Chapter 1
The Memory Function of Sleep Across the Life Span

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Abstract Sleep is the single most common form of human behavior, indicating that sleep likely has an important evolutionary function. Yet the functions of sleep are still debated. Intriguingly, sleep is not static across the life span, changing in duration, pattern, structure, and physiology. This chapter reviews the transformations of sleep, from the first appearance of sleep prenatally to sleep in older adulthood, and assesses how the functions of sleep may change in response. This review focuses on the memory function of sleep and examines sleep-dependent consolidation across declarative, procedural, and emotional memory domains. With respect to the memory function of sleep, changes in SWS in particular appear to have the greatest impact on the resultant age-related alterations in sleep-dependent memory consolidation.

Keywords Sleep · Development · Adolescence · Aging · Slow Wave Sleep · Memory

1.1 Introduction

Across the human life span, approximately a quarter of a century is spent asleep (Martin 2002). This makes sleep the most prevalent of all human behaviors. Why so much of life is dedicated to this behavior, during which no resources or reproductive mates can be attained, is one of the greatest unsolved scientific mysteries. Researchers have debated the function, or functions, of sleep for years (Franken et al. 2009). Studies have examined the role of sleep through many different lenses, including but not limited to genetic, neurological, immunological, behavioral, and epidemiological perspectives. The aim of this chapter is not to attempt to answer the question of why we sleep, nor to be a comprehensive review of all of the potential functions of sleep. Rather, this chapter will examine how these potential functions of

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sleep may change throughout the life span, as individuals progress from early prenatal development to older adulthood. This chapter will also center primarily on these changes throughout human development and with an additional focus on the way sleep may impact cognition and memory.

1.2 Young Adults

1.2.1 Sleep in Young Adults

Sleep is defined as a reversible period of behavioral quiescence with a high arousal threshold (Carskadon and Dement 2005). The adult form of sleep will be considered a baseline from which to compare the development and degradation of sleep across the life span. As such, it is important to describe the architecture and neural underpinnings of adult human sleep.

Sleep is not a static behavioral state. Adult human sleep can be subdivided into two states, rapid eye movement (REM) sleep and non-REM (nREM) sleep. Further, nREM sleep can be subdivided into three sleep stages: nREM1, nREM2, and nREM3 (nREM3 is also known as slow-wave sleep (SWS)). Each sleep stage is physiologically unique and can be characterized through polysomnography (PSG), a montage of electroencephalogram (EEG) waveforms, muscle movements measured by electromyogram (EMG), and eye movements as measured by electrooculogram (EOG; Carskadon and Dement 2005).

In healthy adults, sleep is entered through nREM and characteristically progresses in order of sleep depth (nREM1, followed by nREM2, and then SWS). REM sleep does not usually occur for at least 80 min, after which nREM and REM sleep alternate in cycles lasting approximately 90 min each (Carskadon and Dement 2005). Typically, total sleep time is about 7–8 h in a healthy young adult. While there may be trait-like inter-individual differences (Tucker et al. 2007), as well as potential sex differences (Mongrain et al. 2005) in sleep physiology, the architecture of sleep staging appears to be fairly consistent. Sleep architecture has also been shown to be stable across both morning and evening chronotypes (Mongrain et al. 2005).

The transition from waking to nREM sleep is generated in the hypothalamus (Siegel 2009). During this transition, there is a global reduction in neuronal firing rates, as well as more specific regional reductions (e.g., frontal gyri, anterior cingulate cortex, posterior putamen, caudate nucleus, midbrain, basal forebrain, and inferior cerebellar hemispheres; Braun et al. 1997; Kaufmann et al. 2006). The global reduction of neuronal activation is a result of GABA input from the thalamic reticular nucleus (Steriade 2001). Specifically, the sensory-relay function of the thalamus is inhibited, thus contributing to the unconscious state and to the high arousal threshold that defines sleep. Contrarily, endogenous cortico-cortical neuronal activation increases in nREM sleep (Steriade 2000, 2001).

Slow oscillations, oscillatory waves in the 0–1 Hz frequency range, are a core feature of nREM sleep. They are the result of cortical neurons cycling through an

extended hyperpolarization (downstate) phase, followed by a phase of spontaneous and intense neuronal firing (Steriade 2000, 2001). This intense state of depolarization (upstate) also plays a major role in synchronizing neuronal activity across the cortex as well as additional subcortical structures.

For example, the upstate of the slow oscillation synchronizes the initiation of thalamic sleep spindles. Sleep spindles are bursts of activity in the sigma (10–16 Hz) frequency range that can be observed in nREM sleep. Spindles originate from inhibitory thalamic reticular neurons, of which activation leads to bursting in linked cortical neurons (Achermann and Borbély 1997; De Gennaro and Ferrara 2003; Schabus et al. 2007). The resultant depolarization of cortical neurons from sleep spindles has been suggested to lead to intensive calcium influx, which in turn activates a number of processes within the neuron necessary for long-term potentiation (Ghosh and Greenberg 1995), such as calcium/calmodulin-dependent protein kinase II (CaMKII; Soderling and Derkach 2000; Lisman et al. 2002). Thus, sleep spindles have been specifically implicated in synaptic plasticity of excitatory neurons (Steriade and Timofeev 2003) and in learning and memory more generally (Fogel et al. 2007a; Fogel and Smith 2011; Ulrich 2016).

The upstate of the slow oscillation is also critical for synchronizing hippocampally generated sharp wave ripples. Sharp waves are synchronous bursts of incredibly high-frequency (~200 Hz) activation that progress from pyramidal neurons in the CA3 to the CA1 regions of the hippocampus during SWS (Buzsáki 1989). These events are thought to represent a wide-scale hippocampal network search for previously experienced patterns of activation. Due to this neurological rehearsal of previous experiences, the sharp waves are considered critical to learning and memory trace formation (Buzsáki 1989; Girardeau and Zugaro 2011). Importantly, sharp wave ripples are temporally coupled with slow oscillations that can recruit large networks of neurons and thus organize activation across multiple neurological structures. In addition, the slow oscillation synchronizes the hippocampal ripples with thalamocortical sleep spindles, further supporting the communication between the cortex and the hippocampus during SWS (Siapas and Wilson 1998; Clemens et al. 2007; Mölle et al. 2009).

The interplay between hippocampal, thalamic, and cortical networks through slow oscillatory synchronization of ripples and sleep spindles is associated with cortical synaptic plasticity. This relationship is also thought to be a possible mechanism through which hippocampal-dependent short-term memories are transferred to the more stable cortical storage of long-term memories (Gais et al. 2002; Schabus et al. 2004, 2007; Sirota and Buzsáki 2005; Wierzynski et al. 2009; Mölle et al. 2009; Born and Wilhelm 2012). In further support of this association, experimentally boosting the slow oscillation has been shown to enhance the consolidation of newly formed memories (Marshall et al. 2006).

Another commonly used analytic feature of nREM sleep is slow-wave activity (SWA). SWA is a measure of power in the delta frequency range (0.5–4 Hz) and is often considered a gauge of homeostatic sleep pressure (Achermann et al. 1993; Borbély 2001). The intensity of SWA builds over the course of the day. During the first nREM bout of the night, SWA is greatest in the frontal regions of the brain, an

effect that is especially observable following sleep deprivation (Werth et al. 1997; Finelli et al. 2001). Across subsequent bouts of nREM sleep, SWA is progressively reduced (Achermann and Borbély 1990; Achermann et al. 1993). Greater SWA reflects greater synchrony of activity within the central nervous system (CNS) during sleep (Greene and Frank 2010). SWA has been shown to parallel synaptic density (Feinberg and Campbell 2010) as well as increases in synaptic potentiation (Huber et al. 2004; Huber et al. 2006). Cellular, molecular, and neuromodulatory mechanisms, as well as changes in gene expression, all favor SWS, and specifically SWA, as a time for global synaptic downscaling (Tononi and Cirelli 2003, 2014) and synaptic plasticity (Chauvette et al. 2012) in the brain.

In contrast to the global neuronal deactivation of nREM sleep, during REM sleep, particular brain regions reactivate to levels similar to or exceeding those that occur during the wake state (Braun et al. 1997; Hobson et al. 1998). For example, visual association cortices as well as limbic and paralimbic structures (including the hippocampal formation, parahippocampal gyri, portions of the insula, the amygdala, and the anterior cingulate cortices) become reactivated (Maquet et al. 1996; Braun et al. 1997; Nofzinger et al. 1997; Braun et al. 1998). Conversely, the majority of the frontal association cortices remain inactivated from previous nREM sleep bouts (Braun et al. 1997; Lövblad et al. 1999). Given the limbic reactivation, most researchers support the notion that REM sleep is critical in selectively processing emotional memories (Maquet et al. 1996; Wagner et al. 2001; Hobson and Pace-Schott 2002; Nishida et al. 2009; Lara-Carrasco et al. 2009; Baran et al. 2012; Groch et al. 2013) or in processing motivational or reward-driven experiences (Nofzinger et al. 1997).

REM sleep is also characterized by muscle atonia and the titular rapid eye movements. The muscle atonia results from descending projections of the dorsolateral pontine reticular formation through the medulla and spinal cord to inhibit motor neurons (Hishikawa and Shimizu 1995). Waves generated in the pontine reticular formation that progress through the thalamic lateral geniculate body to the occipital cortex (PGO waves) play a major role in the endogenous visual system excitation characteristic of REM sleep (Callaway et al. 1987). Rhythmic activation of the vestibulo-oculomotor neurons leads to rapid eye movements (Pompeiano 1975; Hobson and Pace-Schott 2002), and the duration of PGO waves has been associated with duration of these eye movement events (Nelson et al. 1983). The endogenous activation of the extrastriate visual cortex in particular is associated with the visual elements of dreaming, another key feature of REM sleep (Braun et al. 1998; Hobson et al. 2000).

1.2.1.1 The Many Functions of Normal Human Sleep

As demonstrated by the dynamic brain activity during sleep, sleep also has dynamic functions. There are many theories as to why we sleep (Siegel 2005). Sleep plays a role in metabolic function (Morselli et al. 2011) as well as metabolite clearance from the CNS (Xie et al. 2013). The reduction in global neuronal firing rates during nREM

sleep has also been used to support the idea that sleep is a time for energy conservation (Berger 1975; Walker and Berger 1980; Berger and Phillips 1995). High levels of neuronal activation during REM sleep are not directly in line with this theory; however, it has been suggested that bouts of REM sleep may be necessary to maintain the CNS core temperature following reduced activation during nREM sleep (Wehr 1992). In addition, given that activation is reduced in a number of neurotransmitter systems during sleep, and during REM sleep specifically (e.g., noradrenaline, histamine, hypocretin, and serotonin), sleep may play an important role in resensitization of these neuronal circuits (Siegel and Rogawski 1988; Tsai et al. 1993; Hipólide et al. 1998, 2005; Pedrazzoli and Benedito 2004; Siegel 2005).

Sleep, and SWS in particular, has been implicated in immune system function and in immunological memory (Moldofsky et al. 1986; Redwine et al. 2000; Besedovsky et al. 2011). Growth hormone is also secreted during SWS (Takahashi et al. 1968; Honda et al. 1969; Sassin et al. 1969; Born et al. 1988; Marshall et al. 1996), which may indicate that sleep is an important part of growth and development. Lastly, as mentioned previously, a primary function of sleep is learning and memory (Stickgold 2005; Diekelmann and Born 2010). Importantly, these many possible outcomes of sleep are not mutually exclusive.

1.2.2 Sleep-Dependent Memory Consolidation in Young Adults

1.2.2.1 Declarative Memory

Memory consolidation, or the process through which a memory trace becomes more stable and less vulnerable to forgetting or interference, is greatest over sleep (Walker 2005; Stickgold 2005; Diekelmann et al. 2009; Diekelmann and Born 2010). Sleep-dependent memory consolidation (SDC) involves cellular and molecular changes, as well as changes at the systems level, to stabilize a particular memory for long-term recall and to integrate the memory into other existing memories.

In one of the earliest studies of memory consolidation over sleep, Jenkins and Dallenbach (1924) found that memory for nonsense syllables was greater following bouts of sleep than following bouts of wake. Since then, the role of sleep on declarative memory has been more thoroughly investigated, and many studies have replicated the improved recall following sleep (Gais and Born 2004a). For example, when individuals were taught a list of semantically unrelated word-pairs either in the morning or in the evening, recall accuracy was significantly greater 12 h later when the intervening interval contained sleep (e.g., Donohue and Spencer 2011; Wilson et al. 2012). These results suggest that during sleep, memories are actively consolidated, leading to a reduction in forgetting and more long-term retention of the encoded information (Ellenbogen et al. 2006).

Particular sleep stages appear to play different roles in memory consolidation in adults (Spencer 2013). For example, SDC of declarative memory is often associated

with time spent in SWS (Gais and Born 2004a, b). Specifically, replay of activation patterns in the hippocampus (Pavlides and Winson 1989) during SWS may be critical to the consolidation of declarative memories (Wilson and McNaughton 1994). Hippocampal replay during early bouts of SWS is observed directly following new learning in rats (Wilson and McNaughton 1994; Skaggs and McNaughton 1996; Louie and Wilson 2001; Ji and Wilson 2007). Similarly, a study by Peigneux et al. (2004) showed that neurological activation within the hippocampus during learning of a new declarative task in young adults was mirrored in a subsequent bout of SWS. Importantly, the reactivation of the hippocampus during SWS was specifically associated with improved performance on this declarative memory task upon waking. Reduced acetylcholine levels in the hippocampus during SWS appear to allow for hippocampal replay, and is necessary for declarative memory consolidation, but not for non-declarative memory consolidation (Gais and Born 2004b).

Targeted experimental reactivation of hippocampal neuronal networks has also been shown to improve declarative memory. During encoding, declarative items were paired with either olfactory (Rasch et al. 2007; Barnes and Wilson 2014) or auditory (Rudoy et al. 2009; Cairney et al. 2014a) stimuli. During subsequent SWS, a subset of the sensory stimuli was presented to the participant. Memory retention for the reactivated items was significantly improved compared to the items that were not cued during sleep.

REM sleep may also play a role in the consolidation of declarative information. Whereas SWS is necessary for initial phases of consolidation, neocortical activation of the hippocampus during REM sleep may reflect a later stage of memory consolidation (Datta 2000; Louie and Wilson 2001; Jones and Wilson 2005). REM sleep has been suggested to be involved in reorganization, integration, and optimization of previously learned material (Laureys et al. 2001; Peigneux et al. 2003; Walker and Stickgold 2010), as well as the integration of unassociated information into currently existing networks, thus enhancing creative problem-solving (Cai et al. 2009). REM sleep may also potentially be a time in which older memory traces are intentionally weakened (Poe et al. 2000), thereby making memory recall more efficient.

