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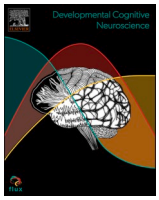

Pediatric sleep electrophysiology: Using polysomnography in developmental cognitive neuroscience

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ABSTRACT

Research suggests a bidirectional relationship between brain and cognitive development and sleep in early childhood. Polysomnography is essential for the investigation of the mechanisms underlying sleep's role in brain and cognitive development. This paper outlines methods for integrating measures of sleep and sleep physiology into cognitive developmental neuroscience research. There are various options when choosing a polysomnography system depending on the research question. We offer considerations such as application time, recording time, montage density and analysis options, and cost. We also review suggestions for modifying procedures with developmental populations to support high quality polysomnography data collection. We hope that this overview will facilitate more developmental cognitive neuroscience studies of sleep to advance our understanding of early brain and cognitive development.

1. Importance of sleep physiology in developmental cognitive neuroscience

A corpus of recent studies has demonstrated that sleep contributes to cognition and cognitive development in early childhood. Infants as young as three months demonstrate better memory consolidation over a nap compared to a wake period (Horváth et al., 2018). Similar benefits have been found in toddlers and preschoolers for declarative (Gomez et al., 2006; Kurdziel et al., 2013; Lokhandwala and Spencer, 2021), procedural (Desrochers et al., 2016) and emotional memory (Kurdziel et al., 2018). Evidence supports a bidirectional relationship between brain development and sleep, with brain development influencing sleep patterns and sleep facilitating brain development (Spencer and Riggins, 2022; Lokhandwala and Spencer, 2022). For example, brain regions, like the thalamus, need to sufficiently mature to produce specific sleep EEG features (Herrera and Tarokh, 2024). Conversely, we see specific sleep EEG features predict neural maturation in the cortex (Kurth et al., 2012; Riggins et al., 2024).

Dynamic interactions between sleep and cognition change across the lifespan. Infants and younger children may require more, and more frequent, sleep for memory consolidation (Riggins and Spencer, 2020) and other sleep functions. As children grow older and transition out of naps, they require less immediate sleep (e.g., can wait for overnight sleep) to protect their memories. Yet, sleep is beneficial for memory consolidation and brain development across all ages. The consistent benefit underscores the importance of understanding sleep architecture and its components, including sleep features and neural oscillations, which may contribute to cognitive processes such as memory.

Studies employing polysomnography (PSG) have advanced our understanding of the mechanisms underlying sleep's role in brain development and plasticity. PSG is a montage of physiological recordings including electroencephalography (EEG; brain activity), electromyography (EMG; muscle activity typically measured at the chin), and electrooculography (EOG; eye movement activity). These physiological recordings are traditionally used to classify sleep macrostructure into four stages: non-rapid eye movement (NREM) 1–3 and rapid eye movement (REM) sleep (Fig. 1). Sleep stages have been individually linked to children's cognitive functions. For example, declarative memory consolidation over an interval with sleep is often associated with how much time is spent specifically in NREM 3, also known as slow wave sleep (SWS; Lokhandwala and Spencer, 2021; Wang et al., 2017). Such specific relations are important for ruling out alternative

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explanations of better performance following sleep than wake, such as the lack of interference from competing memories (see Ellenbogen et al., 2006). More recently, research has focused on the role of sleep microstructures such as sleep spindles and slow oscillations. These features of sleep may represent the mechanisms through which sleep benefits cognition. For example, Kurdziel and colleagues (2013) found that performance benefits for declarative memory were associated with the sleep spindle density (average number of spindles per minute) in a nap. Moreover, sleep microstructures have been suggested to provide a biomarker for brain development (Kurth et al., 2010). As such, PSG is a promising tool for developmental cognitive neuroscience research.

The purpose of this paper is to describe procedures for integrating PSG into experimental paradigms in an effort to encourage and facilitate more research into sleep-related mechanisms supporting cognition in development. First, we outline the changing macro- and micro-features of sleep and provide examples of how these relate to varied outcomes of interest, such as memory. Next, we describe the procedures and considerations for integrating this methodology in developmental studies. We focus on measurement of sleep physiology from infancy through childhood (approximately 0–12 years). Adolescent sleep physiology is generally adult-like and procedures for these populations are well described (e.g., Redline et al., 1998; Torterolo et al., 2022). Additionally, while resources are available for guidance on clinical pediatric PSG (Ibrahim et al., 2021), PSG in cognitive research will likely emphasize neural activity and sleep staging. Therefore, it does not require a full clinical montage (which often includes additional measures such as leg EMG, a nasal canula, and chest plethysmography).

2. Developmental trajectory of sleep macro- and micro-structures

Measures of sleep can be placed into two broad categories: sleep macrostructure and sleep microstructure. Sleep macrostructure refers to how patterns of physiological activity can be organized into discrete sleep stages. Sleep stages include REM and NREM sleep. NREM can be further divided into three stages: NREM 1, NREM 2, and NREM 3/SWS. Stages are associated with different frequency bands of activity, which encapsulate the evolution of sleep processing across the night (Fig. 1). While staging criteria are summarized here, we recommend all interested researchers consult the AASM Scoring Manual for a full description (Troester et al., 2023).

2.1. Active and quiet sleep of newborns

The sleep EEG of newborns varies significantly from other age groups. Many of the defining characteristics of individual sleep stages do not emerge until several weeks post-term and, as a result, the scoring classification is simplified to active sleep and quiet sleep until around 3–5 months. These are precursors to REM and NREM, respectively (Grigg-Damberger et al., 2007; Sheldon, 2014). Initially, half of the sleep period is spent in active sleep and sleep bouts often begin in this stage.

