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Review article

A systematic review and meta-analysis of individual differences in naturalistic sleep quality and episodic memory performance in young and older adults

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ABSTRACT

Better sleep quality has been associated with better episodic memory performance in young adults. However, the strength of sleep-memory associations in aging has not been well characterized. It is also unknown whether factors such as sleep measurement method (e.g., polysomnography, actigraphy, self-report), sleep parameters (e.g., slow wave sleep, sleep duration), or memory task characteristics (e.g., verbal, pictorial) impact the strength of sleep-memory associations. Here, we assessed if the aforementioned factors modulate sleep-memory relationships. Across age groups, sleep-memory associations were similar for sleep measurement methods, however, associations were stronger for PSG than self-report. Age group moderated sleep-memory associations for certain sleep parameters. Specifically, young adults demonstrated stronger positive sleep-memory associations for slow wave sleep than the old, while older adults demonstrated stronger negative associations between greater wake after sleep onset and poorer memory performance than the young. Collectively, these data show that young and older adults maintain similar strength in sleep-memory relationships, but age impacts the specific sleep correlates that contribute to these relationships.

1. Introduction

The role of sleep in remembering the details of past, personally experienced events, or episodic memory, has been firmly established (for review, Rasch and Born, 2013). Previous studies have used experimental protocols that involve manipulating sleep through sleep deprivation (Bonnet and Rosa, 1987; Yoo et al., 2007), sleep restriction (Alberca-Reina et al., 2015), morning vs. evening memory testing protocols (Aly and Moscovitch, 2010; Wilson, Baran, Pace-Schott, Ivry, & Spencer, 2012), and to a lesser extent, introducing naps between encoding and retrieval (Payne et al., 2015; Scullin et al., 2017). While these studies have established that young adults typically experience a sleep-dependent episodic memory benefit, the relationship between sleep and episodic memory in older adults is less clear. Indeed, there is often no observable benefit of sleep for episodic memory performance in older adults (for review, Scullin and Bliwise, 2015a, b, c). However, studies using manipulations of sleep quality and/or duration may omit potentially important information about individual differences in one's sleep patterns that may contribute to the episodic memory performance across age.

Researchers have debated whether aging influences the relationship between sleep quality and memory performance. For example, in their narrative review, Scullin and Bliwise (2015a, b, Scullin and Bliwise, 2015c have argued that neural changes in advanced age may weaken the sleep-memory link. Specifically, age-related neural decline may disrupt sleep-based memory consolidation that is dependent upon intact neural function (e.g., memory transfer from the hippocampus to the neocortex). This is the first meta-analysis to directly address the relationship between sleep quality and memory performance across different stages of the adult lifespan. Assessing these individual differences in sleep-memory associations in young and older adults may help to better inform our understanding of age group differences, or lack thereof, in sleep-memory associations. Moreover, it is currently unknown if methodological parameters (e.g., sleep quality measurement, memory task characteristics) modulate the strength of the sleep-memory association. The goals of this systematic review and meta-analysis are two-fold: to determine if there are age group differences in the magnitude of sleep-memory associations and to assess the strength of sleep-memory

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associations for different study characteristics. This newfound knowledge may help to inform early intervention protocols. For example, if certain sleep and memory measures are shown to be particularly associated with memory performance in old age, they could be utilized in research studies or medical wellness visits to track change over time and apply tailored interventions.

1.1. Sleep study characteristics

1.1.1. The importance of individual differences

Older adults tend to have reduced sleep efficiency and poorer self-reported sleep quality as compared to young adults (Ohayon et al., 2004; Vitiello, 2006). Similarly, older adults tend to perform more poorly on episodic memory tasks than young adults (for a review, Duarte and Dulas, 2020). Episodic memory is typically defined as the memory for specific events and experiences that occurred at particular places and times (e.g., Tulving, 1993). A typical assessment method of episodic memory performance involves deciding whether a previously presented stimulus is old or new. Another episodic memory assessment method includes recalling the stimulus with which an item was previously paired (i.e., cued recall) or recalling previously presented stimuli with no cues (i.e., free recall). There are substantial individual differences in both episodic memory performance and sleep quality (for reviews: Lindenberger, 2014; van Dongen et al., 2005). There are older adults who sleep similarly well, or even better, than some young adults (Ohayon et al., 2004). Thus, research that is limited to sleep manipulations does not capture whether both young and older adults demonstrating better sleep quality show better episodic memory performance. In the current meta-analyses, we include studies that use an individual-differences approach to assess sleep-memory associations.

1.1.2. Sleep measurement methods and protocols

1.1.2.1. Sleep measurement methods. While the association between sleep quality and memory performance has been well established in young adults (for reviews: Rasch and Born, 2013; Scullin and Bliwise, 2015a, b, c), it is currently unclear whether certain sleep assessment methods or protocols reveal stronger associations between sleep quality and memory performance than others. The gold standard for sleep measurement, polysomnography (PSG), allows for the assessment of neural sleep signatures. While there is relatively little work investigating older adults as compared to young adults, current evidence suggests that individual differences in sleep physiology have been associated with those in episodic memory in older adults. For example, older adults demonstrate an association between episodic memory performance and time spent in sleep stages (e.g., slow wave sleep) and measures of sleep architecture (e.g., sleep spindles; for a review, Mander et al., 2017). Other studies have found no such associations in older adults compared to young adults (Baran et al., 2016; Gui et al., 2019; Scullin, 2013; Scullin et al., 2017). There may be specific conditions required to capture sleep-memory associations, however. For example, one study found a positive association between minutes spent in rapid eye movement (REM) sleep and episodic memory performance for object-location pairs only in high performing older adults (Sonni and Spencer, 2015a, b). While PSG is considered the gold standard for sleep measurement, it is important to note that most PSG studies require participants to sleep in the lab environment and are often given no lab adaptation night, or a single night to become accustomed to the sleeping in the lab, which may result in poorer sleep than any subsequent nights (Agnew et al., 1966; Riedel et al., 2001; Tamaki et al., 2005). Neither actigraphy nor self-report have these constraints.

Actigraphy is an objective sleep measurement method in which sleep quality and quantity can be measured over extended time periods (e.g., one week or more) in a relatively unobtrusive manner. These studies tend to find positive associations between sleep quality and episodic memory performance in older adults (Cavuoto et al., 2016; Hokett and Duarte, 2019; Wilckens et al., 2014), sometimes reporting stronger associations for older adults than young adults (Hokett and Duarte, 2019; Wilckens et al., 2014). For example, greater average sleep continuity, over one week, is related to greater memory recall in older adults, but not young adults (Wilckens et al., 2014). Similarly, we have found that greater night-to-night sleep stability is related to better memory performance only in older adults (Hokett and Duarte, 2019). Thus, episodic memory performance may be more sensitive to sleep quality in older adults than young adults for actigraphy-based measurements of sleep. However, it should be taken into account that actigraphy relies on movement to distinguish sleep from wake, and sleep may be overestimated if one is, for example, lying still while awake (Sadeh, 2011). This limitation of actigraphy may be particularly evident for older adults with sleep disorders (Sivertsen et al., 2006; Taibi et al., 2013).

Unlike PSG and actigraphy, self-reported sleep quality relies on participants' judgments about their sleep quality and quantity. Studies have shown relationships between self-reported sleep quality and episodic memory performance that may be particularly strong in older adults (Klaming et al., 2017; Mary et al., 2013). For example, poorer cued recall performance has been linked to greater nighttime awakenings in older adults, but not young adults (Mary et al., 2013). However, it is important to note that self-reported sleep quality has limitations compared to PSG and actigraphy, namely self-reported sleep quality is a subjective measurement that requires participants to assess their own sleep quality, which is often inaccurate (Baker et al., 1999; Matthews et al., 2018). In the current meta-analysis, we will determine whether potential differences in the strength of sleep-memory associations exist between these sleep measurement methods.

1.1.2.2. Sleep opportunity length. The length of the sleep period could contribute to differences in the magnitude of sleep-memory relationships. For example, sleep quality metrics from a full night of sleep may be more strongly related to episodic memory performance than those from a nap. In one study, when stories were encoded in the evening and recalled the following morning after a full night of sleep, older adults showed a relationship between sleep duration and memory recall, but young adults did not show the same relationship (Aly and Moscovitch, 2010). Limited research suggests that older adults do not show sleep-memory associations when sleep quality is measured for a short time period (i.e., nap) while young adults do show strong sleep-memory associations when the sleep opportunity is limited to a nap (Baran et al., 2016; Scullin et al., 2017). Moreover, recent research has shown that longer sleep opportunities, specifically nine hours in bed, may allow for positive associations with prospective memory performance and sleep quality in adults across the lifespan (Scullin et al., 2019). Thus, sleep opportunity length may modulate sleep-memory association strength. The present meta-analysis will assess whether sleep-memory association strength differs based on whether the sleep opportunity is a full night or more compared to when the sleep opportunity is limited to a nap and if there are any age-related differences in sleep-memory associations for full nights of sleep or naps.