1.2.2.2 Procedural Memory

Procedural memories have also been shown to be enhanced over sleep in young adults (Plihal and Born 1997; Fischer et al. 2002; Walker et al. 2005; Wilson et al. 2012). REM sleep has been proposed to play a role in the consolidation of procedural memories (Karni et al. 1994; Plihal and Born 1997; Maquet et al. 2000; Laureys et al. 2001; Smith et al. 2004), although this has been debated (Siegel 2001; Rasch et al. 2009; Laventure et al. 2016). Alternatively, nREM2 sleep and sleep spindles during nREM2 have also been associated with procedural memory consolidation (Smith and MacNeill 1994; Walker et al. 2002; Fogel and Smith 2006; Nishida and Walker 2007; Fogel et al. 2007b; Laventure et al. 2016). It is possible that both nREM and REM sleep contribute to procedural learning, but in different capacities (Stickgold et al. 2000; Smith et al. 2004; Fogel et al. 2015).

In conjunction with the sleep stage discrepancies, the functional role of sleep in procedural memory consolidation is also still controversial (Song et al. 2007; Rickard et al. 2008; Cai and Rickard 2009; Albouy et al. 2013). Recent studies have questioned the magnitude of the effect of sleep on procedural memory (Pereira et al. 2015), as well as whether additional features, such as explicit awareness during procedural learning (Robertson et al. 2004), modify the influence of sleep. Further, the time course of sleep with respect to learning (Brawn et al. 2010) may also factor into the possible benefits of sleep on procedural memory consolidation.

1.2.2.3 Emotional Memory

Emotional memory consolidation has also been shown to benefit from sleep (Wagner et al. 2001; Hu et al. 2006; Holland and Lewis 2007; Sterpenich et al. 2007; Payne et al. 2008; Payne and Kensinger 2010; Lewis et al. 2011; Baran et al. 2012; Deliens et al. 2014). Sleep prioritizes the consolidation of emotional elements of stimuli above more neutral information in the background (Payne et al. 2008). In addition, Baran and colleagues demonstrated that the emotional reactivity to stimuli is protected over sleep (2012). When memory for emotional stimuli was probed after a delay, the strength of neuronal activation and the functional connectivity between cortical networks (especially the medial prefrontal cortex (mPFC)) and the hippocampus were stronger for emotional compared to neutral stimuli (Sterpenich et al. 2007). This relationship was especially observed when sleep followed encoding compared to wake. The mPFC is thought to provide top-down inhibitory control over the amygdala, thus maintaining control of the emotional response (Ochsner and Gross 2005). Sleep has been shown to depotentiate amygdala reactivity to emotional stimuli (van der Helm et al. 2011), whereas sleep deprivation has been shown to reduce the functional connectivity between the mPFC and the amygdala (Yoo et al. 2007). The result of sleep deprivation is thus an inappropriate hyperarousal of the limbic system to emotional stimuli. Sleep-related changes in emotional memory recall, as well as the underlying neurological changes in connectivity, were also shown to be incredibly long-lasting (Wagner et al. 2006; Sterpenich et al. 2009).

A number of studies have supported the role of REM sleep in both emotional processing (Lara-Carrasco et al. 2009; Baran et al. 2012) and emotional memory consolidation (Wagner et al. 2001; Nishida et al. 2009; Groch et al. 2013). During REM sleep, the amygdala, hippocampus, and cortical areas show a distribution of activation which may support a REM sleep benefit on emotion processing (Maquet et al. 1996). Similarly, theta coherence between the amygdala, the mPFC, and the hippocampus during REM sleep was selectively correlated to changes in fear memory in rats (Popa et al. 2010). However, not all research supports a functional role of REM sleep in emotional SDC. For example, in one study, REM sleep deprivation was demonstrated to have no impact on SDC of emotional memories (Morgenthaler et al. 2014).

Recent work has also attributed emotional SDC to SWS. Groch and colleagues suggest that phasic noradrenergic activity in early bouts of SWS supports the

consolidation of memories that require both hippocampal and amygdala activation (2011). Hippocampal-based fear contextual memory was stabilized during SWS in mice due to CA1 network stabilization (Ognjanovski et al. 2014). In humans, targeted memory reactivation using auditory cues during SWS was shown to enhance memory recall for emotional memories (Cairney et al. 2014a). In another study, overnight SWA was pharmacologically enhanced following the encoding of an emotional text. Significant memory improvements were observed in the group with increased SWA compared to the control group (Benedict et al. 2009). Similarly to procedural memory consolidation, new research is supporting a role for multiple sleep stages in the progression of emotional memory consolidation (Cairney et al. 2014b).

Likewise, the cycling between nREM and REM sleep stages may reflect a sequential pattern of consolidation. In rodent studies, nREM sleep is important for early stages of memory consolidation, whereas REM is needed for later stages of consolidation (Giuditta et al. 1995; Louie and Wilson 2001; Ambrosini and Giuditta 2001). A recent study using transgenic mouse models has shown that REM sleep may enhance SWA in the subsequent nREM bout, thereby subsequently enhancing synaptic plasticity indirectly (Kashiwagi and Hayashi 2016). In human research, the sequential relationship between nREM and REM sleep has also been implicated in memory consolidation (Ficca et al. 2000b; Griessenberger et al. 2012; Grosmark et al. 2012; Spencer 2013; Sonni and Spencer 2015).

1.2.3 Summary

A number of studies have supported sleep as a time in which memory consolidation occurs in young adults. Specifically, nREM sleep, and accompanying elements such as slow oscillations, SWA, and sleep spindles, is associated with synaptic plasticity and with the transfer of information from hippocampal to neocortical networks. Importantly, new work is investigating the relationship between nREM and REM sleep with respect to memory processing. Sleep has been shown to improve memory in declarative, procedural, and emotional realms, although the procedural memory literature is inconsistent. Therefore, young adult SDC will be a foundation from which to compare other developmental life stages.

1.3 Prenatal Development and Infancy

1.3.1 Fetal and Infant Sleep

Sleep first develops between 26 and 28 weeks gestational age (Graven and Browne 2008). Early in development, adult-like sleep stages cannot be distinguished. At approximately 30 weeks gestational age, sleep is first differentiated into quiet and active sleep (de Weerd and van den Bossche 2003). Quiet sleep is identifiable by

delta waves and *tracé alternant* patterns of brain activity. *Tracé alternant* are bursts of slow waves intermixed with sharp waves, with alternating periods of quiescence. As such, quiet sleep is considered an immature form of adult nREM sleep. Alternatively, active sleep is identifiable by variability in respiration and heart rate with both slow and rapid eye movements; active sleep is therefore considered to be an immature form of adult REM sleep (Prechtl 1974). Rapid eye movements are first observable at 30 weeks gestational age, and increase through approximately 40 weeks, after which the rate of eye movements declines (Bots et al. 1981; Birnholz 1981; Inoue et al. 1986; Okai et al. 1992). Data from prematurely born infants has supported this pattern of eye movements increasing between 30 and 41 weeks postconceptional age (Dreyfus-Brisac 1970; Petre-Quadens and De Lee 1974). By 47 weeks gestational age, sleep stages can be differentiated into the standard adult stages as the *tracé alternant* are replaced with increasing slow waves (Sterman et al. 1977; Dan and Boyd 2006).

In neonates, sleep accounts for approximately 16–18 h of the day. Neonatal sleep is quite fragmented, alternating rapidly between the active and quiet sleep stages, and with more frequent transitions from sleep to wake (Anders and Roffwarg 1973; Peirano and Algarín 2007). As the forebrain develops, greater control is gained over sleep and waking states (Mirmiran et al. 2003); at 2 weeks of age, neonates are only capable of remaining asleep for 4 h at a time. By the end of the 1st year of life, an infant can remain sleeping without awakening for 7 h (Anders and Keener 1985). Sleep also begins to be consolidated to nocturnal bouts with a reduction in diurnal sleep, and by the end of the 1st year, total sleep time in infants is reduced to about 14 h (Iglowstein et al. 2003).

Characteristic features of the sleep EEG also begin to emerge in the 1st year of life. Sleep spindles are first identifiable around 8 weeks post-gestational age (Metcalf 1969, 1970; Tanguay et al. 1975; Jenni et al. 2004). In the first 6 months of life, spindle density (number of spindles per minute nREM sleep) rapidly increases, spindle amplitude increases, and spindle duration decreases (Tanguay et al. 1975). These changes in spindle architecture are thought to reflect the maturation of the physiological system that produces spindles, including thalamocortical networks, as well as the growth of dendrites and the myelination of neurons.

In concordance with the progressive maturation of the brain, prominent changes in active/REM sleep occur. In newborns, active sleep is entered directly from wakefulness; after the first few months, however, quiet sleep predominates early in the sleep bout, whereas active sleep becomes more prominent later in the sleep bout. This distribution is more in line with adult sleep patterns. The proportion of REM or active sleep across the night also changes, comprising 50% of the night in newborns (Anders and Keener 1985) and decreasing throughout the life span (Ficca et al. 2000a).

The extremely large proportion of REM sleep in early development is thought to play a role in brain maturation. Roffwarg et al. proposed that REM sleep was necessary for CNS development (1966). They suggested that since exogenous activation of the nervous system is limited in utero due to the fetus spending limited time in an awake state, REM sleep was necessary to supply sufficient endogenous

neuronal activation to encourage development. Many studies have supported this hypothesis (Mirmiran et al. 1983a, 2003; Van Someren et al. 1990). For example, pharmacologically or instrumentally suppressing REM sleep for the first few weeks of life resulted in significantly reduced regional brain weights of the cerebral cortex and the medulla oblongata in rat pups (Mirmiran et al. 1983a). However, with further research, the ontogenetic hypothesis has been modified to demonstrate that REM sleep does more than simply mimic the wake state. Suppression of REM sleep in kittens significantly enhanced brain deterioration from monocular deprivation, despite the fact that REM sleep was replaced primarily by active wake (Marks et al. 1995). Further, more recent work has suggested that early REM/active sleep specifically reduces apoptosis during brain maturation (Morrissey et al. 2004). Thus, as the progression of CNS development is reduced with age (Dobbing and Sands 1973), so is the need for REM sleep.

Parallel to the decrease in REM sleep is an increase in SWA across early development. The intensification of SWA has been suggested to reflect the increase in synaptogenesis and synaptic connectivity associated with brain maturation (Frank et al. 2001; Fattinger et al. 2014; Huber and Born 2014). In addition, SWA has been associated with learning and memory consolidation throughout the life span given its relationship to synaptic plasticity (Huber et al. 2004). Important to note is that theta activity (6.5–9 Hz), and not SWA (as in adults; Tononi and Cirelli 2006), appears to indicate sleep pressure in infants (Jenni et al. 2004). In a longitudinal study of nocturnal EEG in human infants, Jenni and colleagues demonstrated that theta activity declined over successive quiet sleep/nREM bouts. At 9 months of age, this decline approached an exponential function, reflecting a dissipation of sleep tendency over consecutive bouts.

Overall, the prominent changes in sleep throughout infancy seem to reflect the drastic maturation of the CNS. Developmental changes in SWA, sleep spindles, and REM sleep are associated with neuronal plasticity, synaptic efficiency, and synaptic proliferation. Given these relationships, it seems likely that sleep would play a pronounced role in SDC in infants.

1.3.2 Sleep-Dependent Memory Consolidation in Infants

As sleep changes so dramatically across infancy, it is difficult to associate any particular component of sleep with specific behavioral changes. In addition, research paradigms for infant memory are often limited by the fact that this population lacks strong verbal communication skills. However, learning and cognition have been associated with sleep in infancy. For example, neonates have been shown to learn during sleep. Adaptation to a conditioned response can be achieved while the newborn is sleeping (Fifer et al. 2010; Reeb-Sutherland et al. 2011). This response may be sleep stage dependent, as work in rats showed that classical conditioning during sleep was only achieved during REM, and not nREM sleep (Mirmiran et al. 1983b). Although in line with the ontogenetic hypothesis of REM sleep, these results

may suggest an additional benefit to the high prevalence of REM in early development given the adaptive benefit of learning during sleep.

Infant sleep habits have also been associated with learning and memory that occurs during wakefulness. Habitual nap duration and nocturnal sleep efficiency as determined by parental questionnaires were associated with improved generalization on an imitation task (Lukowski and Milojevich 2013). Similarly, nighttime sleep quality variables, such as sleep efficiency, were positively correlated with memory encoding in 6-month-old children (Konrad et al. 2016a). In this study, sleep quality measures obtained from 24-h actigraphy recordings were associated with performance on an immediate imitation task. This relationship was not observed in 12-month-old children, however.

1.3.2.1 Declarative Memory

Very few studies have assessed the role of infant sleep on declarative memory consolidation. These studies have also only focused on napping, rather than nocturnal sleep in infants. A benefit of sleep on declarative memory in infants was first demonstrated in a study by Seehagen and colleagues (2015). Following observation of novel behavioral actions with a puppet by experimenters, 6- and 12-month-old infants either napped (nap group) or napped less than 30 min (no-nap group) during a 4-h delay. Following this delay, only infants in the nap group showed significant imitation of the novel actions. Further, following a 24-h delay, the nap condition showed significantly more memory for the actions than the no-nap group.

The Seehagen study is somewhat contradictory to earlier studies on artificial language learning infants. In 15-month-old infants, veridical memory for word strings of an artificial language was not better following a nap, and in fact wake seemed to benefit recall after a 4-h delay. However, napping infants showed a greater abstraction of grammar rules with sleep (Gómez et al. 2006), and this effect was long-lasting, whereas the wake benefit of veridical word recall was not (Hupbach et al. 2009). These studies are difficult to interpret with respect to the role of sleep in declarative memory consolidation in infants. The wake benefit on initial veridical recall, although not a lasting effect, would suggest that sleep does not benefit declarative memory performance. However, the sleep benefit for rule abstraction is important in language learning contexts in particular.

Recent work has further investigated the role of infant sleep on abstraction and generalization. Infants between the ages of 9 and 16 months encoded objects with both specific and general categorical word meanings (Friedrich et al. 2015). Results suggest that napping maintains memory for specific, veridical word meanings while additionally abstracting categorical information. Further, the observed semantic generalization was associated with sleep spindles during the nap. In two studies of deferred imitation, napping in 12-month-old infants was also associated with both veridical recall and generalization of the demonstrated hand puppet actions to novel puppets (Konrad et al. 2016b, c).

1.3.2.2 Procedural Memory

Only one study has investigated the role of sleep on procedural-type memory consolidation in infancy. Three-month-old infants were trained to activate a mobile over their crib with foot kicking behavior. Two weeks later, after induced forgetting had occurred, this memory was reactivated. Duration of sleep following this reactivation was positively associated with recall of the behavior (Fagen and Rovee-Collier 1983). This suggests that memory for procedural information is benefited by sleep in infancy, although the evidence is minimal and warrants additional examination.

1.3.2.3 Emotional Memory

To date, there have been no studies assessing emotional memory consolidation across sleep in infants.

1.3.3 Summary

In sum, the research on SDC in infancy is limited and somewhat contrary. Additional research is needed to replicate current findings and to help better understand the cognitive functions of sleep during this time. Specifically, more research is needed to better understand how physiological differences in sleep are related to changes in the memory consolidation process. To date, no research has examined nocturnal sleep in infants nor emotional memory consolidation in infants. Given the higher proportion of REM sleep during infancy, research on memory consolidation across both the emotional and procedural domains is especially warranted.