2.2. NREM Stage 1

NREM 1 sleep occurs at wake-sleep transitions. It is known to be the lightest stage of sleep as it is easiest to wake someone in this stage. The EEG consists of attenuating alpha band activity (8–13 Hz; Bazanova and Vernon, 2014). As the alpha band frequency subsides, it is replaced by high-frequency, low-amplitude waves. The EOG channels show slow rolling eye movements as blinking slows down. Sleep onset is scored as the first NREM 1 epoch. Once NREM begins, there are few movements in the EMG and EOG channels. Typical sleep contains very little NREM 1. However, greater NREM 1 is seen if a person has difficulty falling asleep due to insufficient sleep pressure (i.e., the homeostatic drive to sleep).

2.3. NREM Stage 2

NREM 2 is characterized by sleep spindles, which are short

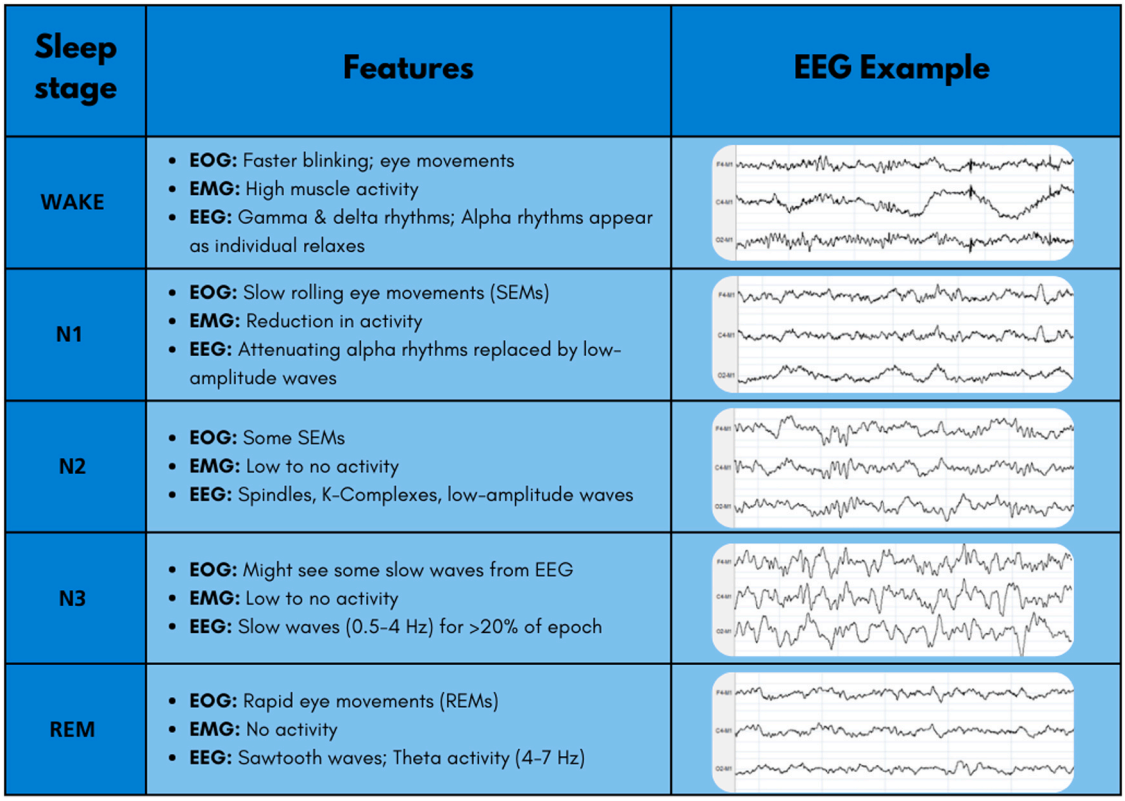


Fig. 1. Identification of sleep stages through PSG recordings.

(0.5–2.5 second) bursts of 9–16 Hz activity (Clawson et al., 2016) and K-complexes (a high-amplitude positive-then-negative wave that stands out from the rest of the record). K-complexes appear between 5 and 6 months of age (Grigg-Damberger et al., 2007). Sleep spindles emerge between 6 weeks and 3 months and evolve in topography, frequency, and duration across early development (Troester et al., 2023). Infant spindles are most prominent over the frontoparietal and central regions, with a shift toward the central midline during toddlerhood. By 6 years, spindles are predominantly located in the frontal brain regions (Kwon et al., 2023). Spindle frequency decreases from infancy to toddlerhood and then increases again (Kwon et al., 2023; Page et al., 2018). Spindles can be divided into fast and slow subtypes based on frequency and topography. Slow spindles are predominantly in the frontal regions, with frequencies of 9–12 Hz. Fast spindles have a frequency of 13–16 Hz and are located in more central-parietal regions (Kwon et al., 2023). While the frequency-based cutoff can be applied at any age range, the emergence of bimodal peaks in spindle frequency data is debated, gradual, and marked by individual differences. Some studies report a difference at 2 years while others do not find a consistent difference until adolescence (Kurth et al., 2012; Kwon et al., 2023).

2.4. NREM Stage 3 (SWS)

Slow wave sleep is often referred to as 'deep sleep' as it is hard to wake someone from this stage. It is characterized by low frequency (0.5–4 Hz) cortical oscillations, known as slow waves. Slow wave activity (SWA) is activity in the delta frequency band, which is most prevalent in NREM 3. SWA begins 2–5 months post-term. The topography of SWA changes across development. In infancy and early childhood, maximal SWA is concentrated in the occipital areas and gradually shifts in a posterior to anterior trajectory following cortical myelination. By middle childhood (8–11 years), SWA becomes richer in the frontal regions (Kurth, 2010).