1.2. Sleep quality and episodic memory measures

1.2.1. Sleep quality and memory phase

Some memory phases may be more sensitive to sleep quality than others. Faster learning acquisition rate has been linked with greater slow wave sleep in young adults (Lerner et al., 2016). This result is consistent with previous research showing reduced recognition performance for young adults who were sleep deprived prior to encoding compared to those who slept normally (Yoo et al., 2007). Researchers have proposed that sleep before encoding prepares the brain to learn and allows the hippocampus to restore its encoding capacity, while sleep deprivation does not allow for this restoration, making encoding more difficult (for a

review, Saletin and Walker, 2012). Studies investigating episodic retrieval have also revealed positive associations between sleep and both short (e.g., 5−10 min; Hokett and Duarte, 2019; Wilckens et al., 2014) and long retention intervals (e.g., 12 h to several months; Igloi et al., 2015; Takashima et al., 2006), but it is currently unknown if the magnitude of these associations varies based on whether retrieval is immediate or delayed. The current meta-analysis will investigate whether sleep-memory association strength differs according to memory phase.

1.2.2. Sleep quality and episodic memory assessment methods

Episodic memory tasks that probe for specific details about prior events, such as the perceptual or semantic context features of the memory, compared to familiarity for the events themselves, are most sensitive to the effects of age (Bender et al., 2010; Duarte and Dulas, 2020; Koen and Yonelinas, 2014; Mitchell and Johnson, 2009). Some research has shown that memory retrieval requiring more cognitive control may be more sensitive to sleep than memory retrieval placing fewer demands on cognitive control (for reviews: Diekelmann et al., 2009; Wilckens et al., 2012). Specifically, performance on high cognitive control tasks such as recollection-based memory tasks (Drosopoulos et al., 2005) and associative memory tasks (Sonni and Spencer, 2015a, b; Studte et al., 2015) is particularly sensitive to sleep in young adults. For example, participants who slept following encoding performed significantly better on a recollection-based memory task as compared to those who remained awake. Interestingly, there were no differences between sleep and wake groups for familiarity-based recognition, which is considered a low cognitive demand task (Drosopoulos et al., 2005).

Although memory tasks requiring high levels of cognitive control generally show a greater benefit of sleep, several studies have also shown reliable sleep-memory relationships in recognition memory tasks, which do not require recollection of specific episodic details in both young (Cellini et al., 2016; Takashima et al., 2006; Wagner et al., 2007) and older adults (Mander et al., 2013a; b). Thus, there is no clear consensus that more controlled memory tasks, such as those assessing recall, recollection, or associative memory, are more sensitive to sleep than tasks assessing recognition. In an effort to fully parse differences in the strength of these sleep-memory relationships, this meta-analysis will explore the magnitude of sleep-memory associations for associative recognition, non-associative recognition, associative recall, and non-associative recall. Moreover, it is largely unknown whether age moderates the strength of these associations. Furthermore, relationships between sleep quality and episodic memory performance have been observed for tasks involving various task and stimulus characteristics, including verbal (Cavuoto et al., 2016; Hokett and Duarte, 2019; Scullin, 2013) and pictorial stimuli (Gui et al., 2019; Igloi et al., 2015), as well as associative, non-associative, spatial, and non-spatial tasks (Sonni and Spencer, 2015a, b; van Dongen et al., 2011; Wilckens et al., 2014), but whether the magnitude of sleep-memory associations differs across these episodic task and stimulus characteristics is unknown. The present meta-analysis will explore potential differences in the strength of the relationship between sleep quality and episodic memory performance across these various episodic memory assessments.

1.3. The present study

The current literature shows that both young and older adults demonstrate associations between sleep quality and episodic memory performance, but whether the strength of the association differs between young and older adults is less clear (Scullin and Bliwise, 2015a, b, c). There is currently no consensus as to the conditions that result in age differences in sleep-memory relationships. A recent meta-analysis found that older adults do not show a sleep benefit in episodic memory performance (Gui et al., 2017). However, this study was limited to studies that compared sleep with wake groups and did not examine individual differences in the quality of the sleep period. As discussed above, individual differences in both sleep and memory are well known across age, but the strength of these associations require further investigation. The present meta-analysis is the first to quantify the magnitude of associations between individual differences in measures of sleep quality and episodic memory performance in young and older adults. We further assess the moderating influences of different episodic memory task characteristics and sleep measurement methods and protocols on these associations. The present meta-analysis will resolve discrepancies about age group differences in relationships between episodic memory performance and sleep quality by quantifying these effects.

We systematically investigated two primary research questions. First, do sleep-memory associations for different sleep protocols (e.g., sleep measurement method; sleep measurement length) differ by age? Across age groups, do certain sleep measurement methods, parameters, or protocols result in stronger sleep-memory associations than others?

Second, we investigated the relationship between sleep quality and different measures of episodic memory. To which episodic memory measures (e.g., recall vs recognition, associative vs non-associative) is sleep quality most sensitive? Are certain phases of episodic memory (e.g., encoding, immediate retrieval, delayed retrieval) more strongly related to measures of sleep quality than other memory stages? Do these sleep-memory relationships for episodic memory measures change as function of age group?

To quantify these associations, a three-level, random effects model was employed, which allows for multiple effect sizes from single studies to be included (Cheung, 2014a, 2014b). For example, effect sizes from studies using both recall and recognition measures were able to be assessed with this model. This is the first meta-analysis to use this approach to investigate sleep-memory associations in young and older adults.

2. Method

2.1. Search strategy

The search strategy involved obtaining empirical research articles from PubMed and recent, relevant review articles (Mander et al., 2017; Scullin, 2017; Scullin and Bliwise, 2015a, b, c). The inclusionary criteria required that articles: (a) include a sample of either young (18–40), middle-aged and older (41+) adults, or both age groups with results reported separately for young and middle-aged to older adults (See Appendix A for mean ages and/or age ranges), (b) report sleep quality using self-report, actigraphy, or polysomnography (PSG), (c) report episodic memory performance measured in a way that involves accurate memory for past events using verbal or pictorial stimuli and assesses memory performance using methods such as free recall, cued recall, remember/know decisions, old/new decisions, intact/rearranged decisions, prior context judgements, and spatial navigation (d) report individual differences using correlations or regression. Exclusionary criteria were: (a) cognitive impairment (e.g., Mild Cognitive Impairment) or neurological disease (e.g., Traumatic Brain Injury or Alzheimer's Disease), (b) sleep disorders (e.g., insomnia, sleep apnea), (c) uncontrolled mood disorders or anxiety, (d) absence of an adult (18+ years) sample or absence of separated age groups when reporting statistics, (e) absence of an episodic memory measure (e.g., only working memory or executive function measure), and (f) manipulation of natural sleep quality (e.g., drug-induced sleep, brain stimulation, sleep deprivation). The search criteria were aimed to match the inclusionary and exclusionary criteria. The search terms that were used are as follows: sleep OR "sleep quality" OR "sleep EEG" OR polysomnography OR actigraphy OR "subjective sleep" OR "self-reported sleep" OR "sleep pattern" OR "sleep continuity" OR "sleep fragmentation" OR awakenings OR "k complex" OR "slow wave activity" OR" sleep spindle") AND (“episodic memory” OR "paired associates" OR "autobiographical memory" OR "context memory" OR "associative memory" OR recognition OR recollection OR recall OR "spatial navigation" OR retention OR

"declarative memory") NOT "sleep deprivation" NOT insomnia NOT "sleep disorder" NOT "sleep apnea" NOT MCI NOT "cognitive impairment" NOT "Alzheimer's disease" NOT "psychological disorder" NOT "mood disorder" NOT drug NOT adolescent NOT children NOT epilepsy NOT "dream recall" NOT infant NOT patients NOT ill NOT stroke NOT "traumatic brain injury" NOT PTSD NOT depression NOT schizophrenia NOT dementia NOT Parkinson's NOT "procedural memory" NOT dream NOT Review NOT commentary NOT meta-analysis NOT rodent NOT rat NOT drosophila NOT animal. The search for research articles concluded in September of 2019.

Following the search, 837 articles were assessed for inclusion in the meta-analysis. Of these, 796 articles were excluded, leaving 41 independent studies. Each study was independently assessed for inclusion/exclusion by three separate reviewers. EH reviewed 837 studies, and AA and JC each reviewed half of the 837. Inter-rater agreement for the articles was 95 %. Disagreements among the reviewers was resolved through discussion. We included an additional 13 independent studies from review articles on sleep-memory associations, resulting in a total sample of 54 independent studies (Mander et al., 2017; Scullin, 2017; Scullin and Bliwise, 2015a, b, c). See Fig. 1.