1.4 Early Childhood

1.4.1 Early Childhood Sleep

Sleep continues to evolve throughout childhood. Total sleep time declines steadily. At 2 years of age, most children sleep between 10 and 15 h across a 24-h period. By 12 years of age, total sleep time drops to between 8 and 10 h (Iglowstein et al. 2003). One of the most obvious sleep-related changes during early childhood is the diminishment of napping. On average, children shift from two midday naps to only one midday nap at about 18 months. Children will transition to a monophasic sleep pattern (only sleeping at night) during the preschool age range (~3 to 5 years;

Weissbluth 1995; Jenni and Carskadon 2007). The likelihood of napping decreases from 50% in 3-year-olds to only about 1% in 7-year-olds (Iglowstein et al. 2003).

It is probable that the reduction in diurnal sleep across development reflects brain maturation (Lam et al. 2011). During early childhood, synaptic thresholds may be reached faster than adults due to less efficient and more synaptically dense neuronal networks (Huttenlocher 1979; Feinberg et al. 1985; Huttenlocher and Dabholkar 1997). As such, children need a period of global downscaling during the day. Almost 50% of the total naptime for a preschool-aged child is dedicated to SWS (Kurdziel et al. 2013), further supporting that the nap is a time for synaptic downscaling. However, as cortical networks develop, the need for the nap decreases until sleep is consolidated to one nocturnal bout.

In line with the changes in sleep pattern are additional changes in sleep physiology. REM sleep continues to decline, reaching the adult proportions (~20% of the night) by approximately 10 years of age (McCarley 2007). Interestingly, REM sleep is relatively lacking during daytime naps in preschool-aged children (Kurdziel et al. 2013). SWA also continues to increase throughout development (Ohayon et al. 2004; McCarley 2007; Kurth et al. 2010). The maturation of delta waves has been shown to mimic the progression of synaptic density and metabolic activity specifically in the frontal cortex (Feinberg et al. 1990). In addition, maturation of specific regions of the cortex has been associated with increases in localized SWA, as well as development of regional-specific cognitive abilities (Kurth et al. 2012). This work further supports that SWA may be used as a measure of cortical maturation (Feinberg et al. 1990; McCarley 2007; Kurth et al. 2012).

An increase in nREM2 sleep is also observed, and sleep spindles continue to mature, throughout childhood. Spindles decrease throughout the 2nd year of life but return to average adult frequency levels within the preschool years (Tanguay et al. 1975). Sleep spindles in early childhood may reflect plasticity and new learning, as in adults (Kurdziel et al. 2013). However, it is also possible that spindle measures reflect more trait-like differences between individuals. For example, in school-aged children, sigma power was positively associated with IQ (Geiger et al. 2011), and spindle density was associated with narrative memory differences in a standardized assessment (Chatburn et al. 2013).

1.4.2 Sleep-Dependent Memory Consolidation in Children

1.4.2.1 Declarative Memory

Like infancy, early childhood is a tentatively explored age range with respect to SDC. Only recently has early childhood been a targeted population for sleep research. Within the declarative domain, the literature supports SDC in children. Some of the first childhood-specific examples of SDC in declarative tasks demonstrate that both 6–8-year-old and 9–12-year-old children recall significantly more word-pairs following a period of nocturnal sleep than following a period of wake

(Backhaus et al. 2008; Wilhelm et al. 2008). Children have also been demonstrated to gain a benefit of nocturnal sleep (Wilhelm et al. 2008; Henderson et al. 2012) or diurnal sleep (napping; Kurdziel et al. 2013) on a declarative 2D object-location task. Specifically, improved declarative memory was associated with sleep spindles in the nap, and this nap benefit remained even following subsequent overnight sleep (Kurdziel et al. 2013).

There have been a number of studies examining the role of sleep in vocabulary learning – an important goal of early childhood education (Axelsson et al. 2016). Williams and Horst (2014) showed that when a nap directly followed learning of new vocabulary words through a storybook, there were significant and sustained improvements in word identification in 3-year-old children. The function of sleep in vocabulary learning has also been examined in a slightly older (7–12 years of age) developmental population (Henderson et al. 2012). Across all measures, sleep was shown to improve retention of new words and led to the incorporation of these words into the children's lexicon.

1.4.2.2 Procedural Memory

Similarly to adults, SDC in the procedural domain during childhood is inconsistent. Children between the ages of 6 and 13 showed no benefit of nocturnal sleep on a serial reaction time task (SRTT; Fischer et al. 2007; Henderson et al. 2012), a task of procedural skill that has been shown to elicit a sleep benefit adults (Walker et al. 2002; Fischer et al. 2002; Korman et al. 2007; Schönauer et al. 2013). One study even showed a wake benefit on the SRTT in children (Wilhelm et al. 2008).

It has been suggested that sleep in children prioritizes consolidation of explicit or more hippocampal-based tasks. This theory has been supported by recent research within the procedural realm. In one experiment, 4–6-year-old children were given extensive training on a sequencing task across 3 days, prior to being assessed for performance improvements across a nap. With this additional training, children were able to show nap-dependent improvements in motor performance (Wilhelm et al. 2012). It was posited that the prioritized explicit knowledge was consolidated across the intervening periods of nocturnal sleep between training sessions, thus allowing for the consolidation of implicit information across the latter nap. Similarly, nap-dependent performance improvements on a modified SRTT task were observed in preschool-aged children, but only following additional overnight sleep (Desrochers et al. 2016). In this study, explicit recall of the implicitly learned motor sequence was also significantly greater when a nap followed encoding compared to equivalent wake. Sleep-dependent prioritization for explicit procedural information has also been demonstrated in adults (Robertson et al. 2004). However, when both children and adults were taught a task implicitly, children demonstrated greater explicit knowledge of the task than adults (Wilhelm et al. 2013).

Additionally, work in children with attention deficit hyperactivity disorder (ADHD) supports the preferential consolidation of explicit features of procedural tasks over sleep. Children with ADHD have hypoactivation of the prefrontal cortex,

leading to impairment of explicit declarative memory consolidation (Prehn-Kristensen et al. 2011a). Compared to healthy controls, children (9–12 years of age) showed SDC of an implicit procedural sequential button-pressing task. It was suggested that due to reduced explicit consolidation in this population, children with ADHD have reduced implicit-explicit competition during overnight sleep and are therefore able to demonstrate implicit SDC (Prehn-Kristensen et al. 2011b).

The hypothesis that children prioritize explicit, hippocampal-dependent features of new information for consolidation is supported by their sleep architecture. Children have significantly greater amounts of SWS (Ohayon et al. 2004) and have greater spectral power in SWA compared to adults (Kurth et al. 2010). SWS and SWA have been associated with hippocampal activation (Moroni et al. 2007; Dang-Vu et al. 2008) as well as consolidation of hippocampal-dependent tasks in adults (e.g., Peigneux et al. 2004). Children's ability to extract the explicit information from a procedural sequencing task over sleep was significantly correlated with SWS, and SWA (Wilhelm et al. 2013), especially within the range of slow oscillations (<1 Hz). Additionally, explicit extraction in children was shown to be associated left hippocampal activation (Wilhelm et al. 2013). Lastly, children with ADHD demonstrated SDC of an implicit procedural task (Prehn-Kristensen et al. 2011b); however, while slow oscillations were associated with declarative memory SDC in healthy controls, this association was not observed in the ADHD population (Prehn-Kristensen et al. 2011a). Thus, the large proportion of sleep dedicated to SWS in children, including during diurnal sleep bouts, may be associated with increased hippocampal-dependent learning.

1.4.2.3 Emotional Memory

In children, SDC has also been examined with respect to emotional memories. Healthy children between the ages of 9 and 12 remember significantly more images overall following sleep than following wake; further, they were shown to preferentially consolidate emotionally valenced images compared to neutral images (Prehn-Kristensen et al. 2013). Consolidation of emotional images in children was associated with nREM sleep, the spectral power of the slow oscillation, and theta oscillations during REM sleep (Prehn-Kristensen et al. 2013). Therefore, emotional memory consolidation in children appears to require an interplay between nREM and REM sleep, similarly to adults. More research is needed to better understand the relationship between sleep physiology and emotional memory consolidation in children.

1.4.3 Summary

Overall, work in early childhood supports a relationship between sleep and memory consolidation. Primarily, the high proportion of SWS, and the increased SWA across

nREM sleep bouts, fosters the consolidation of explicit information and of hippocampal-based memories. This was shown to be consistent across all memory domains. Important to note, however, is that the designation of "childhood" encompasses a huge range of neurological development and accompanying changes in learning capacity. Therefore while the current research supports SDC across childhood, there are many ages and developmental stages within this population that have not been investigated.

1.5 Adolescence

1.5.1 Adolescent Sleep

Following the onset of puberty, a number of physiological and neurological changes occur. Sleep is not spared from these pubertal alterations. Total sleep time declines from the prepubertal ~10 h to the more adult-like 8 h by 16 years of age (Iglowstein et al. 2003). The timing of sleep also changes. As children progress through pubertal stages, their chronotypes shift to more evening-type "night owls" as opposed to the morning-type "early birds." Adolescents tend to fall asleep and wake up later due to a later plasma melatonin offset with age and pubertal stage (Carskadon 1990).

The physiology of sleep changes with adolescence as well. REM sleep duration increases only slightly across adolescence, but still significantly (Feinberg et al. 2012). In addition, theta power in both REM and nREM sleep stages declines (Feinberg and Campbell 2013). The most prominent change in sleep architecture is the reduction of SWS. There is a 40% decline in SWS from prepubertal to mature stages of development, with a corresponding increase in nREM2 (~20%; Jenni and Carskadon 2004). Accompanying this is a decline in SWA (Gaudreau et al. 2001; Jenni and Carskadon 2004; Feinberg and Campbell 2010, 2013). Importantly, however, despite a global reduction in SWA in more mature adolescents, the typical decline of SWA over the course of the night is still observed; therefore, despite reduced spectral power, SWA in the adolescent is functioning to reduce sleep pressure similarly to children and adults (Jenni and Carskadon 2004; Campbell et al. 2011).

The reduction in SWA across adolescence, compared to the marked increase from infancy through childhood, is thought to reflect changes in synaptic connectivity. Postnatal development of neuronal connections leads to increases in SWA (Feinberg and Campbell 2013); however, starting in early adolescence, dramatic pruning of synapses occurs, such that synaptic density at 20 years of age is half what it was at 10 years (Huttenlocher 1979). Therefore it follows that SWA would decline in parallel.

1.5.2 Adolescent Sleep-Dependent Memory Consolidation

Given the vast restructuring of the CNS throughout adolescence, and the relationship between sleep and synaptic pruning, adolescence is an interesting population in which to study SDC. However, very few studies have addressed the relationship between sleep and memory in this age group. Difficulties with studying the role of SDC in adolescence include the variation in pubertal onset for genders (Sisk and Foster 2004), as well as the need to consider the effects of hormonal fluctuations on memory and attention (Sherwin 2012). Nevertheless, SDC in adolescence has begun to receive greater attention in the literature.

1.5.2.1 Declarative Memory

The majority of SDC research in adolescence examines declarative memory consolidation. For example, 17-year-old German high school students displayed significantly enhanced memory for English translations of German words when sleep directly followed learning compared to a 12-h period of wake (Gais et al. 2006). Similarly, using the paired-associates test of declarative memory, Potkin and Bunney (2012) demonstrated a sleep benefit for adolescents between 10 and 14 years of age. Naps in schools were shown to significantly improve retention of declarative information taught in a classroom setting, whereas significant decay was observed without daytime napping (Lemos et al. 2014).

However, not all studies demonstrate a benefit of sleep on declarative memories in adolescence. Holz et al. (2012) showed that performance on a word-pair test was actually better the following morning when a long delay (7.5 h) of wake followed encoding, compared to when encoding occurred directly prior to sleep. Importantly, this effect was not maintained 1 week later. In a different study, no significant sleep benefit was found across a ~50 min nap compared to either a period of activity or passive rest in 16-year-old females; however, performance on the word-pair learning task was significantly correlated with sigma power, suggesting some level of active consolidation over sleep (Piosczyk et al. 2013).

The discrepancies in declarative SDC across adolescence are likely related to the changes in SWS and in the vast restructuring of the brain. Hypoactivation of the prefrontal cortex in ADHD has been shown to reduce declarative SDC in 10–16-year-olds. This reduction in SDC was associated with a dysfunctional slow oscillation in individuals with ADHD. Experimentally increasing the slow oscillation during early SWS through transcranial oscillating direct current stimulation leads to observed improvements in declarative memory consolidation in 10–14-year-olds (Prehn-Kristensen et al. 2014).

1.5.2.2 Procedural Memory

Very few studies have examined SDC of procedural memory in adolescence. In one study, individuals (10–13 years) were taught the procedural task of mirror tracing either in the morning (wake group) or the evening (sleep group). Speed and accuracy at the retrieval period 12 h later were significantly better than during encoding; however, there were no differences between the sleep and wake groups (Prehn-Kristensen et al. 2009). Importantly, the age group tested were early adolescents, encompassing a predominantly prepubertal age range. In a separate study, older adolescents (16–17 years) exhibited significant improvements on a procedural finger tapping task when trained directly prior to sleep, as opposed to 7.5 h prior to sleep. This benefit was long-lasting, remaining for at least 7 days after initial learning (Holz et al. 2012). Therefore, it is possible that SDC of procedural memory in adolescence is dependent on structural neuronal changes that occur throughout puberty.

1.5.2.3 Emotional Memory

Emotional declarative memories have also been examined, albeit rarely, with respect to SDC in adolescence. Following sleep, 10–13-year-olds were better at recognizing pictures from the International Affective Picture System (IAPS; Lang et al. 2008) than following an equivalent period spent awake (Prehn-Kristensen et al. 2009; Prehn-Kristensen et al. 2011a). Memory was greater for emotional (negative) compared to neutral pictures, and performance across sleep was significantly associated with slow oscillation power during nREM sleep (Prehn-Kristensen et al. 2011a). Again, it is important to note that the individuals in these studies were in early adolescence.

1.5.2.4 Sleep-Dependent Memory Consolidation Following Sleep Restriction

Given the later sleep onset in adolescence, but the requirement for early rise times for school attendance, many adolescents are experiencing sleep deprivation over the course of the week (Carskadon 2011). As such, there have been a number of studies examining the role of restricted sleep on memory consolidation in adolescence. For example, Kopasz and colleagues (2010) had 14- to 16-year-olds learn a paired-associate task after which they were sleep restricted (4-h night sleep opportunity) or not (9-h sleep opportunity) at night. After a recovery night, memory performance was assessed. No significant group differences were observed in memory recall performance. This result is possibly due to the lack of a difference in time spent in SWS between the experimental conditions. However, in the sleep deprivation group, performance was significantly correlated with the percentage of nREM sleep across the recovery night, whereas performance did not correlate with any measure of sleep architecture for the control group.