2.5. REM

Rapid eye movement sleep consists mainly of activity in the theta frequency range (4–7 Hz). The EEG frequency during REM increases from 4 to 5 Hz at 5 months to 5–7 Hz in early childhood (Knoop et al., 2021). REM sleep can often resemble wake in the sleep EEG due to the presence of eye movements and the high frequency EEG. However, since muscle atonia occurs during this stage, REM can be distinguished by the EMG channels which remain quiet and stable, unlike during wake.

2.6. Developmental changes in sleep stages

The proportion of sleep spent in REM sleep decreases drastically over the early months of life and then tapers across early childhood, averaging 30 % at age 1 and 20–25 % by age 5 (Sheldon, 2014). Additionally, REM episodes begin to occur later in the sleep bout, following periods of NREM instead of starting the sleep period. REM periods increase in duration during the second half of the night. The sleep cycles, or transitions between NREM and REM, initially last about 60 minutes and increase in duration to adult-like levels of 90 minutes across the first year of life (Grigg-Damberger et al., 2007). As such, it is rare to see REM sleep during daytime naps after this developmental window.

3. Sleep features of interest in developmental cognitive neuroscience

Sleep macrostructure and microstructure relate to brain development and various cognitive functions such as memory and emotional regulation. Understanding the existing literature on the dynamic associations between sleep, brain development, and cognitive functions is necessary to formulate specific, testable hypotheses. To establish a preliminary understanding of the relevant background literature, we provide a brief overview here (for further information, see Mason et al., 2021).

Sleep spindles are generated by the thalamocortical network. They have been associated with sleep-dependent memory consolidation in developmental populations for both procedural and declarative memory tasks (Kurdziel et al., 2013; Friedrich et al., 2019). Fast spindles (13–15 Hz) are localized in more central regions and have been specifically implicated in the consolidation of procedural motor learning (Bothe et al., 2020; Kwon et al., 2023). Slow spindles (in this case defined as 11–13 Hz) have been associated with declarative memory and general cognitive abilities in children (Hoedlmoser et al., 2014).

SWS and SWA have also been associated with memory consolidation during early childhood (Kurdziel et al., 2018; Lokhandwala and Spencer, 2021). For example, in a study of preschool-aged children, the consolidation of emotional memories was associated with SWA during SWS (Kurdziel et al., 2018). SWA may have a particular role in emotion processing as it has also been associated with reducing emotional memory biases (Cremone et al., 2017).

The topography of SWA may be reflective of underlying cortical development. Maximal SWA gradually shifts from occipital regions in early childhood to frontal regions in adolescence and can be summarized as a ratio of the SWA in frontal compared to occipital regions (the F/O ratio). This shift in maximal SWA follows a similar trajectory to the maturation of the cortex. Kurth and colleagues (2010) proposed that regional expression of SWA could be used as a biomarker for cortical maturation. Specifically, the F/O ratio of SWA may potentially serve as a proxy for cortical development.

It is possible that associations of cognitive functions with spindles and SWA may reflect the contribution of both oscillations. Memory replay in the hippocampus occurs in conjunction with hippocampal sharp wave ripples. Synchronization of these ripples with sleep spindles and cortical slow oscillations is thought to facilitate hippocampal-neocortical transfer, or copying, of memories for stabilization in the cortex (Rasch and Born, 2013; Ng et al., 2024). While ripples cannot be measured at the scalp, slow oscillation-spindle coupling has been strongly implicated in the consolidation of memory, with spindles nested in the trough of slow oscillations providing a more optimal benefit on memory consolidation. Slow oscillations and spindles become more precisely coupled across childhood, reflecting development of hippocampal-neocortical memory networks. In infants (2–3 months), spindles and slow oscillations co-occur below chance level, but begin to co-occur with increasing precision in toddlerhood (14–17 months; Kurz et al., 2024). Younger children (5–6 years) display improved temporal coupling between slow oscillations and slow frontal spindles only and are associated with the consolidation of "medium-quality memories" (Joechner et al., 2021). In older children (9 years), stronger coupling of these microstructures has been related to generally better recall in declarative memory tasks (Hahn et al., 2020).

The function of REM sleep, particularly across development, is less understood. It is possible that REM sleep plays a similar role in young children as in adults. For example, REM sleep quantity predicted memory for emotional faces after sleep in 6–13-year-olds (Tessier et al., 2015) similar to relations reported in adults (Wagner et al., 2001). REM is also thought to potentially integrate or generalize memories that were reactivated in NREM sleep (Pereira and Lewis, 2020) in adults and some evidence supports this account in children as well (see Mason and Spencer, 2022). Alternatively, the function of REM may be distinct in development. Supporting this, a recent quantitative analysis provided evidence for an abrupt shift in the function of REM sleep between 2 and 3 years (Cao et al., 2020); prior to this age, REM is predicted to be involved in neural reorganization and learning, while after this age, REM is predicted to have a role in neural repair.

4. Conducting PSG research: choosing the right equipment

Essential to all PSG montages are EEG, EOG, and facial EMG

electrodes as these are considered gold standard for identifying sleep stages (see Fig. 1). However, the montage can be expanded to include other physiological recordings. Clinical montages often include respiratory belts, electrocardiography, oximetry, plethysmography, and leg EMG, which aid in identifying specific sleep disorders. While it may be advantageous to rule out sleep disorders in some developmental studies, many of these (e.g., restless leg syndrome) are uncommon in pediatric populations and would be unnecessary and potentially cumbersome and limiting in most studies. As such, a basic PSG montage including EEG, EOG, and chin EMG is sufficient for most developmental cognitive neuroscience research questions.

PSG equipment varies widely and can consist of cap-mounted electrodes or free-lead electrode devices. The varied options and prices may pose challenges for new users. Here, we review key differences to inform this decision for new users and existing users perhaps considering an upgrade.

