Non-Rapid Eye Movement Sleep Characteristics and Relations with Motor, Memory, and Cognitive Ability from Infancy to Preadolescence

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Abstract

Sleep plays a critical role in neural neurodevelopment. Hallmarks of sleep reflected in the electroencephalogram (EEG) during non-rapid eye movement (NREM) sleep are associated with learning processes, cognitive ability, memory, and motor functioning. Research in adults is well-established; however, the role of NREM sleep in childhood is less clear. Growing evidence suggests the importance of two NREM sleep features: slow wave activity and sleep spindles. These features may be critical for understanding maturational change and the functional role of sleep during development. Here, we review the literature on NREM sleep from infancy to preadolescence to provide insight into the network dynamics of the developing brain. The reviewed findings show distinct relations between topographical and maturational aspects of slow waves and sleep spindles; however, the direction and consistency of these relationships vary, and associations with cognitive ability remain unclear. Future research investigating the role of NREM sleep and development would benefit from longitudinal approaches, increased control for circadian and homeostatic influences, and in early childhood, studies recording daytime naps and overnight sleep to yield increased precision for detecting age-related change. Such evidence could help explicate the role of NREM sleep and provide putative physiological markers of neurodevelopment.

Keywords

slow wave activity; sleep spindles; motor; cognition; development

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1 Introduction

It is well documented that circadian and homeostatic processes change across the lifespan, and the most prominent changes are observed across childhood (Grigg-Damberger et al., 2007). Around two months of age, the infant electroencephalogram (EEG) shows distinct signatures of sleep akin to those in adults, including cyclic alterations of rapid eye movement (REM) and non-rapid eye (NREM) sleep (Ednick et al., 2009). During the first year, the amount of REM sleep decreases, while NREM becomes the predominant state (Ednick et al., 2009; Grigg-Damberger et al., 2007; Iber et al., 2007). NREM sleep consists of multiple stages that reflect the transition from light sleep (stage 1) to deep sleep (slow-wave sleep, SWS), with distinct arousal patterns, and electrophysiological features that are observed in the EEG (Iber et al., 2007). Two prominent NREM features, slow wave activity (SWA) and sleep spindles, are known to reflect neural plasticity, myelination, and brain maturation during sensitive periods (Sejnowski & Destexhe, 2000; Steriade & Timofeev, 2003). Slow wave activity follows a maturational sequence that is non-linear and highly clustered, with scalp topography changes that parallel the maturation of motor and cognitive functioning (Kurth et al., 2012). Sleep spindle features have a distinct topographic distribution, mirroring trait-like aspects that show between- and within-individual variability, representing a biological "fingerprint" (Bódizs et al., 2009; De Gennaro et al., 2005; Finelli et al., 2001) and a possible marker of cognitive ability (Fogel & Smith, 2011).

Sleep plays a vital role in neurobehavioral functioning, and altered NREM sleep may be related to atypical development (Gorgoni et al., 2020; Gruber & Wise, 2016). Research examining adolescents and adults suggests that SWA and sleep spindle characteristics reflect plasticity that is critical for supporting motor functioning, learning, memory consolidation, and cognitive abilities (Barakat et al., 2011; Bódizs et al., 2005; Huber et al., 2004; Lustenberger et al., 2012; Walker et al., 2002; Wilhelm et al., 2014). However, findings in childhood are more variable, and far less is known about the maturation of NREM sleep and its relationship to motor, memory, and cognitive functioning in early life.

SWA and sleep spindles are implicated in many neurodevelopmental disorders, including autism spectrum disorder (ASD) (Farmer et al., 2018; Lehoux et al., 2019; Limoges et al., 2005; Page et al., 2020; Tessier et al., 2015), schizophrenia (Gardner et al., 2014; Lustenberger et al., 2015; Manoach & Stickgold, 2019), and attention deficit hyperactivity disorder (Darchia et al., 2021; Miano et al., 2006; Ringli et al., 2013; Saletin et al., 2017). Established NREM markers have the potential to inform developmental processes and improve early identification; however, there remains a gap in our understanding of how SWA and sleep spindles contribute to healthy maturation and their relation with motor, memory, and cognitive functioning. Given the rapid development in the investigated age range (infancy to preadolescents), a next step is to establish whether specific developmental domains, such as motor, memory, and cognitive abilities are associated with particular NREM features, and at what ages. Elucidating the role of NREM features in typical development may contribute to our understanding of sleep physiology in early development.

1.1 Scope of the review

We provide an integrative review of the literature on the physiological features of NREM sleep and their relations with motor, memory, and cognitive ability to understand healthy maturation and put forward putative physiological markers of neurodevelopment. To ensure a comprehensive search of the literature, we retrieved research from a combination of databases including PubMed, PsycINFO, Web of Science, and Embase. We searched for studies that investigated the physiological features of NREM sleep, and included the following keywords: ("slow wave activity" OR "SWA" OR "slow-wave sleep" OR "SWS" OR "slow oscillations" OR "sleep spindles" OR "sigma band" OR "sigma activity") AND ("motor ability" OR "fine motor" OR "sensorimotor" OR "motor performance" OR "finger tapping" OR "memory" OR "motor performance" OR "cognitive ability" OR "cognition" OR "intelligence").

1.2 Inclusion and exclusion criteria

The literature search was tailored to the specific database using the following inclusion criteria: 1) Peer-reviewed; 2) full-text available through May 31st, 2021; 3) empirical research (e.g., not a review); 4) published in English; and 5) studies including humans ranging in age from infants (3 months) to preadolescents (age 12). This range of ages allows for an investigation of important multi-domain transition periods in development, most notably infancy to toddlerhood, toddlerhood to preschool, and school age to preadolescence. Studies were excluded if the experimental statistics compared participants with a medical or neurodevelopmental disorder (e.g., ASD, ADHD, Down Syndrome, dyslexia) or an adult sample. The reference lists of the studies meeting our inclusion criteria were manually reviewed for other relevant articles.

In the following section we provide a brief overview of the studies' assessment and analysis of sleep physiology. Next, we focus on slow wave activity, and the development of SWA and its relations with motor, memory, and cognitive ability in typical development. Then, we examine sleep spindles, the development of sleep spindle features, and the evidence of sleep spindles as an underlying neural correlate of motor, memory, and cognitive ability in typical development. Finally, we identify gaps in our current understanding of NREM sleep in child development, and offer recommendations for future research.

2 Defining sleep: sleep scoring and analysis

Sleep is quantified with polysomnography (PSG) consisting of EEG, electrooculography (EOG, eye movement) and electromyogram (EMG, muscle movement). The distinction of the sleep stage is determined by features of the EEG, EMG and EOG. Sleep stage are usually identified and scored in 20 or 30 second intervals following established scoring criteria (Iber et al., 2007; Rechtschaffen & Kales, 1968). Sleep is classified into two main states, rapid eye movement sleep (REM) and non-rapid eye movement (NREM) sleep. During REM sleep, the brain exhibits desynchronized activity, with bouts of atonia and rapid eye movements (Iber et al., 2007). NREM sleep is differentiated by the appearance and frequency of slow wave activity and sleep spindles and is delineated into various stages (e.g.,

N1, N2, and N3) based on the percentage of slow wave activity and the presence of sleep spindles and k-complexes (Iber et al., 2007).