In a similar experiment, adolescents that experienced 4 days of sleep restriction did not significantly differ from controls on either a declarative (word-pair) or a procedural (mirror tracing) memory task. Interestingly, time spent in SWS remained constant across sleep restriction conditions, whereas REM sleep declined with restriction. The percentage of time spent in SWS therefore *increased* with decreased sleep time. This suggests that, during adolescence, SWS is conserved despite sleep restriction (Voderholzer et al. 2011).

1.5.3 Summary

Overall, there is clear evidence of SDC in adolescence. However, SDC of procedural and declarative information is inconsistent and may depend on pubertal status. Across the developmental trajectory into adulthood, there seems to be a clear bias of SDC toward declarative information. This may be due to the rapidly increasing power of SWA or to the large percentage of time spent in SWS. Intriguingly, even across multiple nights of sleep deprivation, adolescents were shown to conserve SWS time at the expense of other sleep stages (REM in particular).

Following puberty, however, there are drastic reductions in synaptic density and a resultant parallel reduction in SWA. It is at this point in development where procedural SDC gains more equal footing with declarative SDC. Thus, puberty may be the transition point in which prioritization of hippocampus-dependent, explicit information is diminished. However, further research is needed to examine the interplay between these memory systems across development and the associated role of sleep in these domains.

1.6 Middle-Aged and Older Adulthood

1.6.1 Middle-Aged and Older Adult Sleep

As adults age, they tend to go to bed earlier and wake up earlier, showing a shift toward morning chronotypes. Sleep quality also declines with age (Carrier et al. 1997). Total sleep time decreases, sleep efficiency is reduced, and sleep becomes more fragmented. These changes in sleep time are associated with reductions in health (Newman et al. 1997). In older adults both too short and too long of sleep durations were associated with increased mortality risk (Dew et al. 2003; Gangwisch et al. 2008), whereas the same was not true for middle-aged adults (Gangwisch et al. 2008). Age-related changes in sleep time have also been associated with diabetes mellitus and impaired glucose tolerance (Gottlieb et al. 2005; Yaggi et al. 2006), hypertension (Gangwisch et al. 2006; Gottlieb et al. 2006), and coronary heart disease (Ayas et al. 2003). Interestingly, older adults appear to have a higher tolerance for sleep deprivation than younger adults (Buysse et al. 1993; Stenuit

and Kerkhofs 2005; Bliese et al. 2006; Duffy et al. 2009). It has been suggested that these age-related changes in sleep time might be due to the reduced cell numbers in the ventrolateral preoptic nucleus (VLPO) of the hypothalamus in older adults (Hofman and Swaab 1989; Gaus et al. 2002; Duffy et al. 2009). The VLPO inhibits monoaminergic arousal systems thereby allowing for the transition to sleep from wakefulness (Gaus et al. 2002; Fuller et al. 2006).

Sleep architecture also changes with age. The most dramatic change in sleep architecture is the decline in SWS (Hirshkowitz et al. 1992; Bliwise 1993; Carrier et al. 1997; Ohayon et al. 2004; Cooke and Ancoli-Israel 2011). In a study of adult men, SWS decreased from 18.9% in young adulthood to 3.4% in middle-aged adulthood (up to 50 years of age; Van Cauter et al. 2000). The reduction in SWS time and the fragmentation of SWS in the elderly have been shown to correlate with levels of amyloid beta in the cerebral spinal fluid (Varga et al. 2016b). This supports that SWS functions to clear neuronal metabolites and implicates sleep changes in age-related health risks.

The percentage of the night spent in REM sleep declines with age, although this decline parallels the reduction in sleep time. SWS and REM sleep reductions are compensated by increases in nREM1 sleep and awakenings, whereas nREM2 stays fairly consistent throughout aging (Hirshkowitz et al. 1992; Bliwise 1993; Carrier et al. 1997; Van Cauter et al. 2000; Ohayon et al. 2004; Cooke and Ancoli-Israel 2011; Spencer 2013). As sleep quality declines, there is a corresponding increase in daytime sleepiness with age (Ancoli-Israel 1997). This suggests that age does not diminish sleep need (Duffy et al. 2009). The age-related decline of sleep is thought to be related to disruption of circadian rhythms or to medical causes such as sleep disorders or prescribed medications (Ancoli-Israel 1997; Cooke and Ancoli-Israel 2011).

SWA has also been shown to continue to decrease throughout middle-aged and older adulthood (Landolt et al. 1996; Carrier et al. 2001; Gaudreau et al. 2001). The reduction in SWS and SWA is attributed to progressive atrophy of the mPFC (Mander et al. 2013; Varga et al. 2016a), as well as to reductions in growth hormone with age (Van Cauter et al. 2000). In addition, the progressive decline in SWA across the night is reduced in middle-aged adulthood, suggesting a reduction of homeostatic sleep pressure (Landolt et al. 1996; Carrier et al. 2001; Gaudreau et al. 2001; Darchia et al. 2007). In young adults, sleep spindles typically increase over the course of the night, but this is also attenuated in older adults (Landolt et al. 1996).

Theta and sigma power have also been shown to decrease with age (Landolt and Borbély 2001; Carrier et al. 2001; Gaudreau et al. 2001). Age-related reductions in spectral power are most pronounced in the frontal regions of the brain (Landolt and Borbély 2001). These global reductions in oscillatory power, especially those in nREM sleep, likely reduce synaptic plasticity within the aging brain; thus, there is strong reason to predict that SDC in middle-aged and older adults is impaired (Fogel et al. 2012).

1.6.2 Sleep-Dependent Memory Consolidation in Middle-Aged and Older Adults

Decline in memory is one of the greatest fears in older adults. Yet often the perceived memory loss is not representative of the actual decline in memory capabilities in healthy aging (Bolla et al. 1991). There is neurobiological reason to suspect a decline in cognitive abilities with age. Age-related changes are most prominent in prefrontal gray matter, with smaller degradations in the fusiform, inferior temporal, and superior parietal cortices (Raz et al. 1997). Interestingly, only subtle age-related declines in hippocampal gray matter, and no differences in parahippocampal, or anterior cingulate gyri are observed. In addition there are functional declines in the dopaminergic projections to the prefrontal cortex (Braver and Barch 2002), suggesting specific impairments to cognitive control, attention, and working memory (West 1996).

Global reductions in a number of cognitive abilities are observed across middle-aged and older adulthood. Perceptual speed, inductive reasoning, and spatial orientation are significantly impaired with age (Hedden and Gabrieli 2004). Verbal memory also declines but only later in life. However, autobiographical memory and emotional processing skills appear to remain intact. Within the memory domain, explicit memories show the greatest degradation with age, whereas implicit memory formation remains stable (Fleischman et al. 2004). While memory is generally observed to wane, it is important to assess whether sleep can benefit new memory formation with age.

1.6.2.1 Declarative Memory

A number of studies have shown declines in SDC with age (Harand et al. 2012; Pace-Schott and Spencer 2014). However, conflicting data, especially within the realm of declarative memory, make it difficult to assert a comprehensive argument about age-related changes in memory consolidation. While, compared to young adults, overall memory performance was reduced in middle-aged or older adults, SDC was still observed for declarative tasks – older individuals show improvements across sleep compared to wake (Aly and Moscovitch 2010; Wilson et al. 2012). Elderly women with greater sleep spindle density demonstrated enhanced declarative memory performance compared to those with reduced sleep spindle density (Seeck-Hirschner et al. 2012). In addition, sleep was shown to protect visuospatial declarative memories from interference in older adults, supporting a role of sleep in active memory stabilization (Sonni and Spencer 2015).

Comparatively, some research has shown no sleep benefit for declarative memory in aging populations. Backhaus and colleagues showed age-related reductions in SDC of declarative memory in middle-aged adults using a word-pair associates

task (2007). The impairments in memory were specifically associated with reduced SWS in the first half of the night. Importantly, when younger and middle-aged adults with similar SWS percentages were compared, there were no differences in memory consolidation. Visuospatial declarative memory consolidation was impaired in older adults; however, in this study, frontal SWA was associated with improved memory recall across all individuals, including both older and younger adults (Varga et al. 2016a). Older adults failed to demonstrate SDC of episodic declarative memories (Scullin 2013). Further, there was a strong correlation between SWS and episodic memory performance in younger adults, but no such relationship was observed in the older adults.

These results were paralleled in a more recent study of napping in older and younger adults (Baran et al. 2016). Older adults did not demonstrate a nap benefit on a declarative word-pair task, unlike the younger adults. Moreover, younger adult memory performance was positively correlated with the percentage of SWS and SWA in the nap and negatively associated with post-nap hippocampal activation during recall. This work suggests that even across a nap, systems-level restructuring of declarative information is occurring, leading to more stable long-term memories in younger adults. Older adult memory recall was not associated with either SWS in the nap or with reduced hippocampal activation. The authors concluded that sleep in older adults is less efficient at consolidating declarative memories.

To this end, recent work has examined whether enhancing SWS or oscillations in nREM sleep would recover SDC of declarative memories in older adults (Buckley and Schatzberg 2005). However, the results in this area of research are also conflicting. Westerberg and colleagues used transcranial current to artificially enhance slow oscillations during a nap in older adults in order to increase SWA (Westerberg et al. 2015). With the application of the current, SWA was increased, and declarative memory for word-pairs was improved. Contrarily, in another study, no memory improvements were observed across a nocturnal sleep bout when transcranial stimulation was applied during early SWS (Eggert et al. 2013).

1.6.2.2 Procedural Memory

The findings on SDC of procedural memories in older adults are more consistent. Performance on procedural tasks has been shown to not be improved by sleep in either middle-aged (Wilson et al. 2012) or older adults (Spencer et al. 2007; Brown et al. 2009; Wilson et al. 2012). Importantly, however, most of the procedural memory tasks used in older adults are sequence learning tasks (e.g., SRTT). Therefore, aging may specifically impair SDC of sequential information, not necessarily procedural skill more broadly.

In older rats, hippocampal replay of sequential information was significantly impaired during periods of rest (Gerrard et al. 2008). While the neuronal sequences were equivalently as active during rest in older rats as they were in younger rats, the temporal order of this activation was impaired. Further, the reduction in temporal order of replay was subsequently associated with impaired spatial memory. This

implicates sequence-specific information with impairments during aging. In support of this hypothesis, when older adults were tested on a non-sequential motor task, the mirror tracing task, SDC was observed (Mantua et al. 2016). More research is necessary to disentangle the relationship between sleep and procedural learning in older adults, with especial consideration for dissociating sequential and non-sequential information.

1.6.2.3 Emotional Memory

Lastly, few studies have examined how SDC of emotional information changes with age. Jones and colleagues showed that sleep protected both valence ratings and memory in older adults, but only for positive stimuli, not neutral or negative images (2016). In contrast, sleep in younger adults preserved valence ratings and memory for negative stimuli only.

This shift toward positivity may represent a bias toward well-being. Older adults have a positivity bias, focusing attention and on positive as opposed to neutral or negative stimuli (Carstensen and Mikels 2005; Mather and Carstensen 2005). With age, cognitive performance is significantly enhanced for positive emotional information (Carstensen and Mikels 2005), and even autobiographical memories are reported more positively with age than they were 14 years previously (Kennedy et al. 2004).

Age does not impair the activation of the emotional memory network during encoding of emotional stimuli (Kensinger and Schacter 2008). However, in comparison with younger adults, older adults had greater memory enhancement for positive stimuli during encoding; in addition, older adults showed greater activation in the mPFC and cingulate gyrus during presentation of the positive images. These authors similarly concluded that older adults might focus on more positive information, especially in reference to themselves.

1.6.3 Summary

With the progressive degeneration of the brain, especially in the mPFC, SDC in middle-aged and older adults becomes reduced. Reductions in SWS and SWA reflect subsequent changes in declarative memory consolidation. However, degradation of both the brain and sleep physiology may show strong inter-individual differences across aging, thereby influencing inter-individual differences in SDC. For example, when SWS in older adults parallels those in younger adults, SDC of declarative memory remains intact (Backhaus et al. 2007). Thus, improving SWS, and enhancing nREM sleep oscillations, may be a potential future therapeutic for age-related declines in memory.

Age-related changes in both procedural memory and emotional memory are unique. Changes in sequential neuronal firing may impair SDC of sequential

procedural tasks, but not procedural memory in general. Aging also changes the prioritization of emotional information for SDC. In young adults, negative emotional memories are prioritized for consolidation, whereas positive emotional memories are prioritized in older adults. Despite significant changes in sleep physiology, SDC of procedural and emotional information is not completely diminished.

1.7 Conclusions

Sleep is associated with memory consolidation across the life span. Changes in sleep and SDC reflect developmental changes within the brain. Prenatal brain development is reliant on sleep, and even in early infancy, sleep is associated with improved memory performance. At the other end of the life span, as the brain begins to progressively deteriorate, SDC is also diminished.

During early childhood development, nREM, and particularly SWS, plays the most prominent role in SDC. As synaptic connectivity proliferates with age, SWA subsequently increases. Memory consolidation in early childhood prioritizes explicit and hippocampal-dependent tasks. Following the massive synaptic pruning that occurs during puberty, SWS and SWA progressively decline. As a result, implicit tasks begin to show SDC in late adolescence and across adulthood. With the age-related degradation of frontal brain regions, SWS and SWA continue to decline significantly into older adulthood. As a result, SDC of declarative information becomes less efficient. In sum, the only times in which it is strongly debatable whether sleep benefits declarative memory consolidation are when the most dramatic reductions in SWS are observed: during adolescence and during older adulthood.

The functional role of other sleep stages on SDC is often debated. Primarily, SWS, or features of nREM sleep (slow oscillations, SWA, or sleep spindles), has been associated with all forms of memory consolidation in young children, including procedural and emotional memories. In adults, both REM and nREM2 (sleep spindles in nREM2 especially) have been connected with procedural memory consolidation. However, across the life span, evidence of SDC of procedural memory consolidation is the most inconsistent of the three memory classifications examined in this review. More recently, researchers are considering the relationship between nREM and REM sleep with respect to memory consolidation, rather than focus on one sleep stage in particular.

The evidence to support SDC in emotional memories is the most stable across the life span. With the exception of infancy, an age group for which no research in this area has yet been conducted, emotional memory consolidation is consistently demonstrated to benefit from sleep. Even into older age, prioritization of the consolidation of emotional memories is observed, although there is a positivity bias in consolidation as opposed to the negativity bias observed in other age groups. With respect to emotional memories, the most prominent SDC change across the life span is the attribution to particular sleep stages. In childhood and early adolescence, when the proportion of SWS is high across the night, SWS, SWA, and slow oscillations are

associated with emotional memory consolidation. In adulthood, with progressive declines of SWS occurring, both SWS and REM sleep are related to emotional processing.

The aims of this review were to address how sleep changes across the life span and how these changes influence memory consolidation. While much research has addressed this relationship in healthy young adults, the work in other age ranges is currently lacking. Given the dramatic changes in brain maturation and degradation across the life span, as well as the remarkable changes in sleep architecture and physiology, there is immense need for future research on SDC in infancy, early childhood, adolescence, middle-aged, and older adulthood.

