Understanding the Need for Sleep to Improve Cognition

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Abstract

The restorative function of sleep is shaped by its duration, timing, continuity, subjective quality, and efficiency. Current sleep recommendations specify only nocturnal duration and have been largely derived from sleep self-reports that can be imprecise and miss relevant details. Sleep duration, preferred timing, and ability to withstand sleep deprivation are heritable traits whose expression may change with age and affect the optimal sleep prescription for an individual. Prevailing societal norms and circumstances related to work and relationships interact to influence sleep opportunity and quality. The value of allocating time for sleep is revealed by the impact of its restriction on behavior, functional brain imaging, sleep macrostructure, and late-life cognition. Augmentation of sleep slow oscillations and spindles have been proposed for enhancing sleep quality, but they inconsistently achieve their goal. Crafting bespoke sleep recommendations could benefit from large-scale, longitudinal collection of objective sleep data integrated with behavioral and self-reported data.

Contents

INTRODUCTION

Ideally, we would sleep when feeling sleepy and would wake up at our preferred time feeling refreshed (Webb & Agnew 1975). However, increasing social demands have reduced sleep opportunities and altered societal norms about sleep. This strongly motivates the search for an optimal balance of sleep and wakefulness for a given individual that takes into account the immediate and long-term cognitive consequences of sleep restriction as well as the benefits of good sleep to cognition, health, and well-being.

Sleep is marked by changes in posture and muscle tone, reduced responsiveness to the external environment, and significant changes in brain electrophysiology, metabolism, and blood flow. Its characterization involves consideration of its duration, timing, subjective quality, regularity, continuity, and efficiency (Buysse 2014). At the whole-organism level, the dominant framework for explaining sleep/wake behavior is the two-process model comprising the cyclically varying influence of the hypothalamic circadian pacemaker and a homeostatic accumulation of sleep pressure with duration of wakefulness (Borbely 1982).

Current age-specific sleep guidelines focus on nocturnal sleep duration and were formulated by expert evaluation of data heavily based on self-reported sleep in Western countries (Hirshkowitz et al. 2015). These serve as rough markers for an individual to set expectations but are in need of refinement to accommodate the multiplicity of objective sleep measures available; the different facets of health, well-being, and cognitive function that can be affected by sleep; and interindividual differences. Between 30% and 40% of adults in industrialized societies do not meet current sleep recommendations. Prevailing cultural norms, particularly those surrounding work and social interactions, have significant effects on our sleep habits and limit how actionable recommendations can be.

Inadequate or poor-quality sleep transiently impairs cognitive function if sporadic, and it may elevate the risk of late-life cognitive decline or dementia if sustained. In approaching the challenge of optimizing sleep for cognition in an individual, we first broadly review the age, environmental, and social determinants of sleep before examining selected associations between sleep and cognition, focusing on the benefits sleep has on different cognitive domains and, conversely, on what is lost with its deprivation. Alongside, we examine findings from electroencephalography (EEG) and functional brain imaging that are informative about sleep traits, functions, or deficits. We briefly summarize efforts to improve sleep by enhancing structure. Adolescents and older adults are given special attention, as sleep issues are more pressing in these groups. We close by reviewing how wearable devices and smartphones might contribute to creating bespoke, actionable sleep recommendations in field settings.

AGE, LIGHT, CHRONOTYPE, AND SOCIAL INFLUENCES ON SLEEP

Sleep changes across the life span (Kocevska et al. 2021, Ohayon et al. 2004, Redline et al. 2004). In mid-adolescence, nocturnal sleep duration shortens by at least 1 hour relative to childhood. It then stabilizes through young adulthood before gradually shortening again from around 50 years of age (Adan et al. 2012, Ohayon et al. 2004). Napping, which is common in childhood, becomes less frequent in one's teens and in early- to mid-adult life before increasing later in life (Zhang et al. 2020b). Thus, a single consolidated period of nocturnal sleep (i.e., monophasic sleep) is the predominant sleep pattern adopted from later childhood till late mid-life. Sleep timing shifts later in one's teens (Hagenauer et al. 2009) before regressing slightly to earlier times throughout working life and moving even earlier in one's later years (Kocevska et al. 2021). Sleep efficiency, subjective sleep quality, and continuity all tend to decline in older adults, sometimes together with the emergence of medical issues. In healthy children, adolescents, and young adults, sleep efficiency hovers above 90%, while it can fall to around 80% in adults >60 years old. These and other features of age-related changes in sleep are expanded on later.