In premature infants, neonates, and young infants, scoring criteria account for the gestational and maturational age of the infant, and the presence of active sleep (AS), quiet sleep (QS), and periods of indeterminate sleep (IS). Premature infants and neonates show distinct oscillatory features, such as delta-brushes, tracé alternant, and temporal theta, which are age and region dependent (Wallois et al., 2020; Whitehead et al., 2017). Active sleep resembles REM sleep and is characterized by tense muscle tone or phasic twitches, eye movements fluttering, and rhythmic startles (Grigg-Damberger et al., 2007). Quiet sleep resembles NREM sleep and is characterized by regular breathing, limited or no eye fluttering, and little movement(Grigg-Damberger et al., 2007). Around the first month of life, the circadian rhythm emerges (Shimada et al., 1999) and around three months, infant sleep has features similar to adults, where REM and NREM can be recognized (Grigg-Damberger et al., 2007; Jenni et al., 2004). Infants' REM/NREM cycles range between 45- 60 minutes, with different compositions during nocturnal and daytime sleep (Jenni et al., 2004).

Additional information can be extracted from the sleep EEG to describe changes in the power spectrum (Achermann, 2009). The Fast Fourier Transformation (Cooley & Tukey, 1965) is widely used to transform the signal from the time domain into the frequency domain. Spectral analysis is used to decompose the EEG spectrum into discrete frequency bands (Hz). Change in spectral features including absolute power (the amount of EEG activity within a frequency band) and relative power (the ratio of absolute power in an individual frequency band to the total power of all bands) are widely examined (Cohen, 2014). The most commonly reported features of the sleep EEG include the distribution of power within specific frequency ranges, such as slow wave activity, the presence of specific EEG oscillations such as sleep spindles, and the topographical distribution on the scalp. To quantify spindle activity, visual or automatic spindle detection methods are used. Sleep spindles are defined by symmetry between hemispheres, as well as their amplitude (voltage), frequency (number of waveforms/second), density (number of spindles/minute), and the duration of the spindle burst (De Gennaro & Ferrara, 2003). Similar to the wake EEG in infancy and early childhood (though not discussed here, see review by (Saby & Marshall, 2012)) the sleep EEG power spectrum shows pronounced maturational change with age, with a prominent increase in lower frequencies during the first year of life, and higher frequencies increasing in power across childhood (Chu et al., 2014; Jenni et al., 2004; Kurth et al., 2010; McClain et al., 2016; Novelli et al., 2016; Sankupellay et al., 2011).

3   Neurophysiology of slow wave activity

Slow waves become visible in the infant EEG between 2- 4 months of age (Fattinger et al., 2014; Jenni et al., 2004). During deep sleep, the low-frequency oscillation (< 1 Hz) is generated in nearly all cortical neurons (Steriade et al., 2001; Timofeev, Bazhenov, et al., 2001). When thalamocortical neurons become highly synchronized in local regions, these slow oscillations appear as slow waves on the surface EEG (Vyazovskiy et al., 2009). SWA is defined as high-amplitude (>75μV) and slow frequency (< 4.5 Hz) waves in the scalp EEG, and is a measure of sleep homeostasis and sleep depth (Achermann et al., 2017;

Borbély & Achermann, 1999). The slope of the slow wave serves as a marker of sleep pressure, reflecting greater sleep homeostasis and higher cortical synchronization (Borbély & Achermann, 1999; Esser et al., 2007; Vyazovskiy et al., 2009). Slow waves increase with time spent awake, and over the course of the night, SWA undergoes a local topographical distribution shift, where brain regions alternate between active and inactive states (Nir et al., 2011; Timofeev, Grenier, et al., 2001), with the synchronization of SWA decreasing across successive NREM cycles (Achermann & Borbély, 2003; Riedner et al., 2007). The overnight reduction occurs with the homeostatic decrease of sleep pressure, and thus, SWA has a homeostatic regulatory aspect that is associated with the restorative features of sleep (Riedner et al., 2007).

Slow waves are regulated on a local level, and appear to reflect use-dependent features that are a function of prior experience and learning before sleep (Huber et al., 2006; Huber et al., 2004; Wilhelm et al., 2014). When specific brain regions are enlisted and used extensively during learning, the result is a local increase in SWA in subsequent sleep (Finelli et al., 2000; Huber et al., 2006; Huber et al., 2004; Määttä et al., 2010). Learning throughout the day comes at a cost, and when cerebral processes during wake produce increases in synaptic strength, the need for further synaptic potentiation is reduced (Tononi & Cirelli, 2006, 2014). During NREM sleep, SWA is associated with the downscaling of synaptic strength and restoration of cellular homeostasis, and this allows for further synaptic potentiation and the strengthening of synapses to bolster learning following sleep (Tononi & Cirelli, 2006, 2014).

3.1 Slow wave activity and development

Slow waves originate in deep cortical layers and proliferate across cortical layers with changing network dynamics (Steriade & Timofeev, 2003; Timofeev, Bazhenov, et al., 2001) that are best characterized as traveling waves across the cerebral cortex (Massimini et al., 2004; Schoch et al., 2018). Slow wave activity changes rapidly across the night and with maturation. From early childhood to adolescence, SWA propagates spatially in a postero–anterior direction (Campbell & Feinberg, 2009; Kurth et al., 2010; Massimini et al., 2004). This propagational sequence mirrors the underlying processes of cortical maturation via widespread remodeling of cortical brain circuits during sleep (Kurth et al., 2010; LeBourgeois et al., 2019) which parallel the time course of synaptic density changes (Huttenlocher & Dabholkar, 1997). As new synapses are formed in childhood, global changes in connectivity occur, which manifest as increased cortical synaptic density and SWA (Huber & Born, 2014), that is associated with cortical areas undergoing alterations and the acquisition of regionally specific skills (Kurth et al., 2017; Kurth et al., 2012; Lustenberger et al., 2017).

Features of slow wave activity vary between individuals, though intraindividual features are stable across time; however, this relation becomes evident in adulthood, when the brain reaches full maturity (Ringli & Huber, 2011). Compared to adults, children exhibit a higher percentage of slow wave sleep, which is thought to reflect changes in plasticity and brain myelin. In children, the frontal occipital shift of SWA is predictive of whole brain myelin in later development (LeBourgeois et al., 2019). SWA power follows an inverted U-shape

trajectory with a general increase in childhood and a reduction in adolescence (Campbell & Feinberg, 2009; Jenni et al., 2004; Kurth et al., 2010). Slow waves propagate across longer distances with increasing age (Kurth et al., 2017; Schoch et al., 2018). Topographically, the amplitude of SWA is most prominent over occipital regions during preschool, shifting to central regions in school age, reaches a frontal maximum in puberty (Feinberg & Campbell, 2010; Kurth et al., 2010; Novelli et al., 2016). From birth to preadolescence, the slope of slow wave shows a significant reduction, presumably reflecting processes of synaptic pruning (Buchmann et al., 2011; Kurth et al., 2010). These maturational patterns are consistent with evidence from mechanistic investigations demonstrating that SWA supports remodeling of brain circuits, in which lower-order areas subserving sensorimotor systems mature first, followed by higher-order areas that support cognitive functions maturing later in adolescence (Buchmann et al., 2011; Gogtay et al., 2004; Kurth et al., 2012; Luna & Sweeney, 2004).

3.2 Slow wave activity and relations with neurodevelopment

SWA appears to play an active role in motor, memory and cognitive processes and this relationship is particularly salient in time periods exemplified by great maturational change (Kurth et al., 2010; Timofeev et al., 2020). Neurodevelopmental transitions are associated with a topographic re-distribution of power during NREM sleep (Kurth et al., 2010), and localized changes of SWA over the motor and frontal cortex may be indicative of maturation in these networks (Kurth et al., 2017; Kurth et al., 2012). Research findings across infancy to preadolescence are limited, nonetheless, the findings provide preliminary support for SWA as a neural correlate of motor ability and memory. Table 1 provides a summary of the included studies examining slow wave activity and their main findings on motor, memory, and cognitive ability. Of the ten included studies, 7 studies report on slow wave findings in nap, and the remaining in overnight sleep.