References

Achermann P, Borbély AA (1990) Simulation of human sleep: ultradian dynamics of electroencephalographic slow-wave activity. J Biol Rhythm 5:141–157

Achermann P, Borbély AA (1997) Low-frequency (< 1 Hz) oscillations in the human sleep electroencephalogram. Neuroscience 81:213–222

Achermann P, Dijk D-J, Brunner DP, Borbély AA (1993) A model of human sleep homeostasis based on EEG slow-wave activity: quantitative comparison of data and simulations. Brain Res Bull 31:97–113. https://doi.org/10.1016/0361-9230(93)90016-5

Albouy G, Fogel S, Pottiez H et al (2013) Daytime sleep enhances consolidation of the spatial but not motoric representation of motor sequence memory. PLoS One 8:e52805. https://doi.org/10.1371/journal.pone.0052805

Aly M, Moscovitch M (2010) The effects of sleep on episodic memory in older and younger adults. Mem Hove Engl 18:327–334. https://doi.org/10.1080/09658211003601548

Ambrosini MV, Giuditta A (2001) Learning and sleep: the sequential hypothesis. Sleep Med Rev 5:477–490. https://doi.org/10.1053/smrv.2001.0180

Ancoli-Israel S (1997) Sleep problems in older adults: putting myths to bed. Geriatrics 52:20–30

Anders TF, Keener M (1985) Developmental course of nighttime sleep-wake patterns in full-term and premature infants during the first year of life. I. Sleep 8:173–192

Anders TF, Roffwarg HP (1973) The effects of selective interruption and deprivation of sleep in the human newborn. Dev Psychobiol 6:77–89. https://doi.org/10.1002/dev.420060110

Axelsson EL, Williams SE, Horst JS (2016) The effect of sleep on children's word retention and generalization. Front Psychol 7:1192. https://doi.org/10.3389/fpsyg.2016.01192

Ayas NT, White DP, Manson JE et al (2003) A prospective study of sleep duration and coronary heart disease in women. Arch Intern Med 163:205–209

Backhaus J, Born J, Hoeckesfeld R et al (2007) Midlife decline in declarative memory consolidation is correlated with a decline in slow wave sleep. Learn Mem 14:336–341. https://doi.org/10.1101/lm.470507

Backhaus J, Hoeckesfeld R, Born J et al (2008) Immediate as well as delayed post learning sleep but not wakefulness enhances declarative memory consolidation in children. Neurobiol Learn Mem 89:76–80. https://doi.org/10.1016/j.nlm.2007.08.010

Baran B, Pace-Schott EF, Ericson C, Spencer RMC (2012) Processing of emotional reactivity and emotional memory over sleep. J Neurosci 32:1035–1042. https://doi.org/10.1523/JNEUROSCI.2532-11.2012

Baran B, Mantua J, Spencer RMC (2016) Age-related changes in the sleep-dependent reorganization of declarative memories. J Cogn Neurosci 28:792–802. https://doi.org/10.1162/jocn_a_00938

Barnes DC, Wilson DA (2014) Slow-wave sleep-imposed replay modulates both strength and precision of memory. J Neurosci 34:5134–5142. https://doi.org/10.1523/JNEUROSCI.5274-13.2014

Benedict C, Scheller J, Rose-John S et al (2009) Enhancing influence of intranasal interleukin-6 on slow-wave activity and memory consolidation during sleep. FASEB J 23:3629–3636. https://doi.org/10.1096/fj.08-122853

Berger RJ (1975) Bioenergetic functions of sleep and activity rhythms and their possible relevance to aging. Fed Proc 34:97–102

Berger RJ, Phillips NH (1995) Energy conservation and sleep. Behav Brain Res 69:65–73. https://doi.org/10.1016/0166-4328(95)00002-B

Besedovsky L, Lange T, Born J (2011) Sleep and immune function. Pflugers Arch Eur J Physiol 463:121–137. https://doi.org/10.1007/s00424-011-1044-0

Birnholz JC (1981) The development of human fetal eye movement patterns. Science 213:679–681. https://doi.org/10.1126/science.7256272

Bliese PD, Wesensten NJ, Balkin TJ (2006) Age and individual variability in performance during sleep restriction. J Sleep Res 15:376–385. https://doi.org/10.1111/j.1365-2869.2006.00557.x

Bliwise DL (1993) Sleep in normal aging and dementia. Sleep 16:40–81

Bolla KI, Lindgren KN, Bonaccorsy C, Bleecker ML (1991) Memory complaints in older adults. Fact or fiction? Arch Neurol 48:61–64

Borbély AA (2001) From slow waves to sleep homeostasis: new perspectives. Arch Ital Biol 139:53–61

Born J, Wilhelm I (2012) System consolidation of memory during sleep. Psychol Res 76:192–203. https://doi.org/10.1007/s00426-011-0335-6

Born J, Muth S, Fehm HL (1988) The significance of sleep onset and slow wave sleep for nocturnal release of growth hormone (GH) and cortisol. Psychoneuroendocrinology 13:233–243. https://doi.org/10.1016/0306-4530(88)90021-2

Bots RSGM, Nijhuis JG, Martin CB, Prechtl HFR (1981) Human fetal eye movements: detection in utero by ultrasonography. Early Hum Dev 5:87–94. https://doi.org/10.1016/0378-3782(81)90074-8

Braun AR, Balkin TJ, Wesenten NJ et al (1997) Regional cerebral blood flow throughout the sleep-wake cycle. An H2(15)O PET study. Brain J Neurol 120(Pt 7):1173–1197

Braun AR, Balkin TJ, Wesensten NJ et al (1998) Dissociated pattern of activity in visual cortices and their projections during human rapid eye movement sleep. Science 279:91–95

Braver TS, Barch DM (2002) A theory of cognitive control, aging cognition, and neuromodulation. Neurosci Biobehav Rev 26:809–817

Brawn TP, Fenn KM, Nusbaum HC, Margoliash D (2010) Consolidating the effects of waking and sleep on motor-sequence learning. J Neurosci 30:13977–13982. https://doi.org/10.1523/JNEUROSCI.3295-10.2010

Brown RM, Robertson EM, Press DZ (2009) Sequence skill acquisition and off-line learning in normal aging. PLoS One. https://doi.org/10.1371/journal.pone.0006683

Buckley TM, Schatzberg AF (2005) Aging and the role of the HPA axis and rhythm in sleep and memory-consolidation. Am J Geriatr Psychiatry 13:344–352. https://doi.org/10.1097/00019442-200505000-00002

Buysse DJ, Monk TH, Reynolds CF et al (1993) Patterns of sleep episodes in young and elderly adults during a 36-hour constant routine. Sleep 16:632–637

Buzsáki G (1989) Two-stage model of memory trace formation: a role for "noisy" brain states. Neuroscience 31:551–570

Cai DJ, Rickard TC (2009) Reconsidering the role of sleep for motor memory. Behav Neurosci 123:1153–1157. https://doi.org/10.1037/a0017672

Cai DJ, Mednick SA, Harrison EM et al (2009) REM, not incubation, improves creativity by priming associative networks. Proc Natl Acad Sci 106:10130–10134. https://doi.org/10.1073/pnas.0900271106

Cairney SA, Durrant SJ, Hulleman J, Lewis PA (2014a) Targeted memory reactivation during slow wave sleep facilitates emotional memory consolidation. Sleep 37:701–707

Cairney SA, Durrant SJ, Power R, Lewis PA (2014b) Complimentary roles of slow-wave sleep and rapid eye movement sleep in emotional memory consolidation. Cereb Cortex bht349. https://doi.org/10.1093/cercor/bht349

Callaway CW, Lydic R, Baghdoyan HA, Hobson JA (1987) Pontogeniculooccipital waves: spontaneous visual system activity during rapid eye movement sleep. Cell Mol Neurobiol 7:105–149. https://doi.org/10.1007/BF00711551

Campbell IG, Darchia N, Higgins LM et al (2011) Adolescent changes in homeostatic regulation of EEG activity in the delta and theta frequency bands during NREM sleep. Sleep 34:83–91

Carrier J, Monk TH, Buysse DJ, Kupfer DJ (1997) Sleep and morningness-eveningness in the "middle" years of life (20–59y). J Sleep Res 6:230–237. https://doi.org/10.1111/j.1365-2869.1997.00230.x

Carrier J, Land S, Buysse DJ et al (2001) The effects of age and gender on sleep EEG power spectral density in the middle years of life (ages 20-60 years old). Psychophysiology 38:232–242

Carskadon MA (1990) Patterns of sleep and sleepiness in adolescents. Pediatrician 17:5–12

Carskadon MA (2011) Sleep in adolescents: the perfect storm. Pediatr Clin N Am 58:637–647. https://doi.org/10.1016/j.pcl.2011.03.003

Carskadon M, Dement W (2005) Normal human sleep: an overview. In: Kryger M, Roth T, Dement W, Roehrs T (eds) Principles and practice of sleep medicine. Elsevier Saunders, Philadelphia, pp 13–23

Carstensen LL, Mikels JA (2005) At the intersection of emotion and cognition aging and the positivity effect. Curr Dir Psychol Sci 14:117–121. https://doi.org/10.1111/j.0963-7214.2005.00348.x

Chatburn A, Coussens S, Lushington K et al (2013) Sleep spindle activity and cognitive performance in healthy children. Sleep 36:237–243. https://doi.org/10.5665/sleep.2380

Chauvette S, Seigneur J, Timofeev I (2012) Sleep oscillations in the thalamocortical system induce long-term neuronal plasticity. Neuron 75:1105–1113. https://doi.org/10.1016/j.neuron.2012.08.034

Clemens Z, Mölle M, Eross L et al (2007) Temporal coupling of parahippocampal ripples, sleep spindles and slow oscillations in humans. Brain J Neurol 130:2868–2878. https://doi.org/10.1093/brain/awm146

Cooke JR, Ancoli-Israel S (2011) Normal and abnormal sleep in the elderly. Handb Clin Neurol Ed PJ Vinken GW Bruyn 98:653–665. https://doi.org/10.1016/B978-0-444-52006-7.00041-1

Dan B, Boyd SG (2006) A neurophysiological perspective on sleep and its maturation. Dev Med Child Neurol 48:773–779. https://doi.org/10.1111/j.1469-8749.2006.tb01366.x

Dang-Vu TT, Schabus M, Desseilles M et al (2008) Spontaneous neural activity during human slow wave sleep. Proc Natl Acad Sci 105:15160–15165. https://doi.org/10.1073/pnas.0801819105

Darchia N, Campbell IG, Tan X, Feinberg I (2007) Kinetics of NREM delta EEG power density across NREM periods depend on age and on delta-band designation. Sleep 30:71–79

Datta S (2000) Avoidance task training potentiates phasic pontine-wave density in the rat: a mechanism for sleep-dependent plasticity. J Neurosci 20:8607–8613

De Gennaro L, Ferrara M (2003) Sleep spindles: an overview. Sleep Med Rev 7:423–440

de Weerd AW, van den Bossche RAS (2003) The development of sleep during the first months of life. Sleep Med Rev 7:179–191. https://doi.org/10.1053/smrv.2002.0198

Deliens G, Gilson M, Peigneux P (2014) Sleep and the processing of emotions. Exp Brain Res 232:1403–1414. https://doi.org/10.1007/s00221-014-3832-1

Desrochers PC, Kurdziel LBF, Spencer RMC (2016) Delayed benefit of naps on motor learning in preschool children. Exp Brain Res 234:763–772. https://doi.org/10.1007/s00221-015-4506-3

Dew MA, Hoch CC, Buysse DJ et al (2003) Healthy older adults' sleep predicts all-cause mortality at 4 to 19 years of follow-up. Psychosom Med 65:63–73

Diekelmann S, Born J (2010) The memory function of sleep. Nat Rev Neurosci 11:114–126. https://doi.org/10.1038/nrn2762

Diekelmann S, Wilhelm I, Born J (2009) The whats and whens of sleep-dependent memory consolidation. Sleep Med Rev 13:309–321. https://doi.org/10.1016/j.smrv.2008.08.002
Dobbing J, Sands J (1973) Quantitative growth and development of human brain. Arch Dis Child 48:757–767
Donohue KC, Spencer RMC (2011) Continuous re-exposure to environmental sound cues during sleep does not improve memory for semantically unrelated word pairs. J Cogn Educ Psychol 10:167–177. https://doi.org/10.1891/1945-8959.10.2.167
Dreyfus-Brisac C (1970) Ontogenesis of sleep in human prematures after 32 weeks of conceptional age. Dev Psychobiol 3:91–121. https://doi.org/10.1002/dev.420030203
Duffy JF, Willson HJ, Wang W, Czeisler CA (2009) Healthy older adults better tolerate sleep deprivation than young adults. J Am Geriatr Soc 57:1245–1251. https://doi.org/10.1111/j.1532-5415.2009.02303.x
Eggert T, Dorn H, Sauter C et al (2013) No effects of slow oscillatory transcranial direct current stimulation (tDCS) on sleep-dependent memory consolidation in healthy elderly subjects. Brain Stimulat 6:938–945. https://doi.org/10.1016/j.brs.2013.05.006
Ellenbogen JM, Payne JD, Stickgold R (2006) The role of sleep in declarative memory consolidation: passive, permissive, active or none? Curr Opin Neurobiol 16:716–722. https://doi.org/10.1016/j.conb.2006.10.006
Fagen JW, Rovee-Collier C (1983) Memory retrieval: a time-locked process in infancy. Science 222:1349–1351. https://doi.org/10.1126/science.6658456
Fattinger S, Jenni OG, Schmitt B et al (2014) Overnight changes in the slope of sleep slow waves during infancy. Sleep. https://doi.org/10.5665/sleep.3390
Feinberg I, Campbell IG (2010) Sleep EEG changes during adolescence: an index of a fundamental brain reorganization. Brain Cogn 72:56–65. https://doi.org/10.1016/j.bandc.2009.09.008
Feinberg I, Campbell IG (2013) Longitudinal sleep EEG trajectories indicate complex patterns of adolescent brain maturation. Am J Phys Regul Integr Comp Phys 304:R296–R303. https://doi.org/10.1152/ajpregu.00422.2012
Feinberg I, March JD, Floyd TC et al (1985) Homeostatic changes during post-nap sleep maintain baseline levels of delta EEG. Electroencephalogr Clin Neurophysiol 61:134–137
Feinberg I, Thode HC, Chugani HT, March JD (1990) Gamma distribution model describes maturational curves for delta wave amplitude, cortical metabolic rate and synaptic density. J Theor Biol 142:149–161
Feinberg I, Davis NM, de Bie E et al (2012) The maturational trajectories of NREM and REM sleep durations differ across adolescence on both school-night and extended sleep. Am J Phys Regul Integr Comp Phys 302:R533–R540. https://doi.org/10.1152/ajpregu.00532.2011
Ficca G, Fagioli I, Salzarulo P (2000a) Sleep organization in the first year of life: developmental trends in the quiet sleep–paradoxical sleep cycle. J Sleep Res 9:1–4. https://doi.org/10.1046/j.1365-2869.2000.00172.x
Ficca G, Lombardo P, Rossi L, Salzarulo P (2000b) Morning recall of verbal material depends on prior sleep organization. Behav Brain Res 112:159–163
Fifer WP, Byrd DL, Kaku M et al (2010) Newborn infants learn during sleep. Proc Natl Acad Sci 107:10320–10323. https://doi.org/10.1073/pnas.1005061107
Finelli LA, Borbély AA, Achermann P (2001) Functional topography of the human nonREM sleep electroencephalogram. Eur J Neurosci 13:2282–2290
Fischer S, Hallschmid M, Elsner AL, Born J (2002) Sleep forms memory for finger skills. Proc Natl Acad Sci 99:11987–11991. https://doi.org/10.1073/pnas.182178199
Fischer S, Wilhelm I, Born J (2007) Developmental differences in sleep's role for implicit off-line learning: comparing children with adults. J Cogn Neurosci 19:214–227. https://doi.org/10.1162/jocn.2007.19.2.214
Fleischman DA, Wilson RS, Gabrieli JDE et al (2004) A longitudinal study of implicit and explicit memory in old persons. Psychol Aging 19:617–625. https://doi.org/10.1037/0882-7974.19.4.617