A common question is whether existing EEG equipment (used for standard EEG/event-related potential studies) may be co-opted to study sleep. While this would allow for some sleep measures (e.g., SWA), identifying sleep stages requires additional information (i.e., EMG and EOG channels; see Fig. 1) not measured by typical EEG systems. Additionally, not all equipment is designed to record for long durations and most electrode montages are bulky, making them uncomfortable for sleeping. The standard conductive gels (or solutions used with sponge electrodes) used to preserve the EEG signal can dry out after 1–2 h, causing a sharp degradation in signal quality if used for a longer sleep bout (see 6.3 for more detail). As such, standard EEG equipment is typically insufficient for sleep-related questions.

4.1. PSG montages

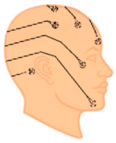
A key distinction between PSG montages is the number of electrodes, particularly electrodes dedicated to EEG. PSG systems can be categorized into low-density (<16 channels), mid-density (16–64 channels), and high-density PSG systems (>64 channels; note we define these specific ranges for discussion purposes). For infant child studies, it is advisable to choose the smallest montage that will meet the research needs, as more electrodes take longer to apply and can decrease comfort and reduce feasibility. What follows are considerations in choosing the most appropriate montage. Table 1 provides a summary of montage options.

Low-density PSG. Low-density PSG (<16 electrodes) is generally unipolar, with one electrode serving as a reference for the other channels. The reference signal is subtracted from each recording electrode to reduce noise. There are several clear advantages of low-density PSG. First, since each electrode requires meticulous placement and adjustment, low-density equipment allows for the fastest application time. Second, low-density PSG devices often feature small, portable amplifiers, making them suitable for ambulatory, in-home use. Third, many of these devices use free-lead electrodes (not mounted in a cap), which can be advantageous for application on diverse hair types. However, fewer channels does not allow for substantial consideration of EEG topography and can lower signal stability or consistency. Specifically, when the number of channels drops below 20, the entropy rate - which measures the variability and unpredictability of channels - increases significantly (Zhang et al., 2021). This increased entropy rate increases the risk of noise or artifacts. Likewise, given that some EEG electrodes may come loose during sleep, fewer electrodes means a smaller margin for error in getting even basic measures (particularly with 3 channels or less).

Mid-Density PSG. Mid-density montages, ranging from 16 to 64 channels, may be free-lead but are typically mounted in a cap. Researchers can opt for a mid-density montage when they want the convenience of applying fewer electrodes, while still covering the full topography of the scalp, particularly on a smaller head. Mid-density PSG offers a good balance between low- and high-density setups. It has the simplicity and cost-effectiveness of low-density PSG, can still be done in the home, and provides some insight into spatial resolution.

High-Density PSG. High-density PSG montages are mounted in fabric or net caps. The highest necessary density for infant research is around 64 channels (Tokariev et al., 2016) but higher-density caps with up to 256 channels may be useful in older children. The primary benefit of high-density PSG is its high spatial resolution, which can detect changes in local sleep, the precise topography of neural activity, or measure traveling waves (Kurth et al., 2017; Schoch et al., 2018). A higher number of electrodes equates to better localization of activity, and thus more precise identification of brain regions and local sleep processes. For instance, when using high-density PSG (128 channels), Wilhelm and colleagues (2014) compared SWA following a motor adaptation task before sleep compared to a control task before sleep. This was used to demonstrate increased SWA following learning that was localized specifically over task-related brain regions, particularly the parietal cortex (i.e., local use-dependent sleep). However, high-density PSG requires much longer application time and potentially more discomfort for the participant. Additionally, increasing the number of electrodes will increase the chances of electrode bridging. Bridging occurs when conductive gel from one electrode spreads to another electrode, causing the signals to merge. High-density EEG also produces large data files, requiring large data storage options particularly for overnight studies.

Table 1
Considerations when choosing a PSG montage.

Density	Number of EEG channels	Approximate price range	Application time	Analysis options	Montage Illustration
Low	< 16	$1,000-$5000	15–30 minutes	Sleep staging; spindle identification	
Mid	16–64	$10,000	30–45 minutes	Sleep staging; feature identification; Power topography	
High	> 64	> $10,000	45–90 minutes	Sleep staging; feature identification; Power topography by electrode Traveling waves	

4.2. Recording time

PSG recordings should reflect a child's typical sleep schedule. Infants generally sleep 13–17 hours each day (Sheldon, 2014), with a single overnight sleep bout ranging from 6 to 12 hours (Mindell et al., 2016). At 2–3 years of age, sleep consolidates to about a 10-hour period overnight and remains largely stable till adolescence (Sheldon, 2014). To properly capture overnight sleep, researchers should plan to record for slightly longer than participants' usual sleep duration (12 + hours). Naps usually last 1–2 hours, however, devices should nonetheless support a longer recording duration (3 + hours) to accommodate any deviations from the planned nap schedule. Some research questions may be addressed using only naps or a partial night data (e.g., first 30 minutes of NREM: Jaramillo et al., 2023; first hour of NREM: Kurth et al., 2012), but this depends on the variables of interest as many change over the course of the night (see Table 2 for list; Kwon et al., 2023; Lopp et al., 2017).

5. Polysomnography procedures in developmental populations

An example study protocol is available in an article by Allard et al. (2019). What is provided here are general procedures that may be adapted based on the questions of interest.

5.1. Recruiting, screening, and consenting participants

Recruitment techniques parallel those in other developmental cognitive neuroscience research.