Sleep timing is strongly influenced by light interacting with the hypothalamic master circadian clock, which in a majority of individuals has a period of slightly more than 24 h (Dijk & Lockley 2002), so without the synchronizing effect of daily timed light exposure, sleep timing tends to progressively delay on successive days. Morning light keeps the drift toward later bedtimes in check, while late-evening light exposure delays sleep onset (Minors et al. 1991). Irrespective of timing, bright light is alerting (Cajochen et al. 2000) and can interfere with sleep. The use of artificial light is widespread, as it enables us to follow a schedule roughly appropriate for the time zone we live in. As such, seasonal effects on sleep duration—for example, longer sleep during winter—persist in many (Friborg et al. 2012) but not all (Lo et al. 2014a, Shochat et al. 2019) societies. In the latter case, greater exposure to evening artificial light may be contributory. Light's influence on sleep can also be seen in how living in a more westerly locale within a time zone is associated with a later bedtime (Giuntella & Mazzonna 2019, Roenneberg et al. 2007). Additionally, the shift from Standard Time to Daylight Savings Time (DST) in countries that implement it is associated with multiple adverse effects related to shortening of sleep and circadian misalignment. These include increased accidents, heart attacks, and strokes and have led to petitions to abolish DST (Rishi et al. 2020).

Persons with an early or morning chronotype are inclined to wake up and to go to bed relatively early, whereas those with a late or evening chronotype prefer to sleep longer in the morning and to go to bed later (Horne & Ostberg 1977). Although persons with a late chronotype generally have shorter nocturnal sleep, the impact of chronotype on their real-world cognitive performance is unexpectedly complicated, as there are significant interactions involving cognitive ability, age, and work culture. For example, a preference for later bedtimes is associated with higher cognitive

ability but, paradoxically, lower scholastic achievement. Such persons tend to flourish later during adulthood, when expression of their abilities allows them to garner jobs with greater flexibility in work timing (Ujma et al. 2020).

Worldwide, bedtime has been delayed by a growing number of nighttime activities (Billari et al. 2018), increased nocturnal light exposure (Wright et al. 2013), increased screen time on devices (Christensen et al. 2016), and the blurring of boundaries between study/work and sleep time. The effect of these trends was magnified during COVID-19 pandemic-related lockdowns, when most persons slept later given the opportunity to do so (Blume et al. 2020, Giuntella et al. 2021, Ong et al. 2021). The propensity to sleep late shows cultural influences and national differences (Jonasdottir et al. 2021, Walch et al. 2016). East Asians, for example, habitually sleep later than persons living in Western countries (Kuula et al. 2019, Ong et al. 2019), but this can vary even within the same country (Wang et al. 2019).

As opposed to bedtimes, which can slide, the start of the regular workday (or school day) tends to be fixed, setting a hard limit for nocturnal sleep duration. Unsurprisingly, regions where persons sleep late but have to wake up early have shortened nocturnal sleep, as exemplified in districts where schools start early, e.g., at 7:30 a.m. (Gradisar et al. 2011).

Insufficient sleep during work (school) days is reflected in increased weekend catch-up sleep. While better than nothing, such catch-up sleep does not replace consistent, adequate weekday sleep (Depner et al. 2019). A larger difference in weekend/weekday sleep timing that arises from sleeping late but rising even later to catch up on sleep results in so-called social jet-lag, because it reverses on the night before a workday, simulating weekend travel between time zones. This has adverse academic (Smarr & Schirmer 2018) and health (Wittmann et al. 2006) consequences.

Daytime napping, a sleep habit of some, can also be evidence of inadequate nocturnal sleep (Ficca et al. 2010). Although it can help offset cognitive impairments associated with short night-time sleep, napping is not a social norm for older students and working adults in Western societies (Alger et al. 2019), and it has diminished in many East Asian, Latin, Mediterranean, and Middle-Eastern countries.

Sleep duration is the most studied parameter related to cognition. Large-scale studies based on online testing suggest that ~7 h time in bed (TIB, versus time asleep) is the sweet spot for optimal cognitive function across a range of ages (Althoff et al. 2017, Sternberg et al. 2013, Wild et al. 2018); this could also be true of older adults (Devore et al. 2016, Lo et al. 2016a), although more representative samples should be collected to confirm these findings. Importantly, the different methods of assessing sleep duration [e.g., self-reports often overestimate polysomnography (PSG)-measured sleep duration] affect the assessment of associations, the ensuing recommendations, and ultimately individual responses to the idea of improving sleep habits.