Fogel SM, Smith CT (2006) Learning-dependent changes in sleep spindles and Stage 2 sleep. J Sleep Res 15:250–255. https://doi.org/10.1111/j.1365-2869.2006.00522.x
Fogel SM, Smith CT (2011) The function of the sleep spindle: a physiological index of intelligence and a mechanism for sleep-dependent memory consolidation. Neurosci Biobehav Rev 35:1154–1165. https://doi.org/10.1016/j.neubiorev.2010.12.003
Fogel SM, Nader R, Cote KA, Smith CT (2007a) Sleep spindles and learning potential. Behav Neurosci 121:1–10. https://doi.org/10.1037/0735-7044.121.1.1
Fogel SM, Smith CT, Cote KA (2007b) Dissociable learning-dependent changes in REM and non-REM sleep in declarative and procedural memory systems. Behav Brain Res 180:48–61. https://doi.org/10.1016/j.bbr.2007.02.037
Fogel S, Martin N, Lafortune M et al (2012) NREM sleep oscillations and brain plasticity in aging. Front Neurol. https://doi.org/10.3389/fneur.2012.00176
Fogel SM, Ray LB, Binnie L, Owen AM (2015) How to become an expert: a new perspective on the role of sleep in the mastery of procedural skills. Neurobiol Learn Mem 125:236–248. https://doi.org/10.1016/j.nlm.2015.10.004
Frank MG, Issa NP, Stryker MP (2001) Sleep enhances plasticity in the developing visual cortex. Neuron 30:275–287. https://doi.org/10.1016/S0896-6273(01)00279-3
Franken P, Kopp C, Landolt H-P, Lüthi A (2009) The functions of sleep. Eur J Neurosci 29:1739–1740. https://doi.org/10.1111/j.1460-9568.2009.06746.x
Friedrich M, Wilhelm I, Born J, Friederici AD (2015) Generalization of word meanings during infant sleep. Nat Commun. https://doi.org/10.1038/ncomms7004
Fuller PM, Gooley JJ, Saper CB (2006) Neurobiology of the sleep-wake cycle: sleep architecture, circadian regulation, and regulatory feedback. J Biol Rhythm 21:482–493. https://doi.org/10.1177/0748730406294627
Gais S, Born J (2004a) Declarative memory consolidation: mechanisms acting during human sleep. Learn Mem 11:679–685. https://doi.org/10.1101/lm.80504
Gais S, Born J (2004b) Low acetylcholine during slow-wave sleep is critical for declarative memory consolidation. Proc Natl Acad Sci 101:2140–2144. https://doi.org/10.1073/pnas.0305404101
Gais S, Mölle M, Helms K, Born J (2002) Learning-dependent increases in sleep spindle density. J Neurosci 22:6830–6834 doi:20026697
Gais S, Lucas B, Born J (2006) Sleep after learning aids memory recall. Learn Mem Cold Spring Harb N 13:259–262. https://doi.org/10.1101/lm.132106
Gangwisch JE, Heymsfield SB, Boden-Albala B et al (2006) Short sleep duration as a risk factor for hypertension: analyses of the first national health and nutrition examination survey. Hypertens Dallas Tex 1979 47:833–839. https://doi.org/10.1161/01.HYP.0000217362.34748.e0
Gangwisch JE, Heymsfield SB, Boden-Albala B et al (2008) Sleep duration associated with mortality in elderly, but not middle-aged, adults in a large US sample. Sleep 31:1087–1096
Gaudreau H, Carrier J, Montplaisir J (2001) Age-related modifications of NREM sleep EEG: from childhood to middle age. J Sleep Res 10:165–172. https://doi.org/10.1046/j.1365-2869.2001.00252.x
Gaus SE, Strecker RE, Tate BA et al (2002) Ventrolateral preoptic nucleus contains sleep-active, galaninergic neurons in multiple mammalian species. Neuroscience 115:285–294
Geiger A, Huber R, Kurth S et al (2011) The sleep EEG as a marker of intellectual ability in school age children. Sleep 34:181–189
Gerrard JL, Burke SN, McNaughton BL, Barnes CA (2008) Sequence reactivation in the hippocampus is impaired in aged rats. J Neurosci 28:7883–7890. https://doi.org/10.1523/JNEUROSCI.1265-08.2008
Ghosh A, Greenberg ME (1995) Calcium signaling in neurons: molecular mechanisms and cellular consequences. Science 268:239–247
Girardeau G, Zugaro M (2011) Hippocampal ripples and memory consolidation. Curr Opin Neurobiol 21:452–459. https://doi.org/10.1016/j.conb.2011.02.005
Giuditta A, Ambrosini MV, Montagnese P et al (1995) The sequential hypothesis of the function of sleep. Behav Brain Res 69:157–166. https://doi.org/10.1016/0166-4328(95)00012-I

Gómez RL, Bootzin RR, Nadel L (2006) Naps promote abstraction in language-learning infants. Psychol Sci 17:670–674. https://doi.org/10.1111/j.1467-9280.2006.01764.x

Gottlieb DJ, Punjabi NM, Newman AB et al (2005) Association of sleep time with diabetes mellitus and impaired glucose tolerance. Arch Intern Med 165:863–867. https://doi.org/10.1001/archinte.165.8.863

Gottlieb DJ, Redline S, Nieto FJ et al (2006) Association of usual sleep duration with hypertension: the Sleep Heart Health Study. Sleep 29:1009–1014

Graven SN, Browne JV (2008) Sleep and brain development: the critical role of sleep in fetal and early neonatal brain development. Newborn Infant Nurs Rev 8:173–179. https://doi.org/10.1053/j.nainr.2008.10.008

Greene RW, Frank MG (2010) Slow wave activity during sleep: functional and therapeutic implications. Neuroscientist 16:618–633. https://doi.org/10.1177/1073858410377064

Griessenberger H, Hoedlmoser K, Heib DPJ et al (2012) Consolidation of temporal order in episodic memories. Biol Psychol 91:150–155. https://doi.org/10.1016/j.biopsycho.2012.05.012

Groch S, Wilhelm I, Diekelmann S et al (2011) Contribution of norepinephrine to emotional memory consolidation during sleep. Psychoneuroendocrinology 36:1342–1350. https://doi.org/10.1016/j.psyneuen.2011.03.006

Groch S, Wilhelm I, Diekelmann S, Born J (2013) The role of REM sleep in the processing of emotional memories: evidence from behavior and event-related potentials. Neurobiol Learn Mem 99:1–9. https://doi.org/10.1016/j.nlm.2012.10.006

Grosmark AD, Mizuseki K, Pastalkova E et al (2012) REM sleep reorganizes hippocampal excitability. Neuron 75:1001–1007. https://doi.org/10.1016/j.neuron.2012.08.015

Harand C, Bertran F, Doidy F et al (2012) How aging affects sleep-dependent memory consolidation? Front Neurol. https://doi.org/10.3389/fneur.2012.00008

Hedden T, Gabrieli JDE (2004) Insights into the ageing mind: a view from cognitive neuroscience. Nat Rev Neurosci 5:87–96. https://doi.org/10.1038/nrn1323

Henderson LM, Weighall AR, Brown H, Gareth Gaskell M (2012) Consolidation of vocabulary is associated with sleep in children. Dev Sci 15:674–687. https://doi.org/10.1111/j.1467-7687.2012.01172.x

Hipólide DC, Tufik S, Raymond R, Nobrega JN (1998) Heterogeneous effects of rapid eye movement sleep deprivation on binding to alpha- and beta-adrenergic receptor subtypes in rat brain. Neuroscience 86:977–987

Hipólide DC, Moreira KM, Barlow KBL et al (2005) Distinct effects of sleep deprivation on binding to norepinephrine and serotonin transporters in rat brain. Prog Neuro-Psychopharmacol Biol Psychiatry 29:297–303. https://doi.org/10.1016/j.pnpbp.2004.11.015

Hirshkowitz M, Moore CA, Hamilton CR et al (1992) Polysomnography of adults and elderly: sleep architecture, respiration, and leg movement. J Clin Neurophysiol Off Publ Am Electroencephalogr Soc 9:56–62

Hishikawa Y, Shimizu T (1995) Physiology of REM sleep, cataplexy, and sleep paralysis. Adv Neurol 67:245–271

Hobson JA, Pace-Schott EF (2002) The cognitive neuroscience of sleep: neuronal systems, consciousness and learning. Nat Rev Neurosci 3:679–693. https://doi.org/10.1038/nrn915

Hobson JA, Stickgold R, Pace-Schott EF (1998) The neuropsychology of REM sleep dreaming. Neuroreport 9:R1–R14

Hobson JA, Pace-Schott EF, Stickgold R (2000) Dreaming and the brain: toward a cognitive neuroscience of conscious states. Behav Brain Sci 23:793–842; discussion 904–1121

Hofman MA, Swaab DF (1989) The sexually dimorphic nucleus of the preoptic area in the human brain: a comparative morphometric study. J Anat 164:55–72

Holland P, Lewis PA (2007) Emotional memory: selective enhancement by sleep. Curr Biol 17:R179–R181. https://doi.org/10.1016/j.cub.2006.12.033

Holz J, Piosczyk H, Landmann N et al (2012) The timing of learning before night-time sleep differentially affects declarative and procedural long-term memory consolidation in adolescents. PLoS One 7:e40963. https://doi.org/10.1371/journal.pone.0040963

Honda Y, Takahashi K, Takahashi S et al (1969) Growth hormone secretion during nocturnal sleep in normal subjects. J Clin Endocrinol Metab 29:20–29. https://doi.org/10.1210/jcem-29-1-20
Hu P, Stylos-Allan M, Walker MP (2006) Sleep facilitates consolidation of emotional declarative memory. Psychol Sci 17:891–898. https://doi.org/10.1111/j.1467-9280.2006.01799.x
Huber R, Born J (2014) Sleep, synaptic connectivity, and hippocampal memory during early development. Trends Cogn Sci 18:141–152. https://doi.org/10.1016/j.tics.2013.12.005
Huber R, Felice Ghilardi M, Massimini M, Tononi G (2004) Local sleep and learning. Nature 430:78–81. https://doi.org/10.1038/nature02663
Huber R, Ghilardi MF, Massimini M et al (2006) Arm immobilization causes cortical plastic changes and locally decreases sleep slow wave activity. Nat Neurosci 9:1169–1176. https://doi.org/10.1038/nn1758
Hupbach A, Gómez RL, Bootzin RR, Nadel L (2009) Nap-dependent learning in infants. Dev Sci 12:1007–1012. https://doi.org/10.1111/j.1467-7687.2009.00837.x
Huttenlocher PR (1979) Synaptic density in human frontal cortex – developmental changes and effects of aging. Brain Res 163:195–205
Huttenlocher PR, Dabholkar AS (1997) Regional differences in synaptogenesis in human cerebral cortex. J Comp Neurol 387:167–178
Iglowstein I, Jenni OG, Molinari L, Largo RH (2003) Sleep duration from infancy to adolescence: reference values and generational trends. Pediatrics 111:302–307. https://doi.org/10.1542/peds.111.2.302
Inoue M, Koyanagi T, Nakahara H et al (1986) Functional development of human eye movement in utero assessed quantitatively with real-time ultrasound. Am J Obstet Gynecol 155:170–174. https://doi.org/10.1016/0002-9378(86)90105-5
Jenkins JG, Dallenbach KM (1924) Obliviscence during sleep and waking. Am J Psychol 35:605–612. https://doi.org/10.2307/1414040
Jenni OG, Carskadon MA (2004) Spectral analysis of the sleep electroencephalogram during adolescence. Sleep 27:774–783
Jenni OG, Carskadon MA (2007) Sleep behavior and sleep regulation from infancy through adolescence: normative aspects. Sleep Med Clin 2:321–329. https://doi.org/10.1016/j.jsmc.2007.05.001
Jenni OG, Borbély AA, Achermann P (2004) Development of the nocturnal sleep electroencephalogram in human infants. Am J Phys Regul Integr Comp Phys 286:R528–R538. https://doi.org/10.1152/ajpregu.00503.2003
Ji D, Wilson MA (2007) Coordinated memory replay in the visual cortex and hippocampus during sleep. Nat Neurosci 10:100–107. https://doi.org/10.1038/nn1825
Jones MW, Wilson MA (2005) Theta rhythms coordinate hippocampal–prefrontal interactions in a spatial memory task. PLoS Biol 3:e402. https://doi.org/10.1371/journal.pbio.0030402
Jones BJ, Schultz KS, Adams S et al (2016) Emotional bias of sleep-dependent processing shifts from negative to positive with aging. Neurobiol Aging 45:178–189. https://doi.org/10.1016/j.neurobiolaging.2016.05.019
Karni A, Tanne D, Rubenstein BS et al (1994) Dependence on REM sleep of overnight improvement of a perceptual skill. Science 265:679–682
Kashiwagi M, Hayashi Y (2016) The function of REM sleep: implications from transgenic mouse models. Brain Nerve Shinkei Kenkyu No Shinpo 68:1205–1211. https://doi.org/10.11477/mf.1416200575
Kaufmann C, Wehrle R, Wetter TC et al (2006) Brain activation and hypothalamic functional connectivity during human non-rapid eye movement sleep: an EEG/fMRI study. Brain 129:655–667. https://doi.org/10.1093/brain/awh686
Kennedy Q, Mather M, Carstensen LL (2004) The role of motivation in the age-related positivity effect in autobiographical memory. Psychol Sci 15:208–214
Kensinger EA, Schacter DL (2008) Neural processes supporting young and older adults' emotional memories. J Cogn Neurosci 20:1161–1173. https://doi.org/10.1162/jocn.2008.20080

Konrad C, Herbert JS, Schneider S, Seehagen S (2016a) The relationship between prior night's sleep and measures of infant imitation. Dev Psychobiol 58:450. https://doi.org/10.1002/dev.21387

Konrad C, Herbert JS, Schneider S, Seehagen S (2016b) Gist extraction and sleep in 12-month-old infants. Neurobiol Learn Mem 134(Part B):216–220. https://doi.org/10.1016/j.nlm.2016.08.021