Inclusion and exclusion criteria may depend on the age group and sleep bout being studied. When studying sleep in developmental cognitive neuroscience, typically the goal is to understand the function of healthy sleep, so screening against diagnosed sleep disorders is important. Sleep disorders are uncommon in children (approximately 4 %; Meltzer et al., 2010), but sleep disruptions (e.g., snoring, bedtime insomnia, somniloquy) are more prevalent and each study should consider whether these should be excluded. It is also important to screen out children with co-morbid conditions. For instance, children with ADHD, diabetes, and anemia show a higher prevalence of sleep problems and disruptions (Yoon et al., 2012; Farabi, 2016; Rodrigues Junior et al., 2024). Additionally, prematurity changes a child's sleep patterns and neurodevelopment. Researchers should appropriately account for this by either making it an exclusion criterion or using corrected age (for broader discussion, see Trickett et al., 2022). Skin conditions on the face and head, such as eczema or dermatitis, may be irritated by the electrodes and the application process. Those with chronic dermatological issues should be adequately informed of the process and potentially excluded to prioritize their comfort.

Consideration should also be given to co-sleeping - whether with a parent, sibling, or pet - as this can significantly influence both sleep quality and consistency (Andre et al., 2021; Mason et al., 2021). Co-sleeping during experimental assessments may also cause equipment disruption due to motion artifacts from external movements. However, comfort is important so it is up to the research team to weigh the pros and cons of allowing bedsharing based on their particular study and PSG system.

Study visits should be scheduled so that the child has not recently traveled across time zones or experienced changes related to daylight saving time, as both would alter their typical circadian rhythm and potentially delay sleep onset and change sleep architecture. Ideally, there would be a 1–2-week buffer between these events and the experimental sessions (Medina et al., 2015; Lucchini et al., 2024). Scheduling should also accommodate the child's usual routine to match their typical behavior and increase the likelihood that they are able to fall asleep. Researchers should ask caregivers about habitual sleep start times and nap habituality. Additionally, adequate time should be allotted for breaks and childcare needs (e.g., diaper changes and feeding) to ensure

Table 2
Potential sleep variables to be analyzed.

Sleep Feature	Metrics for Analysis	Research Examples
Macrostructure		
Sleep stages	- Minutes per stage - Percent of sleep stage in sleep bout	Ventura et al. (2025): NREM 3 duration during a nap at 4 months was positively associated with social-emotional development at 18 months.
Power Spectrum	- Delta or slow wave activity (SWA) - Theta - Sigma - Alpha - Beta	Kurth et al. (2012): Topography of SWA in the first 60 minutes of NREM 2 and NREM 3 sleep predicted cortical development across childhood and adolescence. Wilhelm et al. (2014): Overnight SWA increased in parietal regions after learning a motor adaptation task. Effect was strongest in children. Page et al. (2018): Fine motor skills in infants and toddlers (12–30 mos) were related to delta and greater theta activity in frontal and posterior regions during a nap.
Microstructure		
Spindles, slow waves	- Density - Frequency - Duration - Amplitude - Topography - Inter-hemispheric coherence	Chatburn et al. (2013): Fast spindle density during nighttime sleep was negatively associated with sensorimotor functioning in children. Jaramillo et al. (2023): Fast spindle density in the first 30 minutes of infants' NREM sleep predicted developmental status 6 months later.
Slow oscillation-spindle coupling	- Number of coupling events - Percent of spindles coupled to slow oscillations - Phase amplitude coupling - Coupling strength	Hahn et al. (2020): Increases in SO-spindle coupling strength from childhood to adolescence were related to improved memory consolidation. Kurz et al. (2023): Temporal coupling in the preferred phase during night sleep correlated with recall on a list of words the following day.

that the child is ready to sleep at or before the planned sleep start time.

Visual depictions of the timeline and PSG equipment can benefit caregiver understanding prior to completing the consent procedures. Participants and caregivers should be informed that they can withdraw from the study at any time, including in the middle of a sleep bout. In the event of a withdrawal during the sleep period, staff should be available to remove the equipment (in lab settings), or caregivers should be prepared with appropriate instructions and materials to remove the equipment themselves (in home settings).

5.2. Study location

Depending on the chosen equipment, a sleep study can take place in a sleep lab or in the participants' home. Studies in the sleep lab have the benefit of a consistent, controlled sleep environment. They can also be designed to be child-friendly, comfortable, and sleep-promoting. Lighting is the most significant external cue for sleep and wake cycles, and children have been shown to be more sensitive to light exposure prior to bedtime than adults (Hartstein et al., 2022). Blackout curtains and dimmable lighting can help to control the light in the environment. Temperature controlled rooms are also ideal for promoting sleep. Sleep experts typically recommend sleeping in temperatures between 65 and 70 °F for children (Caddick et al., 2018).

If possible, participants can be given the option to complete the sleep study in the comfort of their own home. This should only be considered for recording sleep of healthy typically developing children. This can be beneficial to enrollment and reduce bias in the sample by making the study more accessible to families who may not be able to travel to the lab. Participants may also have more natural sleep patterns when sleeping at home. However, most in-home methods do not allow researchers to monitor the data in real time or quickly troubleshoot technical issues (e.g., loose electrodes, equipment disconnection, etc.). Therefore, researchers must be particularly meticulous that the equipment is used safely (e.g., keeping cords away from the child). For nap studies, a researcher or parent can watch from a baby monitor, particularly when recording the sleep of an infant or toddler. If the researcher does not remain in the home (e.g., an overnight sleep bout), caregivers should be familiarized with how to keep the equipment safely positioned away from the child and how to remove it. Wrappings around the head and electrodes (see 6.3) should be secured with tape to mitigate any possible choking hazard.