3.2.1 Motor ability—Local changes in SWA are put forth as a marker of synaptic plasticity reflected in motor skill development, whereby the maturation of simple and complex motor skills is predicted by a topographical increase of SWA (Kurth et al., 2012; Lustenberger et al., 2017). Indeed, motor skills generally improve after practice and sleep; however, the formation and establishment of specific types of motor skills requires memory consolidation to stabilize and bolster newly acquired information (Abel & Lattal, 2001; Kuriyama et al., 2004; Walker et al., 2002; Walker & Stickgold, 2004). While these studies provide support for an active role of SWA in the acquisition of motor skills, less is known about the role of SWA in the formation of basic motor functions. Gross motor (e.g., the coordination of large muscles, involving actions such as, sitting up, crawling) and fine motor (e.g., the coordination of small muscles, such as finger and hand movements) are key developmental domains, germane to early childhood; yet, largely ignored in the literature on NREM sleep. Gross motor and fine motor are often assessed using standardized assessments (e.g., Bayley Scales of Infant and Toddler Development) or parent reported checklists (e.g., Ages and Stages) to assess child development across key milestones. Despite the scarcity of NREM research examining these key domains, there is preliminary evidence to suggest that SWA is associated with fine motor ability. In 8-month old infants during nighttime sleep, one study found higher left frontal and occipital SWA (low, 0.75-1.75 Hz and total, 0.75-4.0

Hz) to be positively correlated with fine motor ability (Satomaa et al., 2020). In toddlers, low delta power (0.5-2 Hz) showed a moderate change with age, such that toddlers older than 20 months had significantly greater delta power than toddlers age 12-19 months (Page et al., 2018). The authors also found that across the entire age range (12-30 months) frontal and posterior delta were positively correlated with fine motor ability.

3.2.2.   Memory—The increase of synchronized cortical activity in early childhood may be due to increasing synaptogenesis reflected in SWA, which helps to facilitate more efficient reorganization of cortical circuits, playing a critical role in experience-dependent plasticity and memory consolidation (Fattinger et al., 2014; Wilhelm et al., 2014). The time course of experience-dependent plasticity for memory and cognitive processes, and the extent to which age modulates these relations, is largely unknown. While there is growing interest in understanding how SWA and memory relate, different classifications for memory functions and tasks are seen across studies, reflecting the range of ages included in the review. The literature focused on declarative memory (explicit recall for events or facts), and non-declarative memory, (including procedural memories for motor skill and motor sequences, and emotional memory). The majority of studies report on SWA during nap, and relations with memory performance, encoding, consolidation and task retrieval.

There are some investigations of SWA and early indices of memory in infants. In one study in three-month old infants, a visual comparison task was used to assess habituation and dishabituation before and after a nap. Infants who napped had shorter habituation times, but habituation was not associated with SWA (Horváth et al., 2018). In a different study, 9-to 16-month-old toddlers were presented with words for specific objects and general categories, pre-and-post nap (Friedrich et al., 2015). The infants that napped showed evidence of generalization for recently learned words, however infants' SWA was not associated with retention or generalization of words.

In contrast to these findings, the majority of the reviewed studies found a relation between SWA and memory performance, whereby increased SWA was associated with retention for words and generally faster performance.

Morning and daytime naps are largely composed of NREM sleep (Cremone et al., 2017; Friedrich et al., 2015; Kurdziel et al., 2013; Kurth et al., 2016; Lokhandwala & Spencer, 2021; Page et al., 2018) with the majority of time in SWS (Friedrich et al., 2015; Kurdziel et al., 2013; Lokhandwala & Spencer, 2021). The abundance of slow wave sleep in daytime naps suggests a faster accumulation of sleep pressure in infancy and toddlerhood (Kurth et al., 2016). The increased duration of SWS is associated with toddlers' retention for story sequences (Lokhandwala & Spencer, 2021), and increased SWA in frontocentral regions is associated with infant's retention and extraction of an artificial language (Simon et al., 2017).

A daytime nap in preschool has been shown to benefit emotional memory. Greater SWA during nap predicted faster response times in an emotional memory task (Cremone et al., 2017). Similar research in preschool children also point to a possible interaction in SWA during nap and overnight sleep. Research by Kurdziel et al. (2018) found that SWA during

a midday nap predicted a next-day benefit for emotional memory. When preschoolers were assessed on the next day, the overnight memory improvement was most pronounced for children whose prior daytime nap had more SWA.

Research in older school-age to preadolescence shows a strong relation of an overnight sleep-dependent change of SWA after learning a procedural motor task. Zinke et al. (2017) investigated children's (8-12 years) initial and weeklong learning of a serial reaction time task, and found a negative relation between baseline overnight change in mean reaction time, in which participants were faster in the morning following sleep. Increased SWA mean power during the first 60 minutes of NREM was significantly correlated with reaction time at the end of training. In another motor sequence task, Astill et al. (2014) examined SWA pre- and post-completion of a finger tapping sequence in 10-year-old children. Children with increased duration of slow wave sleep exhibited increased accuracy, and children with faster slow waves (increased frequency) had the fastest performance.

3.2.3. Cognitive ability—While findings regarding SWA and relations with motor and memory performance are generally consistent, only two studies examined SWA and cognitive ability, albeit with mixed results. One study in infants age 7-9 months, found total SWA (0.75–4.0 Hz) in a right occipital site was positively correlated with cognitive ability (Satomaa et al., 2020), however, SWA in the low delta range (0.75-1.75 Hz) was not associated with infants' cognitive ability. SWA in the low delta range (0.5-2 Hz) shows a moderate change with age, yet low delta power was not associated with toddlers' cognitive ability (Page et al., 2018). Slow waves undergo immense change until fully mature, and given that cognitive abilities are rapidly evolving during early development, the stable trait-like aspect may not be present until later in development (Ringli & Huber, 2011). Thus, associations between SWA and in particular low delta activity and cognitive ability may not be actualized until specific brain regions mature. The possible differences between low delta and SWA between the two studies may also be reflective of differences in sleep patterns. In the study by Page et al. (2018) toddlers were recorded during the day and controlled for biphasic sleepers (nighttime and one daytime nap). Whereas Satomaa et al. (2020) examined younger infants, which tend to be polyphasic sleepers (multiple times throughout the day) may contribute to differences in homeostatic build-up and sleep pressure.

4 Neurophysiology of sleep spindles

Sleep spindles are rhythmic thalamocortical oscillations (De Gennaro & Ferrara, 2003; Kandel & Buzsáki, 1997; Steriade, 2006) occurring between 10-16 Hz (the sigma frequency band), and exhibit a waxing and waning presence (Andrillon et al., 2011; De Gennaro & Ferrara, 2003; Gibbs & Gibbs, 1941). In adults, sleep spindles typically occur during both light sleep and slow-wave sleep, and reoccur every 5-15 seconds (Fogel & Smith, 2011; Lüthi, 2014; Tanguay et al., 1975; Timofeev et al., 2012). Spindles are first observed in infants between 1-2 months of age (Tanguay et al., 1975; Wakai & Lutter, 2016) and typically last between 0.5-3 seconds (Rechtschaffen & Kales, 1968), but can last up to 10 seconds (Stockard-Pope et al., 1992).