2.2. Moderators

We ran separate moderation models for each analysis discussed below. With the moderation analyses, we assessed two primary research questions involving sleep quality and episodic memory performance:

The **first** primary question explored whether there were age group differences in the relationship between sleep quality and episodic memory performance for various sleep quality conditions. To this end, several moderators were examined, including: sleep quality measurement method (PSG, actigraphy, self-report); and sleep quality parameters (sleep continuity [e.g., awakenings, sleep efficiency (SE), wake after sleep onset (WASO)], stages [e.g., Stages 1 and 2, REM, NREM, SWS] and architecture [e.g., spindle density]. In addition, the length of PSG and actigraphy data collection was assessed as a moderator by examining moderation effects for a full night of sleep vs a nap..

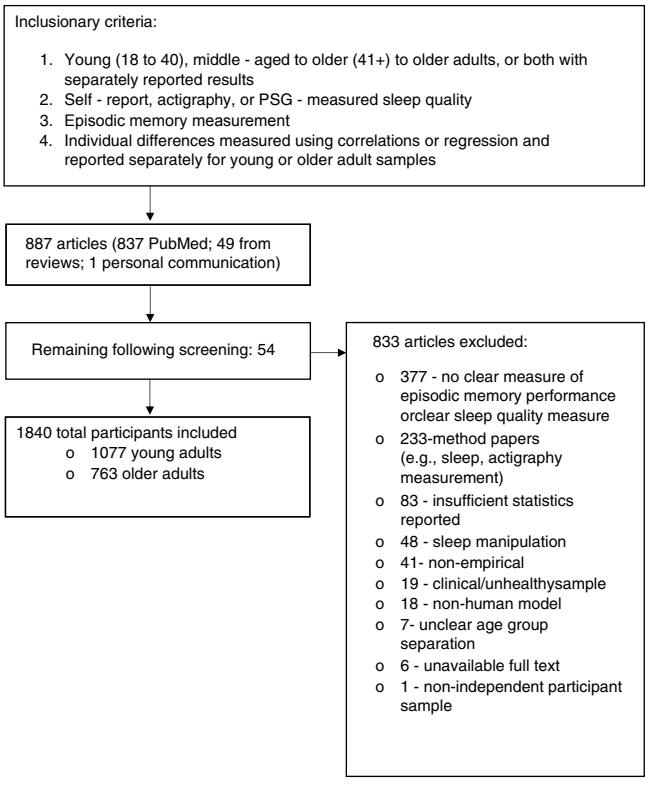

Fig. 1. Data Selection Process for Meta-Analysis.

In addition to examining age-group differences in sleep-memory associations by sleep quality measures, the same sleep variables were examined across age groups. Specifically, differences in the strength of sleep-memory associations for sleep measurement methods, protocols, and parameters were assessed. To examine differences in sleep-memory associations by sleep quality measures, moderation analyses were employed for sleep parameter groups, including sleep continuity, sleep duration and initiation, general sleep quality, sleep stages, and sleep architecture. These sleep parameter groups were developed based on theoretical categorization and to allow for more statistical power for the present meta-analysis. Variable definitions were summarized based on their respective studies (See Table 1). This method was used to determine if different sleep parameter groups resulted in stronger sleep-memory associations than others. Furthermore, the difference in magnitude for sleep-memory associations within sleep groups were examined. For example, within the sleep stages group, the sleep-memory association for slow wave sleep was compared to that for REM sleep. These analyses were collapsed across all measures of episodic memory performance.

The **second** primary question involved the impact of episodic memory task characteristics (e.g., recall vs recognition, associative vs non-associative) and memory phase (encoding, immediate retrieval, delayed retrieval) on sleep-memory associations. For this analysis, age group differences were examined in sleep-memory associations by each episodic memory measure and memory phase. Moreover, across age groups, episodic memory task characteristics and phase were assessed as potential moderators for the sleep-memory associations. For example, moderation analyses were used to determine differences in the magnitude of sleep-memory associations for recall as compared to recognition. See Table 2 for all moderator variables for episodic memory measures. To maintain statistical power, these analyses were collapsed across all sleep quality measures.

2.3. Variable definitions

To examine the aforementioned associations, the variables of interest were operationally defined. The variables included sleep quality and episodic memory performance. Refer to Tables 1 and 2 for definitions for each measure. Because there were only four studies that included adults in the middle-aged category (e.g., mean age within the 40–60 age range), age was not treated as a continuous variable, but dichotomized into a young adult group (mean age = 22) and an older adult group (mean age = 69). If the mean age was not reported, mean age was estimated as the mean of the age range.

2.4. Data analysis

Pearson's r statistics were extracted from independent studies for associations with sleep quality and episodic memory measures. Using Pearson's r, Fisher's z was calculated using an effect size calculator and a statistical toolbox (Lüdecke, 2018). If Pearson correlations were not reported, Fisher's z was estimated using the reported statistics, such as partial r, Spearman's rank, Kendall's tau, and β. Partial r, Spearman's rank, and β were treated as Pearson correlations to estimate Fisher's z. Authors were emailed for missing data. When authors did not respond or no longer had access to the data, the r statistic was estimated using graphing software (https://apps.automeris.io/wpd/) from correlational plots. For aggregation purposes, correlations for measures of sleep disturbance were inversed so that positive effect sizes reflect that sleep has a beneficial relationship with episodic memory performance, while negative effect sizes reflect the opposite. This was necessary to allow for aggregation among measures that may encompass measures of consolidated (e.g., SE) and fragmented (e.g., WASO) sleep quality.

Random-effects models were used to estimate the relationship between sleep quality and episodic memory across studies. This method

Table 1
Variable Definitions for Sleep Parameters.

Variable Group	Variable	Definition
Sleep Continuity	Sleep Efficiency	percent of time asleep while in bed
	Wake after sleep onset	minutes spent awake after initially falling asleep
	Awakenings	frequency of wake periods
	Sleep Disturbance	PSQI-defined sleep disturbance
	Transitions	transitioning into lighter sleep stages; frequency of sleep stage transitions
Sleep Duration and Initiation	Sleep Onset Latency	time taken to fall asleep
	Sleep Duration	total time spent asleep
General Sleep Quality	Global Sleep Quality	subjective average of sleep quality measures
	Sleep Quality Composite	general measure of sleep quality as an average of sleep parameters
	Tiredness Upon Awakening	subjective tiredness rating
	Freshness Upon Awakening	subjective rating of feeling well rested
Sleep Stages	Stage 1	sleep stage composed of low amplitude mixed frequency brain activity; percentage or duration spent in Stage 1
	Stage 2	sleep stage characterized by sleep spindles and K complexes; percentage or duration spent in Stage 2
	Slow Wave Sleep	sleep stage defined by high amplitude, low frequency slow waves; percentage or duration spent in Slow Wave Sleep
	REM Sleep	sleep stage defined by rapid eye movements, low muscle tone, and low amplitude mixed frequency waves; percentage or duration spent in REM sleep
	NREM Sleep	sleep measures collapsed across Stages 1, 2, and/or slow wave sleep; percentage or duration spent in NREM sleep
Architecture	Spindle Density	frequency or proportion of spindles during a sleep period or during a specific sleep stage
	Spindle Activity	measure capturing both spindle amplitude and duration (i.e., intensity)
	Spindle Activity Change	difference between spindle activity before and after experimental task
	Stage 2 Epochs With Spindles Change	difference between number of epochs within Stage 2 that contain spindles before and after experimental task
	Relative Slow Wave Activity	spectral power between 0.5 and 4.0 (to 4.6) Hz divided by absolute spectral power
	Slow Oscillation-Spindle Coupling	temporal proximity of slow oscillations and sleep spindles
	Brain Connectivity During Sleep	brain connectivity modelled during specific sleep stages
	Slow Oscillation Power	slow oscillation power increases/decreases as compared to trials without slow oscillations
	Spindle Power	power in the spindle frequency range (11–15 Hz)
	Delta Power	relative/absolute delta power (.5–4.5 Hz) during sleep period
	Theta Power	relative/absolute theta power (4.5–8.5 Hz) during sleep period
	Alpha Power	relative alpha power during nap
	Sigma Power	relative theta power during nap

NOTE: REM = rapid eye movement; NREM = non-rapid eye movement; Sleep stages are summarized based on the American Academy of Sleep Medicine. All sleep stage measurements correspond to sleep stage quantity.

