, M. M., & Vaughn, B. V. (2018). *The AASM manual for the scoring of sleep and Assosiated events: Terminology and technical specifications. Version 2.5*. American Academy of Sleep Medicine.

Brockmann, P. E., Urschitz, M. S., Schlaud, M., & Poets, C. F. (2012). Primary snoring in school children: Prevalence and neurocognitive impairments. *Sleep and Breathing*, *16*(1), 23–29. https://doi.org/10.1007/s11325-011-0480-6

Bruyneel, M., Sanida, C., Art, G., Libert, W., Cuvelier, L., Paesmans, M., Sergysels, R., & Ninane, V. (2011). Sleep efficiency during sleep studies: Results of a prospective study comparing home-based and in-hospital polysomnography. *Journal of Sleep Research*, *20*(1pt2), 201–206. https://doi.org/10.1111/j.1365-2869.2010.00859.x

Clausen, M., Jonasson, K., Keil, T., Beyer, K., & Sigurdardottir, S. T. (2018). Fish oil in infancy protects against food allergy in Iceland-results from a birth cohort study. *Allergy*, *73*(6), 1305–1312. https://doi.org/10.1111/all.13385

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, *20*(1), 37–46.

Danker-hopfe, H., Anderer, P., Zeitlhofer, J., Boeck, M., Dorn, H., Gruber, G., Heller, E., Loretz, E., Moser, D., Parapatics, S., & Saletu, B. (2009). Interrater reliability for sleep scoring according to the

Rechtschaffen & Kales and the new AASM standard. *Journal of Sleep Research*, *18*(1), 74–84.

Deng, S., Zhang, X., Zhang, Y., Gao, H., Chang, E. I. C., Fan, Y., & Xu, Y. (2019). Interrater agreement between American and Chinese sleep centers according to the 2014 AASM standard. *Sleep & Breathing*, *23*(2), 719–728. https://doi.org/10.1007/s11325-019-01801-x

European Commission. (2017). Integrated Approaches to Food Allergen and Allergy Risk Management | IFAAM Project | FP7 | CORDIS. https://cordis.europa.eu/project/id/312147

Finan, P. H., Richards, J. M., Gamaldo, C. E., Han, D., Leoutsakos, J. M., Salas, R., Irwin, M. R., & Smith, M. T. (2016). Validation of a wireless, self-application, ambulatory electroencephalographic sleep monitoring device in healthy volunteers. *Journal of Clinical Sleep Medicine*, *12*(11), 1443–1451.

Fischer, J., Dogas, Z., Bassetti, C. L., Berg, S., Grote, L., Jennum, P., Levy, P., Mihaicuta, S., Nobili, L., Riemann, D., & Puertas Cuesta, F. J. (2012). Standard procedures for adults in accredited sleep medicine centres in Europe. *Journal of Sleep Research*, *21*(4), 357–368. https://doi.org/10.1111/j.1365-2869.2011.00987.x

Flemons, W. W., Douglas, N. J., Kuna, S. T., Rodenstein, D. O., & Wheatley, J. (2004). Access to diagnosis and treatment of patients with suspected sleep apnea. *American Journal of Respiratory and Critical Care Medicine*, *169*(6), 668–672. https://doi.org/10.1164/rccm.200308-1124PP

Fu, M., Wang, Y., Chen, Z., Li, J., Xu, F., Liu, X., & Hou, F. (2021). Deep learning in automatic sleep staging with a single channel electroencephalography. *Frontiers in Physiology*, *12*, 628502.

Galland, B., Spruyt, K., Dawes, P., McDowall, P. S., Elder, D., & Schaughency, E. (2015). Sleep disordered breathing and academic performance: A meta-analysis. *Pediatrics*, *136*(4), e934–e946. https://doi.org/10.1542/peds.2015-1677

Grote, L., McNicholas, W. T., & Hedner, J. (2020). Sleep apnoea management in Europe during the COVID-19 pandemic: Data from the European sleep Apnoea database (ESADA). *European Respiratory Journal*, *55*(6), 2001323. https://doi.org/10.1183/13993003.01323-2020

Hardarson, E., Islind, A. S., Arnardottir, E. S., & Óskarsdóttir, M. (2023). Error propagation from sleep stage classification to derived sleep parameters in machine learning on data from wearables. *Current Sleep Medicine Reports*, *9*(3), 140–151.