4.1 Sleep spindles and development

In infants, sleep spindles appear between one to two months of age and show remarkable change over both the course of the night and development (Grigg-Damberger et al., 2007; Jenni et al., 2004; Louis et al., 1997; Louis et al., 1992). Change in the maturation of sleep spindle density and duration follows a U-shaped profile (Jenni et al., 2004; Shinomiya et al., 1999). In the first year, spindles increase in density, duration, and frequency in frontal, central, and parietal regions (D'Atri et al., 2018; Jenni et al., 2004). Between 12 and 30 months, spindle power, density, and duration significantly decrease in posterior regions (D'Atri et al., 2018; Page et al., 2018), with minimum spindle density and length observed between 19 to 27 months (Scholle et al., 2007). Thereafter spindle duration and integrated spindle amplitude increase into later childhood and adolescence (Jenni et al., 2004; McClain et al., 2016; Scholle et al., 2007; Shinomiya et al., 1999).

Topographically, spindles first appear centrally and then by 4 months, are expressed maximally in frontocentral scalp locations (Clawson et al., 2016; D'Atri et al., 2018). In infancy, the presentation of the slow frontal spindle has been inferred as a measure of cognitive ability, and compared to fast spindles, shows a different maturational trajectory (D'Atri et al., 2018). The emergence of a slow and fast spindle peak frequency in children 12-30 months is associated with decreased power in posterior regions, with a shift from a single spindle peak (~14 Hz) to a double peak (12 -16 Hz) around 20 - 24 months (D'Atri et al., 2018; Jankel & Niedermeyer, 1985; Page et al., 2018). In toddlers 20-30 month, the reduction in spindle power may be explained by a decrease in the number and duration of sleep spindles (Page et al., 2018). Slow spindles (~12 Hz) are more prominent during deep slow wave sleep, are topographically dominant over frontal regions, whereas fast spindles (14-16 Hz) are more pronounced during stage 2 sleep, are located over centroparietal regions (Andrillon et al., 2011; De Gennaro & Ferrara, 2003; Jankel & Niedermeyer, 1985).

The development of slow and fast spindle peaks is associated with changing anatomical and physiological properties of the thalamocortical system, and are suggested to promote the formation of thalamocortical networks by providing endogenous signals with repetitive and synchronized activity (Clawson et al., 2016; De Gennaro & Ferrara, 2003; Khazipov et al., 2004; Lüthi, 2014; McCormick & Bal, 1997). The mechanistic origin for the presentation of the slow and fast spindle is still debated, but it is relevant to developmental research as fast and slow spindles are differently involved in cognitive processes (Mölle et al., 2011; Schabus et al., 2007). EEG studies in adolescents and adults have shown that slow and fast spindle characteristics reflect individual differences in electrophysiological features such as amplitude, density, and duration, and are associated with cognition and measures of intelligence (De Gennaro et al., 2005; Fogel & Smith, 2011; Hahn et al., 2019; Lustenberger et al., 2012). These spindle measures and their topographies reflect inter-individual variability as well as strong within-individual stability (De Gennaro & Ferrara, 2003). Evidence in adults shows that these features have associated trait-like properties, are critical in learning and memory consolidation during sleep, and may be a physiological marker of intelligence (De Gennaro et al., 2005; Finelli et al., 2001; Fogel & Smith, 2011).

4.2   Sleep spindle features and relations with neurodevelopment

Research findings collectively provide strong evidence that maturation from infancy to preadolescence is associated with frequency changes of sleep spindles (D'Atri et al., 2018; Jenni et al., 2004; Scholle et al., 2007; Shinomiya et al., 1999). Research also shows that spindle features, such as spindle density, change across consecutive NREM sleep cycles, where the density of slow spindles declines over consecutive NREM sleep episodes, and the density of fast spindles increases across sleep cycles (Bódizs et al., 2009; Jobert et al., 1992). There's also variation within each cycle, where spindle density tends to be more prominent at the beginning of a NREM cycle (De Gennaro et al., 2000). Given the changing dynamics of spindle features across maturation and NREM sleep cycles, researchers are tasked with distinguishing which relations with spindle features are due to maturation or the changing sleep physiology and their role in cognitive functioning. Table 2 summarizes the studies examining sleep spindle features in relation to motor, memory, and cognitive ability. Of the 21 included studies examining sleep spindle features, 12 were collected during overnight sleep and the remaining 9 during a daytime nap.

4.2.1   Motor ability—The extant findings regarding motor ability and spindle features are limited, with mixed findings across studies. In 8-month-old infants, occipital slow sigma power in overnight sleep was associated with fine motor ability (Satomaa et al., 2020). Spindle features are known to change with age, and when controlling for age, Page et al. (2018) found no association with toddlers' fine motor ability and sleep spindle features. Research findings in older children are also mixed. Chatburn et al. (2013) examined fast spindle features in 8-year-olds and relations with fine motor (hand positioning test) and sensorimotor ability. The authors found that the total number of fast spindles, and fast spindle density, was negatively correlated with fine motor and sensorimotor functioning. Further, the mean central spindle frequency (maximum power within 9-15 Hz) was negatively correlated with fine motor functioning. In a similar study, Sulkamo et al. (2021) also examined relations with fine motor and sensorimotor ability and spindle density and frequency in children 8-10 years. In contrast to the findings of Chatburn et al. (2013), spindle features were not associated with motor ability. The scarcity of research and varied findings regarding spindle features and relations with motor functioning highlights a need for more research to differentiate specific motor skills (e.g., fine motor, psychomotor, and sensorimotor) associated with sleep spindle features and identify at which ages these relationships may be present. Discerning functional differences in spindle features during nap and overnight sleep and how they bolster specific motor processes could also inform future investigations.

4.2.2   Memory—The reviewed studies highlight the benefits of sleep for declarative and non-declarative memories, with most studies reporting on performance differences in encoding, consolidation and retrieval. Although there are two nap studies that report no significant relation between spindle activity and preschoolers' encoding and recall of a storybook task (Lokhandwala & Spencer, 2021), or infants' retention of words from artificial language (Simon et al., 2017), several of the reviewed studies demonstrate an association between sleep dependent memory processes and general aspects of learning.

The duration of stage N2 sleep in a daytime nap is shown to benefit learning, whereby infants with a longer duration of stage N2 sleep in a daytime nap, have a greater priming effect (inverse N400) for new information (Friedrich et al., 2017). Increased spindle power and mean spindle amplitude are also associated with infants' generalization of newly acquired words. When examining differences between low and high spindle power, the generalization effect (N400) is present for infants with higher spindle power (Friedrich et al., 2015). In another study by the same group, toddlers age 14-17 months show a similar pattern in which higher frontal fast spindle power (13-15 Hz) is associated with the number of retained object-word pairs (Friedrich et al., 2020).

Other reviewed findings show evidence that spindle density enhances encoding and recall performance. Horváth et al. (2018), found higher frontocentral spindle density was associated with faster encoding of a novel stimulus in 3-month-old infants. In toddlers, the number and density of centroparietal fast spindles are associated with encoding object word-pairs (Friedrich et al., 2019). In preschoolers, higher central spindle density is associated with better recall on a visuospatial learning task (Kurdziel et al., 2013).