Table 2
Variable Definitions for Memory Assessment Methods.

Variable Group	Variable	Definition
Memory Task Characteristics	Recall	reproduction of a previously presented stimulus
	Recognition	identification of a previously presented stimulus and/or rejection of new stimuli
	Associative	task that involves remembering two or more stimuli
	Non-Associative	task that involves remembering individual stimuli
	Associative Recall	reproduction of binded/related stimuli
	Non-Associative Recall	reproduction of individual stimuli
	Associative Recognition	identification of binded/related stimuli
	Non-Associative Recognition	identification of individual stimuli
	Verbal	task that only involve words
	Pictorial	task that only involves images
	Verbal + Pictorial	task that involves verbal and pictorial stimuli
	Spatial	task that requires remembering locations
	Non-Spatial	task that is independent of location
Memory Phase	Encoding	Initial learning; learning acquisition score
	Immediate Retrieval	retrieval performance after a short retention interval (less than 5 min)
	Delayed Retrieval	retrieval performance after a longer retention interval (greater than 5 min)

allows for variation in sampling characteristics and variation between studies. To allow for multiple effect sizes from single studies to be included, the three-level, random effects meta-analysis method was employed using the metaSEM package based in R (Cheung, 2014a). Specifically, this three-level model accounts for sampling variance among all effect sizes (level 1), sampling variance between effect sizes within a given study (level 2), and sampling variance between effect sizes across different studies (level 3). This method allows for a more representative meta-analysis in that multiple effect sizes within a study can be considered, even when there is overlap between variables, such as recognition and recall overlapping with associative and non-associative memory (e.g., associative recognition). Although multiple effect sizes within a given study are more likely to be similar, the three-level model controls for this by allowing for correlations within a cluster of effect sizes within the same study (Cheung, 2014b).

Using the three-level model, the mean effect size was calculated (measured as Pearson's correlations) with 95 % confidence intervals for each analysis, as well as the homogeneity statistic *Q*. To quantify the degree of heterogeneity at the level of measures and studies, $I^2_{(2)}$ (heterogeneity related to measures within studies) and $I^2_{(3)}$ (heterogeneity across studies) were computed. Note that in some instances, notably when the sample of effect sizes of studies was extremely small, computation of these heterogeneity indices failed to converge; in that case, these indices were not reported. When appropriate, the amount of variance that was accounted for by moderators was reported using $R^2_{(2)}$ (level 2) and $R^2_{(3)}$ (levels 3).

3. Results

Unless otherwise specified, the following results are collapsed across all sleep measures and all episodic memory measures. All average estimates were converted from Fisher's *z* to Pearson's *r* to facilitate interpretation.

3.1. Average association between sleep quality and behavioral memory performance

There was a significant, positive relationship between sleep quality and episodic memory performance in 616 unique associations across 54 independent studies (Estimate = .20; CI: [.12–.27]; $p < .001$). To assess publication bias, regression analyses were employed to assess funnel plot asymmetry. Significant publication bias was detected ($z = 5.63$, $p < .001$; See Fig. 2). This analysis was followed with the trim-and-fill method (Duval and Tweedie, 2000; Shi et al., 2019). The L_0 estimator detected 42 outliers. However, the R_0 estimator found no evidence of outliers. There was significant heterogeneity among effect sizes ($Q(615) = 1562.77$, $p < .001$; $I^2_{(2)} = .24$ and $I^2_{(3)} = .46$), and thus, moderator analyses were conducted to account for this variability.

3.2. Sleep measure moderators for sleep-memory associations at the behavioral level

3.2.1. Does sleep-memory association strength differ by age?

To address the first question, age group was examined as a moderator for the mean effect size between sleep quality and episodic memory performance. There was no significant moderation effect of age group (slope = 0.02, CI: [-0.05 to .09], $p = .577$, $R^2_{(2)} < .000$ and $R^2_{(3)} = .003$; ($Q(615) = 1562.77$, $p < .001$); $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 54$ (616 effect sizes)); see Table 3. To further assess moderators for the sleep-memory association, several sleep quality measures were examined.

3.2.2. Does sleep-memory association strength differ according to sleep measurement method?

Next, sleep measurement method (PSG, actigraphy, self-report) was assessed as a moderator for sleep-memory associations across age groups. Sleep-memory associations for PSG were significantly greater than self-report (slope = -0.17, CI: [-.32 to -.007], $p = .041$, $R^2_{(2)} = .011$ and $R^2_{(3)} = .064$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 54$ (616 effect sizes)), but not actigraphy (slope = -0.09, CI: [-.22 to .03], $p = .141$, $R^2_{(2)} = .012$ and $R^2_{(3)} = .059$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 54$ (616 effect sizes)). There was no significant difference between actigraphy and self-report (slope = -0.07, CI: [-.24 to .09], $p = .393$, $R^2_{(2)} = .012$ and $R^2_{(3)} = .059$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 54$ (616 effect sizes)); See Table 4.

There were no age group differences for PSG (slope = 0.04, CI: [-.04 to .13], $p = .338$, $R^2_{(2)} = .005$ and $R^2_{(3)} < .000$; ($Q(557) = 1441.67$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.07$, $p < .001$, $k = 45$ (558 effect sizes)) or actigraphy (slope = -.11, CI: [-.26 to .04], $p = .166$, $R^2_{(2)} = .173$ and $R^2_{(3)} = 1.000$; ($Q(37) = 60.247$, $p = .009$), $\tau^2_{(2)} = -0.01$, $p = .173$; $\tau^2_{(3)} < 0.00$, $p = 1.00$, $k = 6$ (37 effect sizes)). Because there were only 8 behavioral studies and 20 effect sizes with self-report data, age group differences were not assessed for self-report.

3.2.3. Do different sleep protocols impact sleep-memory associations?

Moderator analyses were conducted to determine if sleep protocol (naps vs. full night) modulated the strength of the sleep-memory association. There were no significant differences in sleep-memory associations for naps and full nights (slope = 0.09, CI: [-.07. to .26], $p = .278$, $R^2_{(2)} < .000$ and $R^2_{(3)} = .025$; ($Q(595) = 1506.64$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 50$ (596 effect sizes)). See Table 5 for sleep-memory association estimates for naps and full nights of sleep.

To further explore differences in sleep-memory associations by sleep protocol, age group was assessed as a moderator to determine whether

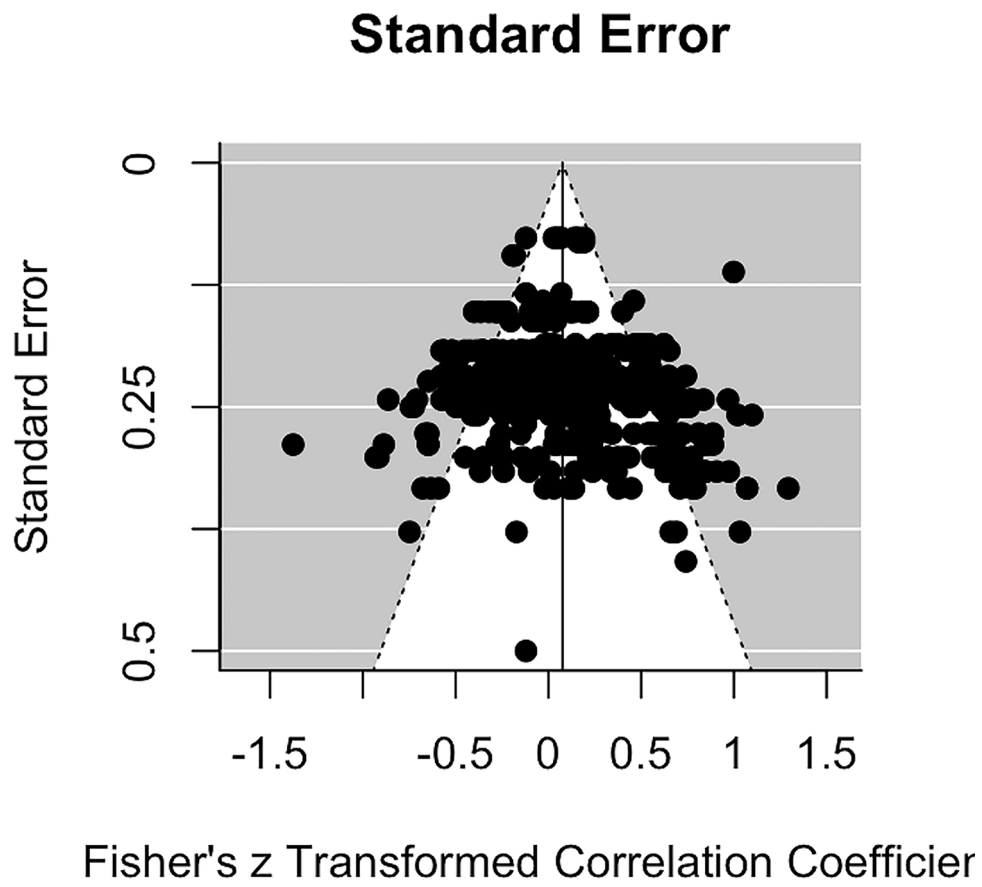

Fig. 2. Funnel plot showing the standard errors of effect sizes between sleep quality and episodic memory performance with the 95 % confidence interval (dashed lines).