Konrad C, Seehagen S, Schneider S, Herbert JS (2016c) Naps promote flexible memory retrieval in 12-month-old infants. Dev Psychobiol 58:866–874. https://doi.org/10.1002/dev.21431

Kopasz M, Loessl B, Valerius G et al (2010) No persisting effect of partial sleep curtailment on cognitive performance and declarative memory recall in adolescents. J Sleep Res 19:71–79. https://doi.org/10.1111/j.1365-2869.2009.00742.x

Korman M, Doyon J, Doljansky J et al (2007) Daytime sleep condenses the time course of motor memory consolidation. Nat Neurosci 10:1206–1213. https://doi.org/10.1038/nn1959

Kurdziel L, Duclos K, Spencer RMC (2013) Sleep spindles in midday naps enhance learning in preschool children. Proc Natl Acad Sci 110:17267–17272. https://doi.org/10.1073/pnas.1306418110

Kurth S, Ringli M, Geiger A et al (2010) Mapping of cortical activity in the first two decades of life: a high-density sleep electroencephalogram study. J Neurosci 30:13211–13219. https://doi.org/10.1523/JNEUROSCI.2532-10.2010

Kurth S, Ringli M, Lebourgeois MK et al (2012) Mapping the electrophysiological marker of sleep depth reveals skill maturation in children and adolescents. NeuroImage 63:959–965. https://doi.org/10.1016/j.neuroimage.2012.03.053

Lam JC, Mahone EM, Mason TBA, Scharf SM (2011) The effects of napping on cognitive function in preschoolers. J Dev Behav Pediatr JDBP 32:90–97. https://doi.org/10.1097/DBP.0b013e318207ecc7

Landolt HP, Borbély AA (2001) Age-dependent changes in sleep EEG topography. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 112:369–377

Landolt H-P, Dijk D-J, Achermann P, Borbély AA (1996) Effect of age on the sleep EEG: slow-wave activity and spindle frequency activity in young and middle-aged men. Brain Res 738:205–212. https://doi.org/10.1016/S0006-8993(96)00770-6

Lang P, Bradley M, Cuthbert B (2008) International affective picture system (IAPS): affective ratings of pictures and instruction manual

Lara-Carrasco J, Nielsen TA, Solomonova E et al (2009) Overnight emotional adaptation to negative stimuli is altered by REM sleep deprivation and is correlated with intervening dream emotions. J Sleep Res 18:178–187. https://doi.org/10.1111/j.1365-2869.2008.00709.x

Laureys S, Peigneux P, Phillips C et al (2001) Experience-dependent changes in cerebral functional connectivity during human rapid eye movement sleep. Neuroscience 105:521–525

Laventure S, Fogel S, Lungu O et al (2016) NREM2 and sleep spindles are instrumental to the consolidation of motor sequence memories. PLoS Biol 14:e1002429. https://doi.org/10.1371/journal.pbio.1002429

Lemos N, Weissheimer J, Ribeiro S (2014) Naps in school can enhance the duration of declarative memories learned by adolescents. Front Syst Neurosci 8:103. https://doi.org/10.3389/fnsys.2014.00103

Lewis PA, Cairney S, Manning L, Critchley HD (2011) The impact of overnight consolidation upon memory for emotional and neutral encoding contexts. Neuropsychologia 49:2619–2629. https://doi.org/10.1016/j.neuropsychologia.2011.05.009

Lisman J, Schulman H, Cline H (2002) The molecular basis of CaMKII function in synaptic and behavioural memory. Nat Rev Neurosci 3:175–190. https://doi.org/10.1038/nrn753

Louie K, Wilson MA (2001) Temporally structured replay of awake hippocampal ensemble activity during rapid eye movement sleep. Neuron 29:145–156. https://doi.org/10.1016/S0896-6273(01)00186-6

Lövblad KO, Thomas R, Jakob PM et al (1999) Silent functional magnetic resonance imaging demonstrates focal activation in rapid eye movement sleep. Neurology 53:2193–2195

Lukowski AF, Milojevich HM (2013) Sleeping like a baby: examining relations between habitual infant sleep, recall memory, and generalization across cues at 10 months. Infant Behav Dev 36:369–376. https://doi.org/10.1016/j.infbeh.2013.02.001

Mander BA, Rao V, Lu B et al (2013) Prefrontal atrophy, disrupted NREM slow waves and impaired hippocampal-dependent memory in aging. Nat Neurosci 16:357–364. https://doi.org/10.1038/nn.3324

Mantua J, Baran B, Spencer RMC (2016) Sleep benefits consolidation of visuo-motor adaptation learning in older adults. Exp Brain Res 234:587–595. https://doi.org/10.1007/s00221-015-4490-7

Maquet P, Péters J-M, Aerts J et al (1996) Functional neuroanatomy of human rapid-eye-movement sleep and dreaming. Nature 383:163–166. https://doi.org/10.1038/383163a0

Maquet P, Laureys S, Peigneux P et al (2000) Experience-dependent changes in cerebral activation during human REM sleep. Nat Neurosci 3:831–836. https://doi.org/10.1038/77744

Marks GA, Shaffery JP, Oksenberg A et al (1995) A functional role for REM sleep in brain maturation. Behav Brain Res 69:1–11. https://doi.org/10.1016/0166-4328(95)00018-O

Marshall L, Mölle M, Böschen G et al (1996) Greater efficacy of episodic than continuous growth hormone-releasing hormone (GHRH) administration in promoting slow-wave sleep (SWS). J Clin Endocrinol Metab 81:1009–1013. https://doi.org/10.1210/jcem.81.3.8772566

Marshall L, Helgadóttir H, Mölle M, Born J (2006) Boosting slow oscillations during sleep potentiates memory. Nature 444:610–613. https://doi.org/10.1038/nature05278

Martin P (2002) Counting sheep: the science and pleasures of sleep and dreams. St. Martin's Press, New York

Mather M, Carstensen LL (2005) Aging and motivated cognition: the positivity effect in attention and memory. Trends Cogn Sci 9:496–502. https://doi.org/10.1016/j.tics.2005.08.005

McCarley RW (2007) Neurobiology of REM and NREM sleep. Sleep Med 8:302–330. https://doi.org/10.1016/j.sleep.2007.03.005

Metcalf DR (1969) The effect of extrauterine experience on the ontogenesis of EEG sleep spindles. Psychosom Med 31:393–399

Metcalf D (1970) EEG sleep spindle ontogenesis. Neuropediatrics 1:428–433. https://doi.org/10.1055/s-0028-1091828

Mirmiran M, Scholtens J, van de Poll NE et al (1983a) Effects of experimental suppression of active (REM) sleep during early development upon adult brain and behavior in the rat. Brain Res 283:277–286

Mirmiran M, Uylings HB, Corner MA (1983b) Pharmacological suppression of REM sleep prior to weaning counteracts the effectiveness of subsequent environmental enrichment on cortical growth in rats. Brain Res 283:102–105

Mirmiran M, Maas YGH, Ariagno RL (2003) Development of fetal and neonatal sleep and circadian rhythms. Sleep Med Rev 7:321–334. https://doi.org/10.1053/smrv.2002.0243

Moldofsky H, Lue FA, Eisen J et al (1986) The relationship of interleukin-1 and immune functions to sleep in humans. Psychosom Med 48:309–318

Mölle M, Eschenko O, Gais S et al (2009) The influence of learning on sleep slow oscillations and associated spindles and ripples in humans and rats. Eur J Neurosci 29:1071–1081. https://doi.org/10.1111/j.1460-9568.2009.06654.x

Mongrain V, Carrier J, Dumont M (2005) Chronotype and sex effects on sleep architecture and quantitative sleep EEG in healthy young adults. Sleep 28:819–827

Morgenthaler J, Wiesner CD, Hinze K et al (2014) Selective REM-sleep deprivation does not diminish emotional memory consolidation in young healthy subjects. PLoS One 9:e89849. https://doi.org/10.1371/journal.pone.0089849

Moroni F, Nobili L, Curcio G et al (2007) Sleep in the human hippocampus: a stereo-EEG study. PLoS One 2:e867. https://doi.org/10.1371/journal.pone.0000867

Morrissey MJ, Duntley SP, Anch AM, Nonneman R (2004) Active sleep and its role in the prevention of apoptosis in the developing brain. Med Hypotheses 62:876–879. https://doi.org/10.1016/j.mehy.2004.01.014

Morselli LL, Guyon A, Spiegel K (2011) Sleep and metabolic function. Pflugers Arch - Eur J Physiol 463:139–160. https://doi.org/10.1007/s00424-011-1053-z

Nelson JP, McCarley RW, Hobson JA (1983) REM sleep burst neurons, PGO waves, and eye movement information. J Neurophysiol 50:784–797

Newman AB, Enright PL, Manolio TA et al (1997) Sleep disturbance, psychosocial correlates, and cardiovascular disease in 5201 older adults: the Cardiovascular Health Study. J Am Geriatr Soc 45:1–7

Nishida M, Walker MP (2007) Daytime naps, motor memory consolidation and regionally specific sleep spindles. PLoS One 2:e341. https://doi.org/10.1371/journal.pone.0000341

Nishida M, Pearsall J, Buckner RL, Walker MP (2009) REM sleep, prefrontal theta, and the consolidation of human emotional memory. Cereb Cortex 19:1158–1166. https://doi.org/10.1093/cercor/bhn155

Nofzinger EA, Mintun MA, Wiseman M et al (1997) Forebrain activation in REM sleep: an FDG PET study. Brain Res 770:192–201

Ochsner KN, Gross JJ (2005) The cognitive control of emotion. Trends Cogn Sci 9:242–249. https://doi.org/10.1016/j.tics.2005.03.010

Ognjanovski N, Maruyama D, Lashner N et al (2014) CA1 hippocampal network activity changes during sleep-dependent memory consolidation. Front Syst Neurosci. https://doi.org/10.3389/fnsys.2014.00061

Ohayon MM, Carskadon MA, Guilleminault C, Vitiello MV (2004) Meta-analysis of quantitative sleep parameters from childhood to old age in healthy individuals: developing normative sleep values across the human lifespan. Sleep 27:1255–1273

Okai T, Kozuma S, Shinozuka N et al (1992) A study on the development of sleep-wakefulness cycle in the human fetus. Early Hum Dev 29:391–396

Pace-Schott EF, Spencer RMC (2014) Sleep-dependent memory consolidation in healthy aging and mild cognitive impairment. In: Meerlo P, Benca RM, Abel T (eds) Sleep, neuronal plasticity and brain function. Springer, Berlin, pp 307–330

Pavlides C, Winson J (1989) Influences of hippocampal place cell firing in the awake state on the activity of these cells during subsequent sleep episodes. J Neurosci Off J Soc Neurosci 9:2907–2918

Payne JD, Kensinger EA (2010) Sleep leads to changes in the emotional memory trace: evidence from fMRI. J Cogn Neurosci 23:1285–1297. https://doi.org/10.1162/jocn.2010.21526

Payne JD, Stickgold R, Swanberg K, Kensinger EA (2008) Sleep preferentially enhances memory for emotional components of scenes. Psychol Sci 19:781–788. https://doi.org/10.1111/j.1467-9280.2008.02157.x

Pedrazzoli M, Benedito MAC (2004) Rapid eye movement sleep deprivation-induced down-regulation of beta-adrenergic receptors in the rat brainstem and hippocampus. Pharmacol Biochem Behav 79:31–36. https://doi.org/10.1016/j.pbb.2004.06.001

Peigneux P, Laureys S, Fuchs S et al (2003) Learned material content and acquisition level modulate cerebral reactivation during posttraining rapid-eye-movements sleep. NeuroImage 20:125–134

Peigneux P, Laureys S, Fuchs S et al (2004) Are spatial memories strengthened in the human hippocampus during slow wave sleep? Neuron 44:535–545. https://doi.org/10.1016/j.neuron.2004.10.007

Peirano PD, Algarín CR (2007) Sleep in brain development. Biol Res 40:471–478. https://doi.org/10.4067/S0716-97602007000500008

Pereira SIR, Beijamini F, Vincenzi RA, Louzada FM (2015) Re-examining sleep's effect on motor skills: how to access performance on the finger tapping task? Sleep Sci 8:4–8. https://doi.org/10.1016/j.slsci.2015.01.001

Petre-Quadens O, De Lee C (1974) Eye movement frequencies and related paradoxical sleep cycles: developmental changes. Chronobiologia 1:348–355

Piosczyk H, Holz J, Feige B et al (2013) The effect of sleep-specific brain activity versus reduced stimulus interference on declarative memory consolidation. J Sleep Res 22:406–413. https://doi.org/10.1111/jsr.12033

Plihal W, Born J (1997) Effects of early and late nocturnal sleep on declarative and procedural memory. J Cogn Neurosci 9:534–547. https://doi.org/10.1162/jocn.1997.9.4.534

Poe GR, Nitz DA, McNaughton BL, Barnes CA (2000) Experience-dependent phase-reversal of hippocampal neuron firing during REM sleep. Brain Res 855:176–180. https://doi.org/10.1016/S0006-8993(99)02310-0

Pompeiano O (1975) The control of posture and movements during REM sleep: neurophysiological and neurochemical mechanisms. Acta Astronaut 2:225–239

Popa D, Duvarci S, Popescu AT et al (2010) Coherent amygdalocortical theta promotes fear memory consolidation during paradoxical sleep. Proc Natl Acad Sci 107:6516–6519. https://doi.org/10.1073/pnas.0913016107

Potkin KT, Bunney WE Jr (2012) Sleep improves memory: the effect of sleep on long term memory in early adolescence. PLoS One 7:e42191. https://doi.org/10.1371/journal.pone.0042191

Prechtl HFR (1974) The behavioural states of the newborn infant (a review). Brain Res 76:185–212. https://doi.org/10.1016/0006-8993(74)90454-5

Prehn-Kristensen A, Göder R, Chirobeja S et al (2009) Sleep in children enhances preferentially emotional declarative but not procedural memories. J Exp Child Psychol 104:132–139. https://doi.org/10.1016/j.jecp.2009.01.005

Prehn-Kristensen A, Göder R, Fischer J et al (2011a) Reduced sleep-associated consolidation of declarative memory in attention-deficit/hyperactivity disorder. Sleep Med 12:672–679. https://doi.org/10.1016/j.sleep.2010.10.010

Prehn-Kristensen A, Molzow I, Munz M et al (2011b) Sleep restores daytime deficits in procedural memory in children with attention-deficit/hyperactivity disorder. Res Dev Disabil 32:2480–2488. https://doi.org/10.1016/j.ridd.2011.06.021

Prehn-Kristensen A, Munz M, Molzow I et al (2013) Sleep promotes consolidation of emotional memory in healthy children but not in children with attention-deficit hyperactivity disorder. PLoS One 8:e65098. https://doi.org/10.1371/journal.pone.0065098