Similar findings of spindle density and relationships with memory performance are present in older children in overnight sleep studies. One study in children 5-6 years found that slow frontal spindles were associated with higher maintenance of medium-quality memories, while increased fast centroparietal spindle density was associated with maintenance of low-quality memories (Joechner et al., 2021). Sulkamo et al. (2021) examined spindle associations with accuracy and speed on a vigilance task. Spindle density in the central left region was positively associated with response accuracy, whereas the topographic expression of central spindles was associated with reaction time for correct responses. In school age children, Zinke et al. (2017) found the number of spindles, and spindle density, were positively associated with next day performance for explicit sequence recall of a motor sequence, but spindle features were not associated with long-term performance. Astill et al. (2014) examined slow and fast spindle relations with procedural performance in a similar age group. The individual differences in sleep spindle frequency predicted performance on a finger tapping task, where children with a higher density of slow spindles were more accurate, and children with more fast spindles had a faster performance. Hoedlmoser and colleagues (2014) demonstrated that learning efficiency, before and after sleep, was associated with higher slow spindle activity in preadolescents; however, spindle activity was not associated with an overnight improvement for cued recall of word-pairs. Though the authors speculate that the task may have been too difficult, these findings suggest that spindles may reflect general learning abilities (Hoedlmoser et al., 2014).

The reviewed studies also highlight some different relations among spindle features and memory performance on a task compared to memory assessed as a domain on the Neuropsychological Developmental Assessment (Brooks et al., 2009) in children around 9 years of age. In one study, Sulkamo et al. (2021) found that central spindle frequency was positively associated with speeded naming, and faster central spindles were associated with poorer performance for facial memory; however, spindles were not associated with narrative memory. Contrary to these findings, Chatburn et al. (2013) found that faster spindle frequencies were positively correlated with narrative memory. Despite differences across

memory tasks, the reviewed findings suggest that increased sigma activity, spindle density, and amplitude bolster memory and learning processes in childhood. Some of the reviewed studies show that not all learned information is retained after sleep, but these studies also show that sleep generally benefits performance. This prompts further investigation to disentangle which memories benefit from sleep and whether specific memories are bolstered differently by spindle features, which would inform our knowledge regarding the specific function of the sleep spindle. (De Gennaro & Ferrara, 2003).

4.2.3 Cognitive ability—Sleep spindle features and their topographic distribution are related to general cognitive abilities in adolescents and adults (Bódizs et al., 2005; Fogel et al., 2007; Lustenberger et al., 2012; Nader & Smith, 2015). The specific relation between spindle features and cognitive ability in childhood is mixed, and inter-individual variation in spindle activity may also explain some of the differences in study findings. Sleep spindles occur independently across brain regions and show a regional distribution that changes with age (Nir et al., 2011). In older populations, spindle features show age-related effects that differ across scalp locations (Martin et al., 2013) which is also evident in childhood (D'Atri et al., 2018).

Other variation among the reviewed studies may be attributed to differences in standardized cognitive assessments compared to cognitive performance on a task. For example, Chatburn et al. (2013) found sleep spindle features were negatively associated with intelligence quotient (IQ). In contrast, Doucette et al. (2015) examined associations between preschoolers' sigma power and processing speed as a proxy for cognitive ability. The authors found a stronger overnight enhancement in processing speed to be associated with greater slow sigma power (slow spindles) over parietal regions. While it can be argued that processing speed may be more reflective of procedural performance, differences in the assessment of cognitive ability are evident. Given the broad age range in the current review, variation in cognitive assessments is expected.

The majority of studies used standardized norm-referenced assessments, which allow for an age-matched comparison; and is important, because of the known age-related changes in spindle features, normed assessments inform whether the relation between spindle features and cognitive ability is explained by age (Ujma et al., 2014; Ujma et al., 2016). One study provides evidence that increased slow sigma power in left central and occipital sites during overnight sleep is associated with infants' visual reasoning (a proxy for cognitive ability); however, it's unclear if there was an effect on age (Satomaa et al., 2020). In contrast, one study in toddlers age 12-30 months found spindle density, duration, and frequency were only predictive of age and not related to toddlers' visual reception or overall developmental functioning (Page et al., 2018). Other research investigations demonstrated a relationship among cognition, age, sex, and correlates of sleep spindles in 4-8- year-old children (Ujma et al., 2016). After controlling for age, only females showed a significant correlation between slow and fast spindle amplitude and cognitive ability score (measured via Raven Colored Progressive Matrices, (Raven et al., 1998)).

The discrepancy in research findings may be due to differences in standardized assessments. As such, research using the same assessment could help address this potential source of

variance. There is some research in 7-12 year old's examining relations between spindle features and the same standardized assessment (measured via Wechsler Intelligent Scale for Children, WISC (Wechsler & Kodama, 1949). Gruber et al. (2013) found that lower sleep spindle frequency correlated with specific domains on the WISC, such as better perceptual reasoning and working memory abilities; however, no other spindle features were associated with overall IQ. In a similar examination, Sulkamo et al. (2021) investigated 9 year-olds and found a positive correlation between central spindle density and the object assembly domain of the WISC, but not with overall IQ. Hoedlmoser et al. (2014) examined 9 year-olds and found that children with greater slow spindle activity in frontal, central, parietal, and occipital regions exhibited higher cognitive abilities (via the WISC subtest scores vocabulary, matrix reasoning, and block design). Geiger et al. (2011) examined children aged 9-12 years and found that the mean peak spindle frequency was negatively correlated with WISC full-scale IQ; but full-scale IQ and fluid IQ (reasoning and problem solving) were positively correlated with sigma power. In a follow-up analysis, Geiger et al. (2012) found that full-scale IQ negatively associated with slow and fast sigma power in central and parietal regions, and that fluid IQ was positively related to spectral power (13-20 Hz) in frontal and parietal areas.

5   Discussion

The current paper reviewed two hallmarks of NREM sleep, slow wave activity and sleep spindles, from infancy to preadolescence, and evidence of their relationships with motor, memory, and cognitive functions. In early childhood, SWA showed a consistent positive relation with fine motor ability. In school age to preadolescence, a generally consistent relation of enhanced performance is predicted by the duration of slow wave sleep or increased SWA. These findings provide support for the notion that SWA plays a role in sustaining plasticity in neurodevelopment and builds on prior research in adolescents and adults that shows a strong use-dependent relationship of motor learning to enhanced SWA (Huber et al., 2004; Kurth et al., 2012; Lustenberger et al., 2017; Wilhelm et al., 2014). Evidence regarding the role of SWA and cognitive ability, however, is limited. Given the changing dynamics of SWA, which are altered by age-related maturation and extensive learning (Huber et al., 2004), additional research is required to tease apart SWA features influenced by age from those influenced by experience or learning.

The reviewed findings show a general pattern of increased sleep spindle activity relating to better motor, memory, and cognitive performance. Investigations of sleep spindle characteristics revealed different relations among domains of cognitive functioning and overall cognitive ability. For example, peak spindle frequency showed a negative relation with full-scale IQ (Geiger et al., 2011), whereas sigma power, the number of fast spindles and spindle density showed positive correlations with domains of cognitive functioning (Doucette et al., 2015; Geiger et al., 2012; Geiger et al., 2011; Gruber et al., 2013). Behavioral measures and task performance varied widely across age groups, making it challenging to pinpoint which learning processes are most benefitted by sleep spindles. Sleep spindles mostly occur in specific regions on the scalp (Nir et al., 2011). In early development, as simple and more complex motor skills are acquired and strengthened, spindles may be more prominent in these maturing cortical regions (Kurth et al., 2012).