Table 3
Examination of age group differences in the average Pearson correlation between sleep quality and episodic memory performance with the 95 % confidence interval.

	Young						Old					
Measure	r	LL	UL	k	j	p	r	LL	UL	k	j	p
Behavioral Average	0.18	0.09	0.27	21	159	<.001	0.20	0.12	0.28	45	457	<.001

NOTE: LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

Table 4
Average Pearson correlation between episodic memory performance and sleep quality for select sleep measurement methods with the 95 % confidence interval.

Sleep Measure	r	LL	UL	k	j	p
PSG	0.22	0.14	0.29	45	558	<.001
Actigraphy	0.13	−0.01	0.26	6	38	0.07
Self-Report	0.05	−0.11	0.21	8	20	0.51

NOTE: PSG = polysomnography; LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

Table 5
Average Pearson correlation between episodic memory performance and sleep quality by sleep protocol with the 95 % confidence interval.

Sleep Protocol	r	LL	UL	k	j	p
Full Night	0.17	0.07	0.27	32	362	<.001
Nap	0.26	0.13	0.38	18	234	<.001

NOTE: LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

effect sizes differed by age group for when the sleep opportunity length was a full night or nap for PSG and actigraphy-measured sleep. There were no significant age group differences for sleep-memory associations based on full nights (slope = 0.007, CI: [-.083 to .10], $p = .872$, $R^2_{(2)} < .000$ and $R^2_{(3)} < .000$; ($Q(361) = 914.90$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.07$, $p = .008$, $k = 32$ (362 effect sizes)) or nap protocols (slope = 0.06, CI: [-.08 to .20], $p = .432$, $R^2_{(2)} < .000$ and $R^2_{(3)} = .032$; ($Q(233) = 591.29$ $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .000$; $\tau^2_{(3)} = 0.06$, $p = .016$, $k = 18$ (234 effect sizes)). See Table 6.

3.2.4. Are there differences in sleep-memory associations by specific sleep quality measures?

Specific sleep parameters were assessed as moderators the relationship between sleep quality and episodic memory performance. For example, the strength of sleep-memory associations for certain sleep parameter groups (e.g., sleep continuity) were compared to that of others (e.g., sleep stages). Then, moderator analyses were conducted to assess differences in sleep-memory associations by specific sleep parameters within sleep groups (e.g., comparison of sleep-memory association for REM sleep as compared to slow wave sleep; See Table 1). There was a significant moderation effect for categorical group. Measures of sleep architecture had stronger effect sizes for sleep-memory associations than sleep continuity (slope = -0.19, CI: [-.30 to -.08], $p < .001$, $R^2_{(2)} = .042$ and $R^2_{(3)} = .163$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.05$, $p < .001$, $k = 54$ (616 effect sizes)); sleep duration and initiation (slope = -0.16, CI: [-.26 to -.06], $p = .002$, $R^2_{(2)} = .042$ and $R^2_{(3)} = .163$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.05$, $p < .001$, $k = 54$ (616 effect sizes)); general sleep quality (slope = -.24, CI: [-.41 to -.08], $p < .001$, $R^2_{(2)} = .042$ and $R^2_{(3)} = .163$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.05$, $p < .001$, $k = 54$ (616 effect sizes)); and sleep stages (slope = -0.14, CI: [-.22 to -.07], $p = .009$, $R^2_{(2)} = .042$ and $R^2_{(3)} = .163$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.05$, $p < .001$, $k = 54$ (616 effect sizes)). There were no other significant differences between sleep groups. See Table 7.

Next, we assessed differences within sleep parameter groups. For the sleep duration and initiation group, there was no significant difference in sleep-memory associations between sleep duration and sleep onset latency (slope = -0.09, CI: [-.02 to .02], $p = .097$, $R^2_{(2)} = 1.000$ and $R^2_{(3)} < .000$; ($Q(63) = 98.20$, $p = .003$), $\tau^2_{(2)} < 0.000$, $p = 1.000$; $\tau^2_{(3)} = 0.05$, $p = .061$, $k = 17$ (64 effect sizes)). In the sleep stages group, REM sleep had weaker effect sizes for sleep-memory associations than slow wave sleep (slope = 0.13, CI: [.04 to .22], $p = .006$, $R^2_{(2)} = .064$ and $R^2_{(3)} = .182$; ($Q(302) = 721.59$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.03$, $p = .030$, $k = 28$ (303 effect sizes)); NREM sleep (slope = 0.20, CI: [.08 to .31], $p = .007$, $R^2_{(2)} = .064$ and $R^2_{(3)} = .182$; ($Q(302) = 721.59$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.03$, $p = .030$, $k = 28$ (303 effect sizes)); and Stage 1 sleep (slope = 0.18, CI: [.05 to .30], $p = .034$, $R^2_{(2)} = .064$ and $R^2_{(3)} = .182$; ($Q(302) = 721.59$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.03$, $p = .030$, $k = 28$ (303 effect sizes)). REM sleep had marginally weaker effect sizes for sleep-memory associations compared to Stage 2 sleep (slope = 0.10, CI: [-.003 to .21], $p = .058$, $R^2_{(2)} = .064$ and $R^2_{(3)} = .182$; ($Q(302) = 721.59$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.03$, $p = .030$, $k = 28$ (303 effect sizes)). There were no other notable differences in sleep-memory associations within the sleep stages group. See Table 8 for the average effect size of sleep-memory associations by sleep parameter.

To determine if there were age group differences in the strength of sleep-memory associations by parameter group, age group was assessed as a moderator for each sleep group. There were no significant age group differences in sleep-memory associations for any of the sleep parameter groups (p's > .065; See Table 9 for average estimates of sleep groups by age group).

Table 7
Average Pearson correlation between episodic memory performance and sleep quality for select sleep parameter groups with the 95 % confidence interval.

Sleep Parameter Group	r	LL	UL	k	j	p
Sleep Continuity	0.11	0.00	0.21	12	63	0.05
Sleep Duration and Initiation	0.14	0.04	0.24	17	64	.007
Sleep Stages	0.15	0.07	0.23	28	303	<.001
Sleep Architecture	0.28	0.20	0.36	25	166	<.001

NOTE: LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

Table 6
Examination of age-related differences in average Pearson correlation for sleep-memory associations by sleep protocol with the 95 % confidence interval.

	YA						OA					
Sleep Protocols	r	LL	UL	k	j	p	r	LL	UL	k	j	p
Full night	0.18	0.07	0.28	25	257	.001	0.17	0.05	0.28	16	105	.005
Nap	0.26	0.14	0.38	18	195	<.001	0.21	0.02	0.38	2	39	.026

NOTE: LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

Table 8
Average Pearson correlation between episodic memory performance and select sleep parameters with the 95 % confidence interval.

Sleep Parameter	r	LL	UL	k	j	p
Wake After Sleep Onset	0.11	−0.03	0.24	8	25	.11
Sleep Onset Latency	0.16	0.01	0.30	7	19	.03
Sleep Duration	0.11	0.00	0.22	16	45	.06
Stage 1	0.20	0.07	0.32	10	28	.002
Stage 2	0.15	0.04	0.26	16	45	.009
Slow Wave Sleep	0.16	0.07	0.26	20	82	<.001
REM sleep	0.02	−0.07	0.12	16	108	.623
NREM sleep	0.20	0.08	0.31	11	42	<.001
Spindle Density	0.18	0.08	0.28	14	83	<.001

NOTE: All sleep stage estimates refer to the percentage or duration for the given sleep stage. LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes; REM = rapid eye movement sleep; NREM = non-rapid eye movement sleep.