For in-home studies, an ambulatory PSG system or one with a wireless connection (such as Bluetooth) is necessary. However, with this comes concerns about interference and lost signals. Interference refers to electrical noise in the recording environment, which deteriorates the PSG signal quality. Lost signals occur when the connection is lost between the EEG amplifier and the recording device. These problems can be attenuated by using local storage (e.g., SD card in the EEG amplifier) and/or a recording laptop placed near the sleeper. If using the laptop in the bedroom, the brightness should be turned down to mitigate light exposure. In large apartment buildings, the greater concentration of electronic devices and building features such as elevators may cause interference. Post-processing (see 7) can improve signal quality in noisy environments. Despite best efforts and practices, some data loss is often inevitable. As such, researchers should plan and budget to recruit 10–20 % more participants than their desired final sample. As with most methods, data loss will be higher in initial studies and can be reduced with experience.

6. PSG application

6.1. Preparation

PSG application is often the most difficult part of the study procedures for infants and children. Introducing the researchers and allowing the parent and child to interact with the equipment they will be wearing can help familiarize participants and ease any discomfort before the application process begins. PSG application time can range in duration from 10 to 60 minutes depending on the electrode density. Thus, it is important to prepare ample distractions for the child and to work quickly during the application process. Activities such as reading a book or playing with age-appropriate toys with infants and young children (<5 years) can be an effective and sufficient distraction. Keeping their hands occupied helps reduce the chance of them pulling at the cap or electrodes. Older children (>5 years) generally require less distraction but still benefit from an activity to promote stillness and compliance. Opting for a movie or show may also be a viable option, but researchers should be mindful that light and overstimulation may delay sleep onset (Hartstein et al., 2022). If the child resists wearing the cap, it can help to model it on a stuffed animal, caregiver, or researcher.

6.2. Choosing free-lead vs. cap electrodes

Free-lead electrodes offer individualized and customizable placement, allowing for additional channels beyond the routine montage. The flexibility and minimalistic setup make them more inclusive for different head shapes and hair types, improving accessibility across diverse populations. Additionally, free-lead electrodes are often ambulatory and more cost-effective. However, their application may vary depending on the researcher's technique, potentially introducing variability between data collections. Researchers should opt for free-lead electrodes when they need maximum flexibility in electrode placement, in-home studies, or a less expensive option.

Electrode caps feature preconfigured, standardized montages, ensuring consistent placement across participants and studies. Additionally, electrode caps often provide more electrode channels, allowing for detailed topographical analysis. However, their fixed design may be less optimal for individuals with varying head shapes and hair types, potentially affecting signal quality and comfort. Researchers should opt for an electrode cap when they need a standardized and efficient setup and at least 32 electrode channels to prioritize topography and can sacrifice a more personalized setup for each participant.

6.3. Free-lead and cap application

When applying free-lead electrodes, the participant's head should be measured according to the international 10–20 system (Homan, 1988). This system standardizes electrode placement by measuring the distance from the bridge of the nose (nasion) to the occipital bone (inion), and the preauricular to preauricular (ear to ear). Electrodes are then positioned at 10 % or 20 % of this reference distance, ensuring consistent electrode placement relative to the participant's head size, and applied to the scalp. Other than required ground (forehead) and reference channels (left and right mastoids), electrodes can be placed as desired with priority given to frontal sites (F3, F4). With additional electrodes, additional electrodes may go to central (C3, C4) and parietal sites (P3, P4).

The infant or child should be seated during the application process, either in a chair or caregiver's lap, to minimize movement. Once situated, researchers can measure the circumference of the head to select the appropriate cap size. A snug-fitting cap ensures optimal contact between the scalp and electrodes, improving signal quality and helping the cap remain securely in place throughout the entire sleep bout. Caps are also designed according to the 10–20 system and measurements should be used to verify the placement of the cap. The cap should be centered and secured under their chin.

When applying the cap, it is important to keep in mind the participant's hair texture. Some hair types may require different techniques to get adequate signal quality and connection, such as opting for free-lead electrodes over an EEG cap or choosing a slightly larger cap size. EEG systems with taller electrodes are often better for afro-textured and thick hair types and provide a solution for improving task-based data collection (e.g., Etienne et al., 2020); however, they are less comfortable to

sleep on, limiting their usefulness in this context. Braid styles (e.g., cornrows, twists, etc.) provide more direct access to the scalp even if electrode positions need to be shifted slightly (for specific suggestions, see Etienne et al., 2020). Lastly, it is important to clearly describe the process and products (rubbing alcohol, gel, etc.) that will be used in advance as it may require specific styling and washing afterward.

The goal should be to have all impedances below 20 kΩ to ensure a strong connection between scalp and electrodes, however, below 50 kΩ is acceptable with high density montages (Kurth et al., 2012; LeBourgeois et al., 2019). Low impedances reduce noise and ensure high quality, usable data. They are achieved by cleaning and exfoliating the scalp well and can be improved by finessing the placement of the conductive gel with a cotton swab. As a final method of securing the electrodes, the head should be wrapped in pre-wrap, prioritizing a secure cover over the ground and reference electrodes (typically Fpz and Cz).

6.4. Face electrode application

Whether using cap or free-lead electrodes, the EOG and EMG leads are best applied last as they are often more bothersome and accessible to the child. Free-lead electrodes may first be positioned with two-sided adhesive electrode collars. Once filled with gel, to prevent a child from pulling off these face electrodes, they should be taped down and any extra cord should be pulled away from their view. Hypoallergenic paper tape, such as surgical tape as opposed to plastic tape, is best for face electrodes.