The reviewed findings show widespread variability across age, study design and the specific tasks for examining cognitive ability and task performance. This is particularly apparent when examining cognitive ability, which may be understood as a construct composed of multiple domains. These measures often include constructs such as language in young children, while older children's constructs include verbal ability, narrative memory, and executive functions. In particular, the contribution of expressive and receptive language may account for a large proportion of this construct (cognitive ability), thus examining potential influences of language ability or verbal IQ that may mediate the relationship. The number of sleep spindles and relations with verbal IQ and performance IQ depicts an intercorrelated relationship in adults (Fogel et al., 2007). Yet, when verbal IQ is controlled, only performance is associated with the number of spindles. Moreover, specific domains may be more sensitive or reflective of developmental constructs in a particular age range. Lower-order proficiencies that develop earlier (e.g., fine motor skills) tended to be positively correlated with SWA. In contrast, more complex skills that develop later (e.g., reasoning, memory, fluid IQ) tended to be negatively correlated with sleep spindle features (Geiger et al., 2012; Geiger et al., 2011; Gruber et al., 2013).

Several factors may influence the relationship between sleep spindles and cognitive ability. Additional heterogeneity can be explained by age, sex, socioeconomic status, and maternal education and whether or not such factors are corrected or included as potential moderators or covariates (Friedrich et al., 2015; Joechner et al., 2021; Page et al., 2018; Ujma et al., 2014; Ujma et al., 2016). It is necessary to differentiate characteristics of age-related maturation from other effects that reflect an age-independent relationship between sleep spindles and domains of cognitive ability and general intelligence. In early childhood, sleep spindles may reflect maturational stages, and as children mature, spindle features reflect more stable trait-like features of intelligence (Ujma et al., 2016).

Other differences in the reviewed findings may be specific to EEG data collection and the quantification of NREM sleep. Some reported studies (Doucette et al., 2015; Geiger et al., 2012; Geiger et al., 2011; Page et al., 2018) used dense-array setups, which provides increased spatial sampling for topographical mapping. Lower-density arrays may be less sensitive to local and spatially distributed features of the EEG and, thus, may not fully capture the local or circumscribed change of SWA or sleep spindles (Lustenberger & Huber, 2012).

Quantification of NREM sleep and spindle detection methods varied in the reviewed literature, with most using manual scoring, spectral analysis, visual or automatic detection to extract spindle features. While some studies demarcated spindles by slow and fast features, others did not. The reviewed findings showed slow and fast spindle frequencies exhibiting different topographical distributions and different relations with intellectual ability (Doucette et al., 2015; Geiger et al., 2011; Joechner et al., 2021). In some studies, individually determined slow and fast spindle frequencies were used to estimate spindle parameters, whereas other studies used a pre-determined spindle frequency range. Spindles in children are generally slower than adults (McClain et al., 2016), and when studies implement a predefined range (e.g., 11-16 Hz) the selected frequency range may not fully capture the changing dynamics of spindle features, making it challenging to detect distinct spindle

peaks. Future research would benefit from investigations of the individual variation in the presentation of the slow and fast spindle peaks and how these peak frequencies change with age.

The reviewed literature examined relations between daytime naps and overnight sleep. Careful consideration and control for the time of the sleep recording, the time awake before the sleep recording, and the number of daytime naps, are critical for reducing circadian and sleep homeostatic effects. Age-related changes in NREM sleep are more prominent in naps compared to nocturnal sleep (Kurth et al., 2016; Louis et al., 1997). During early childhood, children transition from biphasic to monophasic sleep patterns, with an abundance of NREM sleep in daytime naps (Cremone et al., 2017; Friedrich et al., 2015; Kurdziel et al., 2013; Lokhandwala & Spencer, 2021; Page et al., 2018). From 2-to-5 years, the homeostatic build-up in sleep pressure across the day is weakened with age, as evidenced by fewer differences in SWA when naps are taken at different times of the day (Kurth et al., 2016). As children's ability to sustain prolonged periods of wakefulness increases, napping decreases. Changes in habitual napping and the cessation of napping suggests that naps in early childhood may reflect a developmental milestone. The benefits of a daytime nap for preschoolers' (age 3-5.5 years) memory performance are shown to be different in habitual nappers (e.g., naps 5 or more days per week) and non-habitual nappers (naps 2 or less days per week). For non-habitually nappers', memories may be more stable and require less consolidation (Kurdziel et al., 2013). Although the role of napping in childhood is not fully understood, future investigations should consider examining sleep in populations that show a decline in daytime naps. In particular, examining sleep patterns in children that attend child care or preschool may provide valuable insight into nap physiology, because much of the child's daily schedule, including feeding and sleeping is based on the classroom schedule. In some regards, the controlled nature of a child care setting offers a potential environment in which to examine the age-related changes in napping and differences in habitual napping, which is important for understanding the role of NREM sleep and cognitive development.

Research investigating adolescence and adults, not included in the present review, have used cross sectional (Kurth et al., 2012; Wilhelm et al., 2014; Wilhelm et al., 2013) or longitudinal (Hahn et al., 2019; Lustenberger et al., 2017) assessment of NREM features and relations with motor, memory and/or cognitive functions. These studies show that NREM features change well into adolescence and adulthood, and also reflect trait-like aspects. These relations may be evident in earlier ages. Longitudinal investigations of SWA and sleep spindle features across transitional developmental periods, (e.g., toddlerhood, school age, puberty) could help to elucidate the regional and topographical changes, and their relations with cognitive development. Such characterization could provide clues to capture disruptions in early brain development. Alterations in NREM sleep are associated with a range of neurodevelopmental disorders (Gruber & Wise, 2016). Elucidating the role of NREM features in typical development may contribute to our understanding of sleep physiology and help to identify if specific NREM features reflect sensitive periods in early development.

6   Conclusion

A relatively small body of work has studied the physiology of NREM sleep and its relation to motor, memory, and cognitive ability in birth to preadolescence. These studies build upon existing research of NREM sleep in adults, and provide support for NREM sleep oscillations as an early indicator of healthy brain maturation. Both slow waves and sleep spindles are associated with learning and skill development, and yet are not mutually exclusive. Future investigations are needed to characterize the physiological features to help discern functional significance and underscore the individual contributions of SWA and sleep spindles, which could shed light on disrupted NREM features and impairments in motor, memory, or cognitive functions. Given the immense change from infancy to preadolescence, longitudinal measurements of motor, memory, and cognitive abilities and their specific sub-domains (e.g., verbal ability, executive functions) are necessary to tease apart the specific contributions across key transitions in neurodevelopment.

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Data availability:

Data sharing not applicable to this article as no data were generated.

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Table 1

Studies examining slow wave activity in typical development in relation to motor, memory, or cognition