Considering that the sleep parameter groups were comprised of several measures, examining age group differences in sleep-memory associations based on these groups only could mask differences in individual sleep parameters. Thus, age group differences in sleep-memory associations for each individual sleep parameter were examined as well. There was a significant moderation effect for WASO (slope = -0.21, CI: [-.41 to -.010], $p = .040$, $R^2_{(2)} = 1.00$ and $R^2_{(3)} = .083$; ($Q(24) = 42.12$, $p = .009$), $\tau^2_{(2)} < 0.000$, $p = 1.00$; $\tau^2_{(3)} = .03$, $p = .263$, $k = 8$ (25 effect sizes)), demonstrating that older adults show stronger sleep-memory associations with this sleep measure than young adults. Given that there were only 8 studies with the WASO measure, this result is primarily descriptive and should be taken with caution. Differing from WASO, young adults demonstrated stronger effect sizes for the relationship between slow wave sleep and episodic memory performance than older adults (slope = 0.32, CI: [.10 to .53], $p = .003$, $R^2_{(2)} = .225$ and $R^2_{(3)} < .000$; ($Q(81) = 214.65$, $p < .001$), $\tau^2_{(2)} = 0.05$, $p = .013$; $\tau^2_{(3)} = 0.03$, $p = .184$, $k = 20$ (82 effect sizes)). There were no other significant age group moderations for any other sleep parameters (See Table 10 for all average estimates of sleep-memory associations by sleep parameter).

3.3. Memory measure moderators for sleep-memory associations at the behavioral level

3.3.1. Do episodic memory assessment methods impact sleep-memory association strength?

To address the second question, differences in sleep-memory associations were assessed by memory task and stimulus characteristics and phase. Across both young and older adults, differences in behavioral task were assessed as a moderator for the relationship between sleep quality and episodic memory performance. First, memory task characteristics were assessed as moderators for sleep-memory relationships. No significant moderation effects were found for recall vs recognition tasks (slope = 0.04, CI: [-.05 to .13], $p = .362$, $R^2_{(2)} = .003$ and $R^2_{(3)} = .010$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 54$ (616 effect sizes)); associative vs non-associative tasks (slope = -0.063, CI: [-.16 to .03], $p = .182$, $R^2_{(2)} < .000$ and $R^2_{(3)} = .047$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 54$ (616 effect sizes)); or spatial vs non-spatial tasks (slope = -.04, CI: [-.18 to .10], $p = .615$, $R^2_{(2)} = .005$ and $R^2_{(3)} < .000$; ($Q(615) = 1562.77$, $p < .001$), $\tau^2_{(2)} = 0.03$, $p < .001$; $\tau^2_{(3)} = 0.06$, $p < .001$, $k = 54$ (616 effect sizes)). Memory task characteristics were further assessed by categorizing recall and recognition into associative or non-associative categories. There were no significant differences among associative recall, associative recognition, non-associative recall, or non-associative recognition (p's > .051). Furthermore, there were no significant differences among verbal, pictorial, or verbal + pictorial tasks (p's > .518); See Table 11 for all average effect sizes for sleep-memory associations by each memory task characteristic. There were no significant age group moderation effects for sleep-memory associations for any episodic memory task characteristic (p's > .090). See Table 12 for average effect sizes for all sleep-memory associations by memory task characteristic for age group.

3.3.2. Does episodic memory phase impact sleep-memory association strength?

The phase in which memory was tested was also assessed as a moderator. Encoding, immediate retrieval, and delayed retrieval were statistically equivalent to each other (p's > .329). See Table 11 for the average effect sizes for sleep-memory associations by each memory phase. There were no significant age group moderation effects for sleep-

Table 9
Examination of age group differences in average Pearson correlation for sleep-memory associations by sleep parameter group with the 95 % confidence interval.

	Young						Old					
Sleep Parameter Group	r	LL	UL	k	j	p	r	LL	UL	k	j	p
Sleep Continuity	−0.05	−0.22	0.12	6	20	.551	0.09	−0.06	0.23	10	43	.239
Sleep Duration and Initiation	0.13	−0.01	0.26	12	29	.071	0.09	−0.06	0.24	8	16	.244
Sleep Stages	0.13	0.04	0.21	26	240	.004	0.07	−0.06	0.19	7	63	.299
Sleep Architecture	0.26	0.12	0.39	23	154	<.001	0.35	0.07	0.57	7	12	.013

NOTE: LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

Table 10
Examination of age group differences in average Pearson correlation for sleep-memory associations by specific sleep parameters with the 95 % confidence interval.

	Young						Old					
Specific Sleep Parameter	r	LL	UL	k	j	p	r	LL	UL	k	j	p
Wake After Sleep Onset	−0.08	−0.27	0.13	4	9	.459	0.13	−0.03	0.29	7	16	.108
Sleep Duration	0.11	−0.03	0.25	11	29	.119	0.02	−0.14	0.18	9	16	.807
Stage 2	0.07	−0.09	0.24	13	37	.386	0.16	−0.13	0.41	4	8	.281
Slow Wave Sleep	0.18	0.06	0.30	18	64	.004	−0.13	−0.33	0.07	7	19	.196
REM	−0.07	−0.15	0.02	15	87	.112	−0.02	−0.17	0.13	5	23	.783
NREM	0.27	0.11	0.41	10	34	<.001	0.06	−0.21	0.33	4	8	.645
Spindle Density	0.18	0.02	0.33	14	82	.026	0.43	−0.42	0.88	1	1	.324

NOTE: All sleep stage estimates refer to the percentage or duration for the given sleep stage. LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes; REM = rapid eye movement sleep; NREM = non-rapid eye movement sleep.

Table 11
Average Pearson correlation for sleep-memory associations by episodic memory task measure with the 95 % confidence interval.

Memory Measure	r	LL	UL	k	j	p
Recall	0.18	0.09	0.26	30	291	<.001
Recognition	0.22	0.13	0.30	26	325	<.001
Associative	0.22	0.14	0.30	37	389	<.001
Non-Associative	0.16	0.06	0.25	20	227	.001
Associative Recall	0.18	0.07	0.28	20	201	.002
Non-Associative Recall	0.14	0.03	0.26	11	90	.02
Associative Recognition	0.27	0.15	0.37	17	188	<.001
Non-Associative Recognition	0.18	0.07	0.28	10	134	<.001
Spatial	0.23	0.08	0.36	6	50	.002
Non-Spatial	0.19	0.12	0.27	49	566	<.001
Verbal	0.22	0.12	0.33	28	333	<.001
Pictorial	0.17	0.05	0.29	20	243	.10
Verbal + Pictorial	0.16	−0.06	0.36	7	40	.16
Encoding	0.34	0.03	0.59	3	16	.03
Immediate Retrieval	0.19	0.08	0.28	14	92	<.001
Delayed Retrieval	0.19	0.11	0.27	51	508	<.001

NOTE: LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

memory associations for memory phase (p's > .369). See Table 12 for average effect sizes for all sleep-memory associations by memory phase and age group.

4. Discussion

The present meta-analysis assessed how multiple factors, including sleep and memory assessment method and age, affect the association between individual differences in sleep quality and episodic memory performance. Specifically, this meta-analysis assessed (1) if young and older adults demonstrate similar associations between sleep quality and episodic memory performance and (2) if differences in study characteristics (e.g., sleep parameters, memory task and stimulus characteristics) influence the strength of sleep-memory associations across age. This is the first meta-analysis to investigate these questions. Although sleep assessment method (actigraphy, PSG, self-report) did not impact the strength of sleep-memory associations, age group moderated these associations for different sleep quality parameters. Specifically, whereas young adults demonstrated greater sleep-memory associations for slow wave sleep, older adults demonstrated greater sleep-memory associations for WASO. Across age, sleep-memory associations for measures of sleep architecture were greater than that for all other sleep categories (see Table 1). Future directions and implications of these findings will be discussed below.

4.1. Do different sleep protocols modulate sleep-memory association strength?

Sleep-memory associations can be measured using various sleep protocols. For example, there are differences across sleep and memory studies in sleep assessment method (PSG, actigraphy, self-report) and sleep opportunity length (full night, nap). Regarding sleep assessment method, the present meta-analysis found no age group differences in sleep-memory associations for PSG or actigraphy. Because of fewer effect sizes for self-report, age group differences in sleep-memory associations for self-report measures could not be calculated. Across age groups, relationships between sleep quality and memory performance were statistically similar for PSG, actigraphy, and self-report. However, sleep-memory associations were significantly stronger for PSG-measured sleep quality as compared to self-report. This finding is not surprising, as PSG is typically referred to as the gold standard of sleep quality measurement. Self-reported sleep is often linked to overestimation of sleep duration and underestimation of sleep disruption (Jackson et al., 2018; King et al., 2017). Nonetheless, significant associations between sleep quality and episodic memory performance have been found for PSG (Mander et al., 2013a; b; Scullin, 2013; Scullin et al., 2017), actigraphy (Cavuoto et al., 2016; Hokett and Duarte, 2019; Wilckens et al., 2014), and self-report measures (Klaming et al., 2017; Mary et al., 2013). However, it is important to note that each of these measurement methods is heterogeneous, considering that each measurement method can assess multiple metrics of sleep quality. Some sleep parameters can be measured using various methods. For example, sleep continuity (e.g., number of awakenings) could be assessed with self-report, actigraphy or PSG. Thus, some sleep-memory associations may be moderated by specific sleep parameters or parameter categories instead of measurement method, which necessitates additional moderation analyses including these sleep parameters (described below).