6.5. Child-centered application modifications

The standard PSG application process (e.g., Butkov and Keenan, 2017) should be adjusted to prioritize the safety and comfort of the child. The parent and child should be informed on what is happening during each step. When talking to the child, researchers can use different terms to help their understanding. For example, rubbing alcohol can be referred to as the "cleaning water" and conductive gel as "silly shampoo." Instead of using wooden cotton-tip applicators, baby cotton swabs may be sufficient for cleaning and improving impedances on the scalp. These are much softer on the child's skin and look more familiar. Some children are very hands-on and will want to be involved in the process. In this case, offering a clean cotton swab or syringe and letting them "help" can offer a sense of inclusion and control, mitigating the fear of a new experience. Choice can also be integrated in ways that are congruent with preserving data quality. Pre-wrap for around the cap or free-lead electrodes is available in a multitude of colors. Letting the child choose which they prefer and a fun backpack to keep the device in (for units with a small, attached amplifier) during sleep (hung beside the bed or crib) can give them autonomy and make the process more enjoyable.

Other family members, such as siblings, may be present during the study. As with any developmental study, having dedicated sibling sitters to engage the non-participating children can help minimize distractions. Additional support to assist parents with any needs can ultimately reduce participant burden and enhance retention rates. In lab settings, accommodating extra family members requires space for them to sleep or play. In the home setting, such arrangements are not a concern though more time may need to be invested to ensure siblings do not play with the equipment once the researcher leaves. Children should not bedshare with siblings or pets during the sleep study.

After the child is done sleeping, researchers or parents can remove the electrodes. We recommend providing a verbal description and leaving written instructions for parents if they will be removing the electrodes. For longer sleep bouts, EEG electrode gel may partially dry out and make the cap difficult to remove. Applying a warm, damp towel to the head for a few minutes can soften the gel and help the cap removal be more comfortable. For a low-density, free-electrode montage, hair detangler sprayed liberally around the electrode can help loosen it from the hair. The tape covering EOG and EMG electrodes can be removed more easily with the help of baby oil, rubbing alcohol, mineral oil, or adhesive remover wipes. It is important to do this step slowly to minimize tugging and irritation of the skin. If in a laboratory setting, provide access to facilities for showering and washing the hair after removal if possible.

6.6. Troubleshooting

Children typically have shorter attention spans than adults, so it is important to be aware of timing and move as quickly as possible while also being gentle and patient. Simple breathing exercises can be very useful for getting preschool-aged and older children to wind down and sit still. Instructing them to use breathing exercises, such as "smell the flowers" then "blow out the candles" about 3 times can help them take deep breaths and calm themselves. Some children may need a snack or bathroom break. Other children need to "get their sillies out" and run or jump around to release energy before sitting for PSG application. For infants, breastfeeding, stimulating toys, books, and singing may be helpful. Often a combination of these strategies can be most effective. Researchers should check in periodically with the caregiver and child to ensure their comfort.

Despite preparation, some children may still be uncomfortable or uncooperative with the electrode application. In this case, it is important to work quickly to minimize the child's discomfort. At signs of distress, the researcher should pause and follow the lead of the child and their caregiver. It may be necessary to reduce the number of electrodes (if using a mid- or high-density system) or adjust electrode placement. The ground and reference electrodes should be the first priority, followed by channels that are most frequently used in the sleep scoring montage (see below) or those relevant to the research questions.

7. Processing and analyzing developmental PSG data

Before scoring and analyzing any PSG data, the raw file needs to be filtered and processed to improve the signal-to-noise ratio. The American Academy of Sleep Medicine (AASM) recommends a particular processing pipeline beginning with removing power line noise (50 or 60 Hz, depending on location), use of a notch filter, and then bandpass filter (Troester et al., 2023; Widmann et al., 2015). EEG and EOG signals are high-pass filtered at 0.3 Hz and low-pass filtered at 35 Hz. EMG signals are high- and low-pass filtered at 10 Hz and 100 Hz, respectively. Such routine filtering can be accomplished in proprietary programs or open-source code (e.g., EEGLab [https://eeglab.org]).

Following filtering, the next step to process PSG data is re-referencing. Re-referencing reduces noise from the physical properties of the skull. The standard recommendation for re-referencing during sleep stage scoring is to use the contralateral mastoid. However, it is not uncommon for researchers to use the average of the mastoid electrodes (Lokhandwala and Spencer, 2021) or a global average of all electrodes (Page et al., 2021) depending on what electrode data is available.

Data should be carefully examined for bad channels, significant artifacts, and persistent noise. Bad channels and artifacts can be identified visually or using computational methods such as power spectral density plots or independent components analysis (ICA). These EEG issues can be dealt with either through removal of the offending channel/artifact or via interpolation (for review, see Kaya, 2021 or Mannan et al., 2018).

Once a PSG record has been filtered and re-referenced, it is ready for sleep stage scoring. Records are commonly exported as European Data Format (EDF) files which can then be uploaded to your scoring platform of choice. As with pre-processing, sleep scoring can be accomplished in a variety of platforms ranging from licensed (e.g., REMLogic) to open access (e.g., Hume in MATLAB). The AASM has specific guidelines for scoring criteria (Troester et al., 2023) which we will only briefly summarize. The scoring montage, or collection of signals, should include EEG (typically F3, F4, C3, or C4), EOG, and EMG channels and be viewed

in 30 second epochs. A viewing scale of approximately 200μV is appropriate and should be kept consistent across participant records when scoring. Each stage (wake, NREM 1, NREM 2, NREM 3/SWS, and REM) is characterized by specific criteria summarized in Fig. 1.

Given the complexity (and some subjectivity) of sleep stage scoring, appropriate training is critical. One option is to have files professionally scored by companies who employ registered sleep technologists. A second option is to have lab staff trained to identify sleep stages in PSG records. There are short courses in polysomnography that may be beneficial, but a section of the curriculum or a course specific to pediatric PSG is essential for scoring infant and child data. A third option is to run in-house trainings. Particularly in this last case (but worth considering for any training approach), the best practice is to have trainees score "known" records. Known records may be a set of records that are professionally scored or scored by a trusted reliable sleep expert. This should be a variety of records in terms of length, age, and variation in how clean the data is. Interrater reliability in sleep scoring has a Cohen's kappa of 0.76, which should be used as a benchmark for in-house coding (Lee et al., 2022).