First author, year	Sample characteristics [a]	Study design, total sleep time mean (SD) [b]	Sleep recording [c]	Sleep measure(s) [d]	Domain(s), task [e]	Main findings
Horváth, 2018	3 months n=45:15M, 30F sleep analysis n=15	Experimental nap: 41 (21.5) min	PSG, 6 EEG channels (F3, F4, C3, C4, O1, O2)	Spectral analysis, SWA (1 - 4.5 Hz)	Memory, habituation (visual paired comparison)	SWA was not associated with habituation.
Simon, 2017	6.5 (6-7) months n=37 sleep analysis n=21	Experimental nap: 64 (33.3) min	PSG, 6 EEG channels (F3, F4, C3, C4, O1, O2)	Spectral analysis, SWA (1 - 4.5 Hz)	Memory, encoding & retention (artificial language)	Greater absolute frontocentral SWA was associated with increased retention for extracted words.
Satomaa, 2020	7.9 (7.4 - 9) months n=56: 24M, 32F	Observational overnight: 543 (50.3) min	PSG, 6 EEG channels (F4, C4, F3, C3, O2, C1)	Spectral analysis, SWA (low, 0.75-1.75 Hz; total, 0.75-4.0 Hz)	Fine motor, cognitive ability (Bayley-III)	Higher left frontal and occipital SWA correlated with infants' fine motor. Higher right occipital SWA correlated with infants' cognitive ability.
Friedrich, 2015	12 (9-16) months n=90: 52M, 38F sleep analysis n=36	Experimental nap: 45 (21) min	PSG, 6 EEG channels (F3, F4, C3, C4, P3, P4)	Spectral analysis, SWA (.6- 4 Hz)	Memory, retention & generalization (specific vs category)	SWA was not associated with infant's retention for generalized word meaning.
Page, 2018	20 (12-30) months n=30: 14M, 16F	Observational nap: 77 min	128 EEG channels	Spectral analysis, SWA (0.5-2 Hz)	Fine motor, cognitive ability (MSEL)	Increased frontal and posterior SWA was correlated with fine motor ability. SWA was not associated with cognitive ability.
Lokhandwala, 2021	51.2 (36 -71) months n=22: 15M, 7F	Experimental nap: 94 (13.2) min	PSG, 32 EEG channels	Amplitude density-SWA (0.5-4 Hz)	Memory, immediate & delayed recall (storybook task)	Longer SWS duration was associated with better immediate post-nap recall for story sequences.
Kurdziel, 2018	51.5 (34 - 64) months n=49: 19M, 30F sleep analysis n=20	Experimental nap: 71 (22.9) min overnight: 522 (71.3) min	PSG, EEG 32 or 7 EEG channels (F3, F4, Cz, C3, C4, O1, O2)	Spectral analysis, SWA (0.5-4 Hz)	Memory, accuracy & recall (positive & negative stimuli)	SWA during nap was associated with memory decay for positive stimuli. Higher SWA during daytime nap, predicted the overnight improvement in memory.
Cremone, 2017	55.4 (37-69) months n=43: 25M, 18F sleep analysis n=11	Experimental nap: 69 (16.2) min	PSG, 32 EEG channels	Spectral analysis, SWA (0.5-4 Hz)	Memory, response time & congruency (dot probe task)	Greater SWA was associated with faster response times, but was not associated with congruency for emotional stimuli.
Zinke, 2017	10 (8-12) years n=25: 11M, 14F	Experimental overnight: 576 (8.5) min	PSG, 9 EEG channels (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4)	Spectral power, whole night or the first 60 minutes, SWA (0.6 - 4 Hz)	Memory accuracy, speed & retrieval (serial reaction time test); Vigilance, retrieval time (psychomotor vigilance task)	Greater SWA mean power density was associated with faster retrieval time for a novel sequence.
Astill, 2014	10.7 years n=30: 11M, 19F	Experimental overnight: 432 (4.6) min	PSG, 2 EEG channels (FPz, Cz)	Automated slow wave detection-duration, amplitude, and density	Memory, speed & accuracy (finger tapping task)	Higher percent of SWS was associated with the overnight improvement in

First author, year	Sample characteristics [a]	Study design, total sleep time mean (SD) [b]	Sleep recording [c]	Sleep measure(s) [d]	Domain(s), task [e]	Main findings
						accuracy. Children with faster slow waves had the fastest performance.

Studies are ordered by mean participant age.

[a] Sample characteristics- Mean age (range, when provided); sample size, sex: M, males; F, females; Unless indicated, the reported study sample reflects the numbers of participants included in the sleep analysis (EEG/PSG).

[b] Study design, total sleep time- Research studies are listed as experimental or observational, and followed by a description of when sleep was collected (nap or overnight sleep), and if the study collected multiple sleep recordings this is also shown. The total sleep time is shown in minutes, and listed as mean and standard deviation (when provided) or the range.

[c] Sleep recording- PSG, polysomnography; EEG, electroencephalogram, EEG channels used in the analysis

[d] Sleep measures- Only the slow wave activity features relevant for this review are reported. SWA, slow wave activity; SWS, slow wave sleep

[e] Behavioral measures- Only motor, memory and/or cognitive domains relevant for this review are reported. Bayley-III, Bayley Scales of Infant and Toddler Development; MSEL, Mullen Scales of Early Learning.

Table 2

Studies examining sleep spindle features in typical development in relation to motor, memory, or cognition

First author, year	Sample characteristics[a]	Study design, total sleep time mean (SD)[b]	Sleep recording[c]	Sleep measure(s)[d]	Domain(s), task[e]	Main findings
Horváth, 2018	3 months n=45;15M, 30F sleep analysis n=15	Experimental nap: 41 (21.5) min	PSG, 6 EEG channels (F3, F4, C3, C4, O1, O2)	Spectral power (10-15 Hz), automated spindle detection	Memory, habituation (visual paired comparison)	Infants with higher frontal spindle density processed visual information faster (decreased habituation time).
Simon, 2017	6.5 (6-7) months n=37 sleep analysis n=21	Experimental nap: 64 (33.3) min	PSG, 6 EEG channels (F3, F4, C3, C4, O1, O2)	Spectral power (10-15 Hz)	Memory, encoding & retention (language)	No significant correlations between sigma power and retention.
Friedrich, 2017	7 (6-8) months, n=107; 60M, 47F sleep analysis n=69	Experimental nap: 28 - 49 min	PSG, 8 EEG channels (F3, Fz, F4, C3, C4, P3, Pz, P4)	Spectral power (12-15 Hz), automated spindle detection-number, density, amplitude, mean length	Memory, encoding & retention (formation of word meaning)	Infants with longer naps displayed a primary effect for more generalized words. Infants with a longer duration of N2 displayed a greater inverse in the N400 priming effect.
Satomaa, 2020	7.9 (7.4 - 9) months n=56; 24M, 32F	Observational overnight: 543 (50.3) min	PSG, 6 EEG channels (F4, C4, O2, F3, O1, C3)	Spectral power slow: 10-12.5 Hz fast: 12.5-15 Hz	Fine motor, cognitive ability (Bayley-III)	Right occipital slow sigma was associated with fine motor ability. Left central and occipital slow sigma correlated with cognitive ability.
Friedrich, 2015	12 (9-16) months n=90; 52M, 38F sleep analysis n=36	Experimental nap: 45 (21) min	PSG, 6 EEG channels (F3, F4, C3, C4, P3, P4)	Spectral power (10-15 Hz), automated spindle detection-density, mean peak-to-peak amplitude, mean length	Memory, retention & generalization (object-word pairs)	Spindle power was associated with higher generalization for specific words (N400).
Friedrich, 2019	14-16 months n=30; 15M, 15F	Experimental nap learn: 63 (23.7) min no-learn: 55 (19.8) min	PSG, 8 EEG channels (F3, Fz, F4, C3, C4, P3, Pz, P4)	Spectral power, automated spindle detection-number, density, amplitude	Memory, encoding (object-word pairs)	The number and density of centroparietal fast spindles were associated with encoding for object word pairs. When similar unknown words were not generalized, there was higher spindle activity.
Friedrich, 2020	14-17 months n=60; 34M, 26F sleep analysis n=30	Experimental nap: 57 (21.8) min	PSG, 8 EEG channels (F3, FZ, F4, C3, C4, P3, PZ, P4)	Automated spindle detection-spindle number, density, amplitude, length	Memory, encoding & retention (object-word pairs)	Infants who napped after encoding retained more object-word pairs. Infants with higher frontal fast spindle (13-15 Hz) amplitude had better memory for the context of a word.
Page, 2018	20 (12-30) months n=30;14M, 16F	Observational nap: 77 min	128 EEG channels	Spectral power (10-17 Hz), automated spindle detection-frequency, amplitude, duration, and density	Fine motor, cognitive ability (MSEL)	Spindle density, duration, and frequency changed with age. When controlling for age, spindle features were not associated with fine motor or cognitive ability.
Kurdziel, 2013	46.8 (36-67) months n=40: 5M, 31F sleep analysis n=14	Experimental nap: 73 (19.9) min	PSG, 4 EEG channels (F3, F4, C3, C4)	Spectral power (9-15 Hz), manual spindle detection-peak frequency, density, amplitude	Memory, delayed & immediate recall (Visuo-spatial learning)	Spindle density showed a negative correlation with immediate recall and a positive correlation with delayed recall.