Prehn-Kristensen A, Munz M, Göder R et al (2014) Transcranial oscillatory direct current stimulation during sleep improves declarative memory consolidation in children with attention-deficit/hyperactivity disorder to a level comparable to healthy controls. Brain Stimulat 7:793–799. https://doi.org/10.1016/j.brs.2014.07.036

Rasch B, Büchel C, Gais S, Born J (2007) Odor cues during slow-wave sleep prompt declarative memory consolidation. Science 315:1426–1429. https://doi.org/10.1126/science.1138581

Rasch B, Pommer J, Diekelmann S, Born J (2009) Pharmacological REM sleep suppression paradoxically improves rather than impairs skill memory. Nat Neurosci 12:396–397. https://doi.org/10.1038/nn.2206

Raz N, Gunning FM, Head D et al (1997) Selective aging of the human cerebral cortex observed in vivo: differential vulnerability of the prefrontal gray matter. Cereb Cortex 7:268–282. https://doi.org/10.1093/cercor/7.3.268

Redwine L, Hauger RL, Gillin JC, Irwin M (2000) Effects of sleep and sleep deprivation on interleukin-6, growth hormone, cortisol, and melatonin levels in humans. J Clin Endocrinol Metab 85:3597–3603. https://doi.org/10.1210/jcem.85.10.6871

Reeb-Sutherland BC, Fifer WP, Byrd DL et al (2011) One-month-old human infants learn about the social world while they sleep. Dev Sci 14:1134–1141. https://doi.org/10.1111/j.1467-7687.2011.01062.x

Rickard TC, Cai DJ, Rieth CA et al (2008) Sleep does not enhance motor sequence learning. J Exp Psychol Learn Mem Cogn 34:834–842. https://doi.org/10.1037/0278-7393.34.4.834

Robertson EM, Pascual-Leone A, Press DZ (2004) Awareness modifies the skill-learning benefits of sleep. Curr Biol CB 14:208–212. https://doi.org/10.1016/j.cub.2004.01.027

Roffwarg HP, Muzio JN, Dement WC (1966) Ontogenetic development of the human sleep-dream cycle. Science 152(3722):604–619. https://doi.org/10.1126/science.152.3722.604

Rudoy JD, Voss JL, Westerberg CE, Paller KA (2009) Strengthening individual memories by reactivating them during sleep. Science 326:1079–1079. https://doi.org/10.1126/science.1179013

Sassin JF, Parker DC, Mace JW et al (1969) Human growth hormone release: relation to slow-wave sleep and sleep-waking cycles. Science 165:513–515. https://doi.org/10.1126/science.165.3892.513

Schabus M, Gruber G, Parapatics S et al (2004) Sleep spindles and their significance for declarative memory consolidation. Sleep 27:1479–1485

Schabus M, Dang-Vu TT, Albouy G et al (2007) Hemodynamic cerebral correlates of sleep spindles during human non-rapid eye movement sleep. Proc Natl Acad Sci 104:13164–13169. https://doi.org/10.1073/pnas.0703084104

Schönauer M, Geisler T, Gais S (2013) Strengthening procedural memories by reactivation in sleep. J Cogn Neurosci 26:143–153. https://doi.org/10.1162/jocn_a_00471

Scullin MK (2013) Sleep, memory, and aging: the link between slow-wave sleep and episodic memory changes from younger to older adults. Psychol Aging 28:105–114. https://doi.org/10.1037/a0028830

Seeck-Hirschner M, Baier PC, Weinhold SL et al (2012) Declarative memory performance is associated with the number of sleep spindles in elderly women. Am J Geriatr Psychiatry 20:782–788. https://doi.org/10.1097/JGP.0b013e31823033da

Seehagen S, Konrad C, Herbert JS, Schneider S (2015) Timely sleep facilitates declarative memory consolidation in infants. Proc Natl Acad Sci U S A 112:1625–1629. https://doi.org/10.1073/pnas.1414000112

Sherwin BB (2012) Estrogen and cognitive functioning in women: lessons we have learned. Behav Neurosci 126:123–127. https://doi.org/10.1037/a0025539

Siapas AG, Wilson MA (1998) Coordinated interactions between hippocampal ripples and cortical spindles during slow-wave sleep. Neuron 21:1123–1128

Siegel JM (2001) The REM sleep-memory consolidation hypothesis. Science 294:1058–1063. https://doi.org/10.1126/science.1063049

Siegel JM (2005) Clues to the functions of mammalian sleep. Nature 437:1264–1271. https://doi.org/10.1038/nature04285

Siegel JM (2009) The neurobiology of sleep. Semin Neurol 29:277–296. https://doi.org/10.1055/s-0029-1237118

Siegel JM, Rogawski MA (1988) A function for REM sleep: regulation of noradrenergic receptor sensitivity. Brain Res 472:213–233

Sirota A, Buzsáki G (2005) Interaction between neocortical and hippocampal networks via slow oscillations. Thalamus Relat Syst 3:245–259. https://doi.org/10.1017/S1472928807000258

Sisk CL, Foster DL (2004) The neural basis of puberty and adolescence. Nat Neurosci 7:1040–1047. https://doi.org/10.1038/nn1326

Skaggs WE, McNaughton BL (1996) Replay of neuronal firing sequences in rat hippocampus during sleep following spatial experience. Science 271:1870–1873

Smith C, MacNeill C (1994) Impaired motor memory for a pursuit rotor task following stage 2 sleep loss in college students. J Sleep Res 3:206–213

Smith CT, Nixon MR, Nader RS (2004) Posttraining increases in REM sleep intensity implicate REM sleep in memory processing and provide a biological marker of learning potential. Learn Mem 11:714–719. https://doi.org/10.1101/lm.74904

Soderling TR, Derkach VA (2000) Postsynaptic protein phosphorylation and LTP. Trends Neurosci 23:75–80. https://doi.org/10.1016/S0166-2236(99)01490-3

Song S, Howard JH, Howard DV (2007) Sleep does not benefit probabilistic motor sequence learning. J Neurosci 27:12475–12483. https://doi.org/10.1523/JNEUROSCI.2062-07.2007

Sonni A, Spencer RMC (2015) Sleep protects memories from interference in older adults. Neurobiol Aging. https://doi.org/10.1016/j.neurobiolaging.2015.03.010

Spencer RMC (2013) Neurophysiological basis of sleep's function on memory and cognition. Int Sch Res Not 2013:e619319. https://doi.org/10.1155/2013/619319

Spencer RMC, Gouw AM, Ivry RB (2007) Age-related decline of sleep-dependent consolidation. Learn Mem Cold Spring Harb N 14:480–484. https://doi.org/10.1101/lm.569407

Stenuit P, Kerkhofs M (2005) Age modulates the effects of sleep restriction in women. Sleep 28:1283–1288

Steriade M (2000) Corticothalamic resonance, states of vigilance and mentation. Neuroscience 101:243–276

Steriade M (2001) Active neocortical processes during quiescent sleep. Arch Ital Biol 139:37–51. https://doi.org/10.4449/aib.v139i1.203

Steriade M, Timofeev I (2003) Neuronal plasticity in thalamocortical networks during sleep and waking oscillations. Neuron 37:563–576. https://doi.org/10.1016/S0896-6273(03)00065-5

Sterman MB, Harper RM, Havens B et al (1977) Quantitative analysis of infant EEG development during quiet sleep. Electroencephalogr Clin Neurophysiol 43:371–385. https://doi.org/10.1016/0013-4694(77)90260-7

Sterpenich V, Albouy G, Boly M et al (2007) Sleep-related hippocampo-cortical interplay during emotional memory recollection. PLoS Biol 5:e282. https://doi.org/10.1371/journal.pbio.0050282

Sterpenich V, Albouy G, Darsaud A et al (2009) Sleep promotes the neural reorganization of remote emotional memory. J Neurosci 29:5143–5152. https://doi.org/10.1523/JNEUROSCI.0561-09.2009

Stickgold R (2005) Sleep-dependent memory consolidation. Nature 437:1272–1278. https://doi.org/10.1038/nature04286

Stickgold R, Whidbee D, Schirmer B et al (2000) Visual discrimination task improvement: a multi-step process occurring during sleep. J Cogn Neurosci 12:246–254

Takahashi Y, Kipnis DM, Daughaday WH (1968) Growth hormone secretion during sleep. J Clin Invest 47:2079–2090

Tanguay PE, Ornitz EM, Kaplan A, Bozzo ES (1975) Evolution of sleep spindles in childhood. Electroencephalogr Clin Neurophysiol 38:175–181. https://doi.org/10.1016/0013-4694(75)90227-8

Tononi G, Cirelli C (2003) Sleep and synaptic homeostasis: a hypothesis. Brain Res Bull 62:143–150

Tononi G, Cirelli C (2006) Sleep function and synaptic homeostasis. Sleep Med Rev 10:49–62. https://doi.org/10.1016/j.smrv.2005.05.002

Tononi G, Cirelli C (2014) Sleep and the price of plasticity: from synaptic and cellular homeostasis to memory consolidation and integration. Neuron 81:12–34. https://doi.org/10.1016/j.neuron.2013.12.025

Tsai LL, Bergmann BM, Perry BD, Rechtschaffen A (1993) Effects of chronic total sleep deprivation on central noradrenergic receptors in rat brain. Brain Res 602:221–227

Tucker AM, Dinges DF, Van Dongen HPA (2007) Trait interindividual differences in the sleep physiology of healthy young adults. J Sleep Res 16:170–180. https://doi.org/10.1111/j.1365-2869.2007.00594.x

Ulrich D (2016) Sleep spindles as facilitators of memory formation and learning. Neural Plast. https://doi.org/10.1155/2016/1796715

Van Cauter E, Leproult R, Plat L (2000) Age-related changes in slow wave sleep and REM sleep and relationship with growth hormone and cortisol levels in healthy men. JAMA 284:861–868

van der Helm E, Yao J, Dutt S et al (2011) REM sleep depotentiates amygdala activity to previous emotional experiences. Curr Biol 21:2029–2032. https://doi.org/10.1016/j.cub.2011.10.052

Van Someren EJW, Mirmiran M, Bos NPA et al (1990) Quantitative analysis of eye movements during REM-sleep in developing rats. Dev Psychobiol 23:55–61. https://doi.org/10.1002/dev.420230106

Varga AW, Ducca EL, Kishi A et al (2016a) Effects of aging on slow-wave sleep dynamics and human spatial navigational memory consolidation. Neurobiol Aging 42:142–149. https://doi.org/10.1016/j.neurobiolaging.2016.03.008

Varga AW, Wohlleber ME, Giménez S et al (2016b) Reduced slow-wave sleep is associated with high cerebrospinal fluid Aβ42 levels in cognitively normal elderly. Sleep 39:2041–2048

Voderholzer U, Piosczyk H, Holz J et al (2011) Sleep restriction over several days does not affect long-term recall of declarative and procedural memories in adolescents. Sleep Med 12:170–178. https://doi.org/10.1016/j.sleep.2010.07.017

Wagner U, Gais S, Born J (2001) Emotional memory formation is enhanced across sleep intervals with high amounts of rapid eye movement sleep. Learn Mem 8:112–119. https://doi.org/10.1101/lm.36801

Wagner U, Hallschmid M, Rasch B, Born J (2006) Brief sleep after learning keeps emotional memories alive for years. Biol Psychiatry 60:788–790. https://doi.org/10.1016/j.biopsych.2006.03.061

Walker MP (2005) A refined model of sleep and the time course of memory formation. Behav Brain Sci 28:51–64. https://doi.org/10.1017/S0140525X05000026

Walker JM, Berger RJ (1980) Sleep as an adaptation for energy conservation functionally related to hibernation and shallow torpor. In: PS MC, GJB RHJ, Van De Poll NE, Corner MA (eds) Progress in Brain Research. Elsevier, Amsterdam, pp 255–278

Walker MP, Stickgold R (2010) Overnight alchemy: sleep-dependent memory evolution. Nat Rev Neurosci 11:218.; author reply 218. https://doi.org/10.1038/nrn2762-c1

Walker MP, Brakefield T, Morgan A et al (2002) Practice with sleep makes perfect: sleep-dependent motor skill learning. Neuron 35:205–211. https://doi.org/10.1016/S0896-6273(02)00746-8

Walker MP, Stickgold R, Alsop D et al (2005) Sleep-dependent motor memory plasticity in the human brain. Neuroscience 133:911–917. https://doi.org/10.1016/j.neuroscience.2005.04.007

Wehr TA (1992) A brain-warming function for REM sleep. Neurosci Biobehav Rev 16:379–397. https://doi.org/10.1016/S0149-7634(05)80208-8

Weissbluth M (1995) Naps in children: 6 months-7 years. Sleep 18:82–87

Werth E, Achermann P, Borbély AA (1997) Fronto-occipital EEG power gradients in human sleep. J Sleep Res 6:102–112

West RL (1996) An application of prefrontal cortex function theory to cognitive aging. Psychol Bull 120:272–292

Westerberg CE, Florczak SM, Weintraub S et al (2015) Memory improvement via slow-oscillatory stimulation during sleep in older adults. Neurobiol Aging 36:2577–2586. https://doi.org/10.1016/j.neurobiolaging.2015.05.014

Wierzynski CM, Lubenov EV, Gu M, Siapas AG (2009) State-dependent spike-timing relationships between hippocampal and prefrontal circuits during sleep. Neuron 61:587–596. https://doi.org/10.1016/j.neuron.2009.01.011

Wilhelm I, Diekelmann S, Born J (2008) Sleep in children improves memory performance on declarative but not procedural tasks. Learn Mem 15:373–377. https://doi.org/10.1101/lm.803708

Wilhelm I, Prehn-Kristensen A, Born J (2012) Sleep-dependent memory consolidation – what can be learnt from children? Neurosci Biobehav Rev 36:1718–1728. https://doi.org/10.1016/j.neubiorev.2012.03.002

Wilhelm I, Rose M, Imhof KI et al (2013) The sleeping child outplays the adult's capacity to convert implicit into explicit knowledge. Nat Neurosci 16:391–393. https://doi.org/10.1038/nn.3343

Williams SE, Horst JS (2014) Goodnight book: sleep consolidation improves word learning via storybooks. Front Psychol. https://doi.org/10.3389/fpsyg.2014.00184

Wilson MA, McNaughton BL (1994) Reactivation of hippocampal ensemble memories during sleep. Science 265:676–679. https://doi.org/10.1126/science.8036517

Wilson JK, Baran B, Pace-Schott EF et al (2012) Sleep modulates word-pair learning but not motor sequence learning in healthy older adults. Neurobiol Aging 33:991–1000. https://doi.org/10.1016/j.neurobiolaging.2011.06.029

Xie L, Kang H, Xu Q et al (2013) Sleep drives metabolite clearance from the adult brain. Science 342:373–377. https://doi.org/10.1126/science.1241224

Yaggi HK, Araujo AB, McKinlay JB (2006) Sleep duration as a risk factor for the development of type 2 diabetes. Diabetes Care 29:657–661

Yoo S-S, Gujar N, Hu P et al (2007) The human emotional brain without sleep – a prefrontal amygdala disconnect. Curr Biol 17:R877–R878. https://doi.org/10.1016/j.cub.2007.08.007