Ever-evolving technological advances hold the potential for automation in state scoring, feature identification, and power spectral analysis. Based on the significant developmental changes of the sleep EEG, caution is recommended in applying these methods to pediatric records without evidence for their population-specific accuracy. Methods that do not allow for customization of parameters (e.g., adjusting the expected spindle frequency of 2-year-olds (9–16 Hz) vs. adults (12–15 Hz)), or those hinging on machine learning algorithms that have only been trained on adult data are ill-advised. However, there is much promise for more accurate application to developmental populations as more researchers move toward open-access data repositories.

8. Sleep metrics derived from PSG data

From scored sleep data, there are a number of variables that may be of interest. Macrostructure (i.e., sleep stages) can be measured in terms of minutes spent in a sleep stage or expressed as percent of total sleep time. With these metrics, it is best to have entire night (or nap) recordings or standardized periods of time (e.g., first two hours of sleep) to ensure that similar segments of the sleep bout are being compared.

Microstructures of sleep are also valuable metrics to consider for analysis. Both sleep spindles and slow waves can be measured in terms of density (average per minute), average frequency, duration, and amplitude. The occurrence of both spindles and slow waves can also be examined by their topographic distribution, which are known to shift across infancy and early childhood development (Kwon et al., 2023). Spindles are also characterized by their interhemispheric coherence, that is, how synchronized their activity is between hemispheres. Asynchronous spindle activity past 2 years of age could suggest atypical neural development (Gruber and Wise, 2016).

A combination of spindles and slow oscillations (<1 Hz) is of particular interest in developmental research. Slow oscillation-spindle coupling is thought to reflect consolidation of memory traces, with more precise temporal coupling often correlating with improved memory performance following sleep (Joechner et al., 2021). The precision of this coupling appears to develop over childhood (see 3). Coupling can be measured and quantified in a few ways, including total number of coupled slow oscillations and spindles, preferred coupling phase, and coupling strength (see Ng et al., 2024). Preferred coupling phase describes the average point in the slow oscillation that the corresponding spindle reaches maximum amplitude, while coupling strength quantifies how precisely the two microstructures are aligned – with higher strength suggesting better coordination and synchronization.

Measures related to initiation or maintenance of sleep, such as wake after sleep onset (WASO), sleep onset latency, REM onset latency, or sleep efficiency can be useful in assessing children's sleep quality (e.g., Butler et al., 2024). PSG data can offer a more detailed assessment of sleep quality, expand our understanding of the impact that poor – or adequate – sleep can have on daytime cognitive functioning, and offer insights into the mechanisms underlying this relationship.

9. Considerations for longitudinal studies

Only a handful of longitudinal PSG studies have been conducted to date (Hahn et al., 2020; Kurth et al., 2016). However, understanding the development of sleep and sleep functions requires longitudinal studies to measure change over time (see Grammer et al., 2013). Longitudinal PSG studies require additional considerations including measurement frequency, equipment, and analytical plans. First, it is worth considering when changes in sleep physiology are likely to occur and how quickly these changes unfold when choosing timing and frequency of assessments. For example, the F/O ratio changes gradually and linearly from 2 to 20 years of age (Kurth et al., 2010), reflecting a rate of change that can be captured with less frequent sampling. Comparatively, sleep spindle amplitude increases rapidly from 1 to 3 years (Clawson et al., 2016), requiring more frequent sampling to map the developmental trajectory. Second, the choice of PSG montage should be suitable to accommodate changes in head size and behaviors. For example, in our experience, toddlers are more likely to tug on electrode wires than at younger ages. A montage that minimizes accessible electrodes may then be best for this age range. Additionally, analyses may need to be normalized in order to control for developmental changes in average EEG frequencies. Finally, it is also important for sleep scoring to be completed by a consistent scoring expert.

10. Discussion

This paper described methods for using PSG in developmental cognitive neuroscience studies. We have distilled our suggestions down to several key takeaway points, summarized in Table 3. We hope to strike a balance between maintaining the rigorous standards for PSG application (and subsequent data quality) and participants' comfort, compliance, and safety. Suggestions for modifications at the equipment, application, and design levels may be generalized to meet researchers' specific needs.

Investing adequate time and resources into the study of sleep is critical due to its vital role in brain maturation and function. During sleep, the brain supports learning, memory consolidation, and overall cognitive development. By studying sleep patterns and features, researchers can gain insights into the typical interplay between sleep and neural maturation, as well as deviations across developmental disorders.

Table 3
PSG considerations for developmental neuroscience research.

Domain	Considerations
Equipment	– Opt for the sufficient montage – Options like free-lead electrodes are more easily adapted for diverse hair types – Low, mid, or high density
Application	– Invest time in the set up: explain the materials and procedures to the child and parent, prepare toys and distractions in advance – Offer breaks and build in extra time to avoid rushing – Embed options for choice to increase autonomy and control (soft q-tips, various colored pre-wrap, fun child backpacks to hold equipment during sleep) – Practice age-appropriate strategies to reduce discomfort and promote compliance
Design	– Scheduling – Use age-appropriate pre-processing, staging, and analysis criteria

CRediT authorship contribution statement

Spencer Rebecca: Writing – review & editing, Funding acquisition, Conceptualization. **Gaudette Lena:** Writing – review & editing, Writing – original draft. **Swift Allison:** Writing – review & editing, Writing – original draft. **Horger Melissa:** Writing – review & editing, Writing – original draft. **Holmes Jennifer:** Writing – review & editing, Writing – original draft.

Data statement

No data set is associated with this paper

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rebecca Spencer reports financial support was provided by National Institutes of Health. 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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