Previous research has not investigated whether the measured sleep duration (i.e., nap or full night) affects sleep-memory associations. As compared to naps, one might suspect that full nights of sleep would result in greater sleep-memory associations, particularly for older adults (e.g., Aly and Moscovitch, 2010). Some research has shown that naps may support memory performance for young but not older adults (Baran et al., 2016; Scullin et al., 2017). However, in the present meta-analysis, no significant differences in sleep-memory associations were found for full nights of sleep as compared to naps. Research in young adults has shown that naps and full nights of sleep may yield similar episodic memory benefits (Payne et al., 2015; van Schalkwijk et al., 2019). For example, there was a similar benefit for both nap and overnight sleep for emotional memory performance compared to wake periods in young adults (Payne et al., 2015). However, there are few studies investigating associations between sleep and memory performance for naps,

Table 12
Examination of age group differences in the average Pearson correlation for sleep-memory associations by episodic memory task measure with the 95 % confidence interval.

	Young						Old					
Memory Measure	r	LL	UL	k	j	p	r	LL	UL	k	j	p
Recall	0.18	0.06	0.30	23	180	.003	0.12	−0.01	0.25	14	111	.073
Recognition	0.20	0.10	0.29	24	277	<.001	0.24	0.10	0.37	8	48	<.001
Associative	0.24	0.14	0.34	32	292	<.001	0.21	0.09	0.33	14	97	<.001
Non-Associative	0.11	0.01	0.20	16	165	0.02	0.10	−0.03	0.22	7	62	0.13
Associative Recall	0.24	0.07	0.39	17	127	.005	0.17	−0.01	0.34	8	74	0.069
Associative Recognition	0.22	0.09	0.34	15	165	.001	0.31	0.12	0.48	6	23	.002
Non-Associative Recognition	0.16	0.03	0.29	11	112	.02	0.16	−0.03	0.34	2	25	0.11
Verbal	0.16	−0.03	0.34	19	201	<.001	0.01	−0.21	0.23	16	132	<.001
Pictorial	0.18	0.06	0.31	20	226	.004	0.01	−0.21	0.23	3	17	0.91
Spatial	0.11	−0.25	0.45	6	36	.55	−0.11	−0.50	0.32	2	14	0.63
Non-Spatial	0.20	0.12	0.28	40	421	<.001	0.21	0.12	0.29	19	145	<.001
Immediate	0.18	0.08	0.28	12	62	.04	0.02	−0.07	0.10	4	30	.51
Delayed	0.20	0.12	0.28	43	380	<.001	0.18	0.08	0.28	19	128	<.001

NOTE: LL = lower confidence interval; UL = upper confidence interval; k = the number of studies; j = the number of effect sizes.

particularly in older adult samples (e.g., Baran et al., 2016; Scullin et al., 2017). Future research should manipulate sleep opportunity measurement length in young and older samples to effectively determine the optimal length of sleep measurement to detect sleep-memory associations.

4.2. Do specific sleep parameters show age-related differences in sleep-memory associations?

In the present meta-analysis, similar relationships between episodic memory performance and sleep quality were observed across age for most sleep quality parameters. There were, however, significant differences for two sleep quality parameters: slow wave sleep quantity and WASO. For slow wave sleep quantity, young adults demonstrated larger effect sizes for sleep-memory associations than did older adults. Indeed, several studies have found relationships between slow wave sleep and memory performance in young adults, but not older adults (Baran et al., 2016; Scullin, 2013; Sonni and Spencer, 2015a, b). This age-related discrepancy could occur for several reasons. First, the function of slow wave sleep could change in older adults in such a way that it is no longer beneficial for memory performance. Slow wave sleep is thought to prepare the brain to encode new information by allowing previously encoded information to be reactivated and transferred from the hippocampus to cortex (for a review: Saletin and Walker, 2012). By contrast, older adults may experience overactive synaptic downscaling during slow wave sleep, such that slow wave sleep may actually impair cognitive performance (Scullin, 2013).

A second explanation for age effects in the link between memory performance and slow wave sleep could be because of functional reorganization of the sleep stages in old age. Although the present meta-analysis did not show an age group moderation for REM sleep-memory associations, some evidence suggests that REM sleep may particularly contribute to episodic memory performance in old age. One study concluded that older adults may have a stronger biological drive for REM and less for slow wave sleep, as compared to young adults. Specifically, following sleep deprivation, older adults have reduced slow wave sleep quantity and REM latency, or quicker entry into REM sleep compared to young adults (Bonnet, 1986). Furthermore, REM sleep duration may increase in older adults (Scullin and Gao, 2018). REM sleep duration is positively associated with memory performance in older adults (Hornung et al., 2007; Sonni and Spencer, 2015a, b). Interestingly, older adults who demonstrated correlations between greater, natural REM duration and greater memory performance were high performing older adults (Sonni and Spencer, 2015a, b). Although speculative, this may suggest that some, well-performing older adults, may be more capable of compensation (Cabeza et al., 2018) for impoverished slow wave sleep through functional reorganization and reliance on intact REM sleep. Future longitudinal studies examining intraindividual variability would be informative for understanding how changes in one's sleep patterns over time, relate to changes in episodic memory performance.

Older adults demonstrated a stronger relationship between WASO and memory performance than young adults. WASO shows one of the most marked age-related changes in sleep quality; the increase is exponential over age (Ohayon et al., 2004). Previous research has shown relationships between WASO and episodic memory performance in older adults (Bastien et al., 2003; Scullin, 2013; Wilckens et al., 2014), while the same relationship is not always shown in young adults (Wilckens et al., 2014). These findings could be explained by WASO potentially affecting the underlying physiology of sleep quality. For example, some research has shown that WASO may be related to reduced delta power, which is prominent during slow wave sleep (Wilckens et al., 2016). Thus, WASO could contribute to the functional shift of slow wave sleep in old age, such that sleep disruption may reduce memory consolidation during slow wave sleep. Moreover, researchers have previously argued that the greater sleep disruption imposed by WASO could be related to interruption in sleep stage transitions (Wilckens et al., 2014). According to the sequential hypothesis, the cycling of sleep stages allows for memory consolidation to occur (Giuditta et al., 1995). Greater WASO may interrupt sleep stage cycling and result in poorer memory performance (Mazzoni et al., 1999). However, more research on associations between WASO and memory performance is needed to better understand these age-related differences.

4.3. Which sleep quality parameters show the strongest sleep-memory association?

While many sleep quality parameters have been linked to episodic memory performance (for reviews: Mander et al., 2017; Scullin and Bliwise, 2015a, b, c), the magnitude of these associations has not been previously assessed. There were two notable findings. First, among the different sleep stages, REM sleep quantity resulted in smaller effect sizes for sleep-memory associations than NREM and Stage 2 sleep. Previous research has often related REM sleep to episodic memory consolidation for emotional events (for a review: Payne and Kensinger, 2010). However, many of these studies did not examine individual differences and were therefore, not included in the present meta-analysis. Furthermore, REM sleep has also been associated with forming novel connections and inference (Cai et al., 2009; Ellenbogen et al., 2007), which could result in more gist or false memory (for review: Stickgold and Walker, 2013). Indeed, greater REM sleep duration has been recently linked to greater false memory (Scullin et al., 2017). Thus, REM sleep may not be as conducive to episodic memory performance. Second, sleep architecture metrics were more strongly related to memory performance than were measures of sleep continuity, sleep duration and latency, sleep stages, and general sleep quality. Sleep architecture included spindle density, spindle activity, and sleep spindle slow oscillation coupling, all of which resulted in strong correlations with episodic memory performance (Helfrich et al., 2018; Mander et al., 2013b; Schabus et al., 2004). However, studies examining sleep at this level are few and often limited to young adult samples. This lack of studies limits the ability to examine differences in sleep-memory association strength for specific metrics of sleep architecture and the assessment of age group differences in sleep-memory associations for specific metrics of sleep architecture.