Hunter, S. J., Gozal, D., Smith, D. L., Philby, M. F., Kaylegian, J., & Kheirandish-Gozal, L. (2016). Effect of sleep-disordered breathing severity on cognitive performance measures in a large community cohort of young school-aged children. *American Journal of Respiratory and Critical Care Medicine*, *194*(6), 739–747. https://doi.org/10.1164/rccm.201510-2099OC

Kainulainen, S., Korkalainen, H., Sigurþardóttir, S., Myllymaa, S., Serwatko, M., Sigurþardóttir, S. Þ., Clausen, M., Leppänen, T., & Arnardóttir, E. S. (2021). Comparison of EEG signal characteristics between polysomnography and self applied Somnography setup in a pediatric cohort. *IEEE Access*, *9*, 110916–110926.

Keil, T., McBride, D., Grimshaw, K., Niggemann, B., Xepapadaki, P., Zannikos, K., Sigurdardottir, S. T., Clausen, M., Reche, M., Pascual, C., Stanczyk, A. P., Kowalski, M. L., Dubakiene, R., Drasutiene, G., Roberts, G., Schoemaker, A. F. A., Sprikkelman, A. B., Fiocchi, A., Martelli, A., … Beyer, K. (2010). The multinational birth cohort of EuroPrevall: Background, aims and methods. *Allergy*, *65*(4), 482–490. https://doi.org/10.1111/j.1398-9995.2009.02171.x

Korkalainen, H., Aakko, J., Nikkonen, S., Kainulainen, S., Leino, A., Duce, B., Afara, I. O., Myllymaa, S., Töyräs, J., & Leppänen, T. (2019). Accurate deep learning-based sleep staging in a clinical population with suspected obstructive sleep apnea. *IEEE Journal of Biomedical and Health Informatics*, *24*(7), 2073–2081.

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, *33*(1), 159–174. https://doi.org/10.2307/2529310

Lee, P. L., Huang, Y. H., Lin, P. C., Chiao, Y. A., Hou, J. W., Liu, H. W., Huang, Y. L., Liu, Y. T., & Chiueh, T. D. (2019). Automatic sleep staging in patients with obstructive sleep apnea using Single-Channel frontal EEG. *Journal of Clinical Sleep Medicine*, *15*(10), 1411–1420. https://doi.org/10.5664/jcsm.7964

Lee, Y. J., Lee, J. Y., Cho, J. H., & Choi, J. H. (2022). Interrater reliability of sleep stage scoring: A meta-analysis. *Journal of Clinical Sleep Medicine*, *18*(1), 193–202.

Light, M. P., Casimire, T. N., Chua, C., Koushyk, V., Burschtin, O. E., Ayappa, I., & Rapoport, D. M. (2018). Addition of frontal EEG to adult home sleep apnea testing: Does a more accurate determination of sleep time make a difference? *Sleep and Breathing*, *22*(4), 1179–1188. https://doi.org/10.1007/s11325-018-1735-2

Lucey, B. P., Mcleland, J. S., Toedebusch, C. D., Boyd, J., Morris, J. C., Landsness, E. C., Yamada, K., & Holtzman, D. M. (2016). Comparison of a single-channel EEG sleep study to polysomnography. *Journal of Sleep Research*, *25*(6), 625–635. https://doi.org/10.1111/jsr.12417

Magalang, U. J., Chen, N. H., Cistulli, P. A., Fedson, A. C., Gíslason, T., Hillman, D., Penzel, T., Tamisier, R., Tufik, S., Phillips, G., & Pack, A. I. (2013). Agreement in the scoring of respiratory events and sleep among international sleep centers. *Sleep*, *36*(4), 591–596. https://doi.org/10.5665/sleep.2552

Marcus, C. L., Brooks, L. J., Draper, K. A., Gozal, D., Halbower, A. C., Jones, J., Lehmann, C., Schechter, M. S., Sheldon, S., & Shiffman, R. N. (2012). Diagnosis and management of childhood obstructive sleep apnea syndrome. *Pediatrics*, *130*(3), e714–e755. https://doi.org/10.1542/peds.2012-1672