First author, year	Sample characteristics [a]	Study design, total sleep time mean (SD) [b]	Sleep recording [c]	Sleep measure(s) [d]	Domain(s), task [e]	Main findings
Doucette, 2015	4.3 years n=10: 5M, 5F	Observational overnight: 545 (77.2) min	128 EEG channels	Spectral power, manual detection slow: 10-13 Hz fast: 13.25-17 Hz	Cognitive processing, reaction time (computer task)	Higher parietal slow sigma power was associated with faster processing speed.
Lokhandwala, 2021	51.2 (36-71) months n=22: 15M, 7F	Experimental nap: 94 (13.2) min	PSG, 32 EEG channels	Automated spindle detection (C3)	Memory, encoding & recall (storybook task)	Sleep spindle density was not associated with post-nap, nor 24-hour recall of a storybook sequence.
Joechner, 2021	70 months n=24: 11M, 13F	Experimental overnight base: 586 min learn:592 min	PSG, 7 EEG channels (F3, F4, C3, Cz, C4, Pz, Oz)	Spectral analysis, (9-16 Hz), time frequency analysis, automated spindle detection-frequency, density, amplitude	Memory, encoding & recall (scene-word)	Increased fast centroparietal spindle density was associated with memory gains for low-quality memories. Slow frontal spindle density, amplitude and child's age were related to memory maintenance for medium-quality memories.
Ujma, 2016	6.2 (3.8-8.4) years n=28:13M, 15F	Observational overnight: 540 (45.2) min	PSG, 19 or 32 EEG channels	Automated spindle detection-individual average slow and fast spindle frequency density, duration, amplitude	Cognitive ability (Raven CPM)	Age and spindle amplitude were correlated. When age was controlled, slow and fast spindle amplitude were associated with cognitive ability in females.
Chatburn, 2013	8.2 (4.1-12.7) years n=27:13M, 14F	Observational overnight: 438 (34.4) min	PSG, 2 EEG channels (C3, C4)	Automatic and manual detection-number, frequency, density, duration	Fine motor, sensorimotor (NEPSY); Cognitive ability (Stanford Binet Intelligence Scale)	Mean central spindle frequency negatively correlated with fine motor ability. Number of fast spindles was negatively associated with sensorimotor. Fast spindle density was negatively associated with fine motor and sensorimotor. Mean central spindle frequency was negatively correlated with nonverbal working memory and planning domains. Fast spindle density was associated with better narrative memory.
Gruber, 2013	8.7 (7-11) years n=29:15M, 14F	Observational overnight: 513 (58.1) min	PSG, 8 EEG channels (F3, F4, C3, C4, P3, P4, O1, O2)	Bandpass filter (11-15 Hz) Automated spindle detection-frequency, density, amplitude, duration	Cognitive ability (WISC-IV)	Spindle frequency negatively correlated with reasoning and memory domains. Other spindle features were not associated with cognitive ability.
Hoedlmoser, 2014	9.4 (8-11) years n=54: 29M, 25F	Observational overnight base: 559.4 min learn: 554.3 min	PSG, 12 EEG channels	Automated & semi-automated spindle detection-mean spindle activity (duration x amplitude)	Memory, cued & delayed recall (word pair); Cognitive ability (WISC-IV)	Sleep spindle activity was related to learning efficiency, but not associated with improvement in declarative memory. Higher slow spindle activity correlated with higher cognitive abilities.
Sulkamo, 2021	9.6 (8.9-10.8) years n= 17: 7M, 10F	Observational overnight: 527 min	PSG, 6 EEG channels (Fp1, Fp2, C3, C4, O1, O2)	Automated spindle detection-local, bilateral, and diffuse spindle density	Fine motor & sensorimotor (NEPSY); psychomotor, speed & accuracy (CogniSpeed); cognitive ability (WISC-III)	Spindles were not associated fine motor or sensorimotor. Diffuse and bilateral central spindles were negatively associated with reaction time and accuracy. Local central spindles were positively associated with accuracy. Bilateral central spindle density was associated with object assembly.

First author, year	Sample characteristics[a]	Study design, total sleep time mean (SD)[b]	Sleep recording[c]	Sleep measure(s)[d]	Domain(s), task[e]	Main findings
Zinke, 2017	10 (8-12) years n=25: 11M, 14F	Experimental overnight: 576 (8.5) min	9 EEG channels (F3, Fz, F4, C3, Cz, C4, P3, P4)	Spectral power (11-15 Hz) number, density	Memory accuracy, speed & retrieval (serial reaction time test); Vigilance, reaction time (psychomotor vigilance task)	Spindle number and density were positively correlated with sequence recall. Mean sigma density was associated with retrieval time.
Geiger, 2011	10.5 (9.1-12.5) years n=14: 8M, 6F	Observational, overnight base: 442.2 min post: 477.3 min	128 EEG channels	Spectral analysis, individual relative sigma	Cognitive ability (WISC-IV)	Sigma power was positively correlated with full-scale and fluid intelligence. Individual spindle peak frequency was negatively correlated with full scale intelligence.
Geiger, 2012	10.5 (9.1-12.5) years n=14: 8M, 6F	Observational overnight sleep: 457 (28.3) min	128 EEG channels	Spectral power slow:10-13.25 Hz fast: 15.5-20 Hz	Cognitive ability (WISC-IV)	Power (10-13.25 Hz; 15.5-20 Hz) in central and parietal areas was negatively correlated with full-scale intelligence. Power (13-20 Hz) in frontal and parietal regions showed a positive association with fluid intelligence.
Astill, 2014	10.7 years n=30:11M, 19F	Experimental overnight: 432 (4.6) min	PSG, 2 EEG channels (FPz, Cz)	Spindle detection-amplitude, density, duration	Memory, speed & accuracy (finger tapping)	More slow spindles were associated with the overnight improvement in accuracy. Children with increased fast spindle density had the fastest performance.

Studies are ordered by mean participant age.

[a] Sample characteristics- Mean age (range, when provide); sample size, sex: M, males; F, females; Unless indicated, the reported study sample reflects the numbers of participants included in the sleep analysis (EEG/PSG).

[b] Study design, total sleep time- Research studies are listed as experimental or observational, and followed by a description of when sleep was collected (nap or overnight sleep), and if the study collected multiple sleep recordings this is also shown. The total sleep time is shown in minutes, and listed as mean and standard deviation (when provided) or the range.

[c] Recording setting- PSG, polysomnography; EEG, electroencephalogram, EEG channels used in the analysis

[d] Sleep measures- Only the sleep spindle features relevant for this review are reported.

[e] Behavioral measures- Only motor, memory and/or cognitive domains relevant for this review are reported. Bayley-III, Bayley Scales of Infant and Toddler Development; MSEL, Mullen Scales of Early Learning; Raven CPM, Raven's Colored Progressive Matrices; NEPSY, Neuropsychological Developmental Assessment; WISC-IV, Wechsler Intelligence Scale for Children; WISC-III, Wechsler Intelligence Scale for Children