4.4. Do sleep-memory associations differ by memory assessment methods and memory phase?

There were no age-related differences in sleep-memory associations according to memory task type (i.e., recall, recognition). However, one might expect age-related differences in these sleep-memory associations, considering that older adults often perform more poorly than young adults on tasks with greater demands on cognitive control, including recall and recollection (for reviews: Duarte and Dulas, 2020; Koen and Yonelinas, 2014). The research appears to be mixed with some studies showing stronger associations between sleep quality and episodic memory performance in older than younger adults for associative memory tasks (Hokett and Duarte, 2019; Sonni and Spencer, 2015a, b) and others showing associations in young adults only for both associative and non-associative memory tasks (Baran et al., 2016; Gui et al., 2019; Scullin, 2013; Scullin et al., 2017). This discrepancy may be related to different sleep measurement methods used in different studies. For example, older adults have demonstrated stronger correlations between sleep quality and memory performance for WASO than young adults (Wilckens et al., 2014) while young adults have demonstrated stronger correlations with slow wave sleep than older adults (Baran et al., 2016; Scullin, 2013), which was confirmed in this meta-analysis. Taken together, the present study suggests that age differences in sleep-memory associations occur for different sleep measures, but not memory measures.

The present results are in contrast to a previous meta-analysis that found no sleep-based benefit for episodic memory consolidation for

older adults as compared to young adults (Gui et al., 2017). Gui et al. (2017), however, did not examine individual differences in sleep-memory associations. It is important to note that Gui et al. (2017) found significant moderators for sleep-based memory benefits. Specifically, young adults demonstrated greater sleep benefits for memory performance with longer sleep duration and reduced sleep onset latency while older adult groups had greater sleep benefits with greater sleep efficiency and reduced sleep onset latency. These findings suggest that there are contributing factors that should be assessed for a full picture of age-related differences in sleep-memory mechanisms. Future experimental research assessing sleep-based memory benefits in young and older adults should thoroughly examine the underlying sleep periods of both age groups to determine if certain sleep parameters are more sensitive to episodic memory performance.

In addition to memory task characteristics, the present meta-analysis examined if sleep-memory association strength was modulated by memory phase. There were no significant differences in sleep-memory association strength between different phases of episodic memory. Specifically, there were no differences in sleep-memory associations whether memory performance assessed for initial learning acquisition or immediate or delayed retrieval. Sleep has been related to both learning and retrieval in young and older adults (Klaming et al., 2017; Mander et al., 2013b, c; Mander et al., 2017; Rasch and Born, 2013). Researchers have argued that sleep allows for the hippocampus to restore its encoding capacity (for a review: Saletin and Walker, 2012). Researchers have also found relationships between sleep quality and retrieval performance (Hokett and Duarte, 2019; Mander et al., 2013b; Sonni and Spencer, 2015a, b; Wilckens et al., 2014). This is the first meta-analysis to demonstrate that these associations are statistically equivalent. However, there were fewer encoding than retrieval studies in the present meta-analysis. Future research should aim to assess learning acquisition in order to better assess the interrelationship among learning ability, retrieval performance, and sleep quality.

4.5. Strengths and limitations

The present meta-analysis has several strengths. First, it includes a large participant sample size (1840) and sample of correlational effect sizes (616). Second, this analysis was comprised of a cognitively healthy participant sample. Poor cognitive health in older adults may inflate associations between sleep quality and cognitive performance (for a review, Scullin and Bliwise, 2015c). Third, instead of examining age group differences in memory performance benefits of sleep vs. wake protocols (Gui et al., 2017), the present meta-analysis examined individual differences within the sleep period.

There are also limitations for this meta-analysis. There were more younger adult participants than older participants and more studies including younger adults compared to those that included older adults, which limited the ability to look at age-related differences for some of the variables of interest. There was also considerable heterogeneity in measures of sleep architecture. Such heterogeneity limits the ability to determine if any single measure of sleep architecture is more strongly related to episodic memory performance.

An additional limitation involved missing data on racial/ethnic group, as the majority of the included studies omitted this demographic information. This brings into question the generalizability of the current sleep and memory literature. Considering that racial/ethnic minorities sleep more poorly than other groups (Bei et al., 2016; Cunningham et al., 2016; Johnson et al., 2019; Turner et al., 2016), the sleep-memory link in these groups warrants more attention. Research has shown that Black and Latino adults sleep for fewer hours and demonstrate poorer sleep quality than other racial/ethnic groups (for a review, Johnson et al., 2019). Such racial/ethnic group discrepancies in sleep quality have been explained by race-related stress, even when controlling for measures of socioeconomic status and education (Hicken et al., 2013; Slopen and Williams, 2014). Despite this, there is little information on the interplay among racial/ethnic group, sleep quality, and episodic memory ability. We have found that poorer sleep quality in Black participants was more strongly related to reduced memory-related neural activity than in White participants (Hokett and Duarte, 2019). However, future research is needed to fully characterize these race-related discrepancies in sleep quality and sleep-memory associations. To assess race-related differences in sleep quality and episodic memory performance, participant samples examining these measures must be more diverse.

4.6. Conclusion

This is the first meta-analysis to examine individual differences in sleep quality and episodic memory performance in young and older adults. Young and older adults demonstrated similar strength sleep-memory relationships across memory performance measures (i.e. recall, recollection, recognition, etc.), sleep assessment method (i.e. PSG, actigraphy, self-report), and memory phase (i.e. encoding, retrieval). However, there were age-related differences in the specific sleep quality variables that were associated with memory performance, with stronger slow wave sleep-memory associations for the young and stronger WASO-memory associations for the old. Given the association between WASO and memory performance in older adults, routine assessments for WASO may allow for early detection of potential memory decline. In other words, sleep assessments during wellness checks may be particularly important indicator of cognitive health in older adults. Future directions for sleep and memory researchers should include assessing longitudinal trajectories of sleep quality and episodic memory performance, as well as recruiting more diverse participant samples. Moreover, researchers should aim to assess relationships between memory and measures of sleep architecture to better assess which measures of sleep architecture are most strongly related to memory performance.

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Appendix A

Authors	MeanAge	Age Range
Alger & Payne, 2016	19.46	–
Aly and Moscovitch, 2010	74.5	69–80
Ashton et al., 2018	20.87	–
Baran et al., 2010	20.2	–

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(*continued*)

Authors	MeanAge	Age Range
Baran et al., 2016	23.2	18–25
Baran et al., 2016	67	60–75
Bastien et al., 2003	63.35	≧ 55
Cairney et al., 2014	20.53	–
Cairney et al., 2015	22.67	19–28
Cavuoto et al., 2016	73.78	–
Cellini et al., 2016	23.71	–
Conte et al., 2012	70.1	65–85
Cox et al. 2018	21.3	18–33
Gui et al., 2019	21.59	18–25
Gui et al., 2019	66.27	58–78
Hanert et al., 2017	23.5	21–26
Helfrich et al., 2018	73.8	–
Helfrich et al., 2018	20	–
Hennies et al. 2016	21.55	–
Hokett and Duarte, 2019	67.6	56–76
Hokett and Duarte, 2019	24.1	18–37
Igloi et al., 2015	24	18–30
Kaur et al., 2019	69.1	50–90
Lahl et al., 2008	24.8	20–29
Lau et al. 2010	21.21	–
Lerner and Gluck, 2018	22.15	–
Lerner et al., 2016	21.2	–
Mander et al., 2013a	20.5	–
Mander et al., 2013a	71.9	–
Mander et al., 2013b	20.4	–
Mander et al., 2013b	72.1	–
Mander et al., 2015	75.1	–
Mary et al., 2013	21.02	18–30
Mary et al., 2013	69.67	65–75
Maurer et al., 2015	23.3	21–28
Mazzoni et al., 1999	68	61–75
Muehlroth et al., 2019	23.61	19–28
Ruch et al., 2012	23.5	–
Saletin et al., 2011	20.4	18–30
Schabus et al., 2004	24.4	–
Schabus et al., 2008	24.4	20–30
Schmidt et al., 2006	24.4	–
Schoch et al., 2017	24.4	–
Scullin, 2013	70.66	–
Scullin, 2013	19.73	–
Scullin et al., 2017	21.4	18–29
Scullin et al., 2017	69.69	58–83
Sherman et al., 2015	66.8	60–78
Sonni and Spencer, 2015a, b	24	18–30
Sonni and Spencer, 2015a, b	64.5	50–79
Sopp et al., 2018	22.5	–
Studte et al., 2016	21.7	–
Studte et al., 2015	22.1	–
Takashima et al., 2006	24.8	–
Takeuchi et al., 2014	20.9	–
Tamminen & Payne et al., 2010	20.3	–
Tucker and Fishbein, 2008	23.3	–
Varga et al., 2016	68.2	–
Varga et al., 2016	20	–
Wagner et al., 2007	24.5	19–30
Wamsley et al., 2010	21.16	–
Wang and Fu, 2009	21.54	19–27
Weber et al., 2014	23.72	–
Westerberg et al., 2012	72.7	63.2–79.1
Wilckens et al., 2014	62.68	55–77
Wilckens et al., 2014	23.05	21–30

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