Masa, J. F., Corral, J., Sanchez de Cos, J., Duran-Cantolla, J., Cabello, M., Hernández-Blasco, L., Monasterio, C., Alonso, A., Chiner, E., Aizpuru, F., Vázquez-Polo, F. J., Zamorano, J., Montserrat, J. M., Collaborating group, Garcia-Ledesma, E., Pereira, R., Cancelo, L., Martinez, A., Sacristan, L., … Embid, C. (2013). Effectiveness of three sleep apnea management alternatives. *Sleep*, *36*(12), 1799–1807. https://doi.org/10.5665/sleep.3204

Munro, B. H. (2005). *Statistical methods for health care research* (Vol. 1). lippincott Williams & Wilkins.

Myllymaa, S., Muraja-Murro, A., Westeren-Punnonen, S., Hukkanen, T., Lappalainen, R., Mervaala, E., Töyräs, J., Sipilä, K., & Myllymaa, K. (2016). Assessment of the suitability of using a forehead EEG electrode set and chin EMG electrodes for sleep staging in polysomnography. *Journal of Sleep Research*, *25*(6), 636–645.

Nikkonen, S., Somaskandhan, P., Korkalainen, H., Kainulainen, S., Terrill, P. I., Gretarsdottir, H., Sigurdardottir, S., Olafsdottir, K. A., Islind, A. S., Óskarsdóttir, M., Arnardóttir, E. S., & Leppänen, T. (2024). Multicentre sleep-stage scoring agreement in the sleep revolution project. *Journal of Sleep Research*, *33*(1), e13956.

Sabil, A., Vanbuis, J., Baffet, G., Feuilloy, M., le Vaillant, M., Meslier, N., & Gagnadoux, F. (2019). Automatic identification of sleep and wakefulness using single-channel EEG and respiratory polygraphy signals for the diagnosis of obstructive sleep apnea. *Journal of Sleep Research*, *28*(2), e12795. https://doi.org/10.1111/jsr.12795

Sedky, K., Bennett, D. S., & Carvalho, K. S. (2014). Attention deficit hyperactivity disorder and sleep disordered breathing in pediatric populations: A meta-analysis. *Sleep Medicine Reviews*, *18*(4), 349–356. https://doi.org/10.1016/j.smrv.2013.12.003

Shambroom, J. R., Fábregas, S. E., & Johnstone, J. (2012). Validation of an automated wireless system to monitor sleep in healthy adults. *Journal of Sleep Research*, *21*(2), 221–230. https://doi.org/10.1111/j.1365-2869.2011.00944.x

Sheldon, S. H., Ferber, R., Kryger, M. H., & Gozal, D. (2014). *Principles and practice of pediatric sleep medicine* (2nd ed.). Elsevier Saunders. https://expertconsult.inkling.com/read/sheldon-principles-practice-pediatric-sleep-medicine-2nd/chapter-29

Somaskandhan, P., Leppänen, T., Terrill, P. I., Sigurdardottir, S., Arnardottir, E. S., Ólafsdóttir, K. A., Serwatko, M., Sigurðardóttir, S. Þ., Clausen, M., Töyräs, J., & Korkalainen, H. (2023). Deep learning-based algorithm accurately classifies sleep stages in preadolescent children

with sleep-disordered breathing symptoms and age-matched controls. *Frontiers in Neurology*, *14*, 1162998. https://doi.org/10.3389/fneur.2023.1162998

Wang, H., Lin, G., Li, Y., Zhang, X., Xu, W., Wang, X., & Han, D. (2021). Automatic sleep stage classification of children with sleep-disordered breathing using the modularized network. *Nature and Science of Sleep*, *13*, 2101–2112. https://doi.org/10.2147/NSS.S336344

Younes, M., Soiferman, M., Thompson, W., & Giannouli, E. (2017). Performance of a new portable wireless sleep monitor. *Journal of Clinical Sleep Medicine*, *13*(2), 245–258.

Zhang, X., Dong, X., Kantelhardt, J. W., Li, J., Zhao, L., Garcia, C., Glos, M., Penzel, T., & Han, F. (2015). Process and outcome for international reliability in sleep scoring. *Sleep & Breathing*, *19*, 191–195.

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