Among the other sleep measures, late bedtimes are associated with poorer adolescent academic performance (Hysing et al. 2016) and slower processing speed (Althoff et al. 2017). The global trend for later bedtimes should be of concern. Although lower bedtime variability is beneficial for cardiometabolic health, experimentally induced bedtime variability has thus far yielded inconclusive findings on cognitive performance (Bei et al. 2016). Finally, while sleep quality is intuitively important, it is challenging to explicitly define (Meltzer et al. 2021), as the term's usage varies across authors who use different weightings of subjective sleep quality (i.e., the self-rated satisfaction of sleep) and objective sleep measures (for example, sleep stages) (Ohayon et al. 2017).

SHORT-TERM BEHAVIORAL CONSEQUENCES OF INSUFFICIENT SLEEP: A SELECTIVE OVERVIEW

Until recently, most of our knowledge about the short-term cognitive effects of insufficient sleep has come from small, controlled laboratory studies, each involving tens of participants. Total sleep

deprivation (TSD) protocols keep participants awake for 1 to 3 successive nights. Although less frequently encountered in real life, TSD allows for more efficient exploratory studies prior to evaluation with ecologically more realistic but time-consuming partial sleep deprivation (PSD) studies. Most of these studies restricted nocturnal sleep to 3–6 h per night for 5 days or longer. Attention and long-term memory have been the most intensively studied cognitive domains, and participants have mostly been young or working-age adults. Their findings have informed us about the cognitive benefits of sleep and the cognitive functions that are more likely to be affected when we are sleep deprived. However, excepting vigilance, they are limited for devising guidance on how much sleep to get.

Vigilance and Attention

Vigilance indexes one's ability to detect the unpredictable onset of stimuli over several minutes or longer. It is commonly measured using the Psychomotor Vigilance Task (PVT), which involves stopping a reaction time clock that appears with uniform probability at intervals ranging from 2 to 10 s. The PVT is highly sensitive to both TSD and PSD and has been validated in a multitude of laboratory and field settings (Dorrian et al. 2005). Reaction times averaged over a 10-min trial deteriorate over successive nights of sleep restriction (**Figure 1a**), accompanied by increased variability in reaction times. Deceptively simple, this task yields robust results over repeated administrations and is devoid of practice effects, unlike most other cognitive tasks. Response speed deteriorates with time-on-task, and this effect is compounded by the severity of each night's sleep restriction and by accumulated nights of sleep restriction (Lo et al. 2022). Incentivizing performance with money can improve response speed (**Figure 1b**), but overall sleep deprivation increases the perceived cost of effort required to sustain attention (Massar et al. 2019b). Remarkably, sensitivity to time intervals and the conditional probability of an imminent stimulus are preserved during sleep deprivation. Thus, the sleep-deprived brain, despite blanking out at times, remains able to reallocate depleted cognitive resources to more probable event timings (Kong et al. 2015).

Systematic evaluation of graduated levels of PSD where 3–7 h of sleep opportunity were provided in different configurations (e.g., 3, 5, 7 h or 4, 6, 8 h TIB) revealed clear effects of greater sleep restriction on vigilance (Belenky et al. 2003, Van Dongen et al. 2003). Lapses in attention on the PVT (approximately twice the median response time with adequate sleep) have been shown to scale linearly with accumulated number of hours awake (Van Dongen et al. 2003). However, when examining these findings from the perspective of sleep opportunity provided, it can be seen that greater performance differences exist between 6.5 h and 8 h TIB than between 5 h and 6.5 h of sleep (**Figure 1a**), suggesting that tens of minutes of extra sleep at the threshold of sufficiency may have outsized benefits (Lo et al. 2020). Hence, performance may fall off more sharply just before the threshold of sleep sufficiency than it does at shorter sleep durations.

Following 5–14 nights of PSD to 4–5 h TIB (Banks et al. 2010, Belenky et al. 2003, Van Dongen et al. 2003), or 3-night cycles of PSD to 3 h TIB (St. Hilaire et al. 2017), PVT performance did not fully recover following 8–10 h TIB recovery sleep. These findings in adults, including the greater sensitivity of vigilance to sleep loss compared to processing speed or objective sleepiness, have recently been extended to adolescents. When PSD was extended to a second simulated work/study week following a weekend of 9 h TIB recovery sleep, there was a further decline in vigilance observed as early as the first re-exposure night. Performance, in fact, fell to a lower level than that recorded on the last (and worst) night of sleep restriction in the previous week (Lo et al. 2017), highlighting incomplete recovery even with a weekend of recovery sleep.

Multiple studies have shown that while sleep-restricted persons feel sleepy, there is a dissociation between progressive deterioration in objective measures of vigilance and plateauing of subjective sleepiness after several successive nights of sleep restriction. This dissociation does not
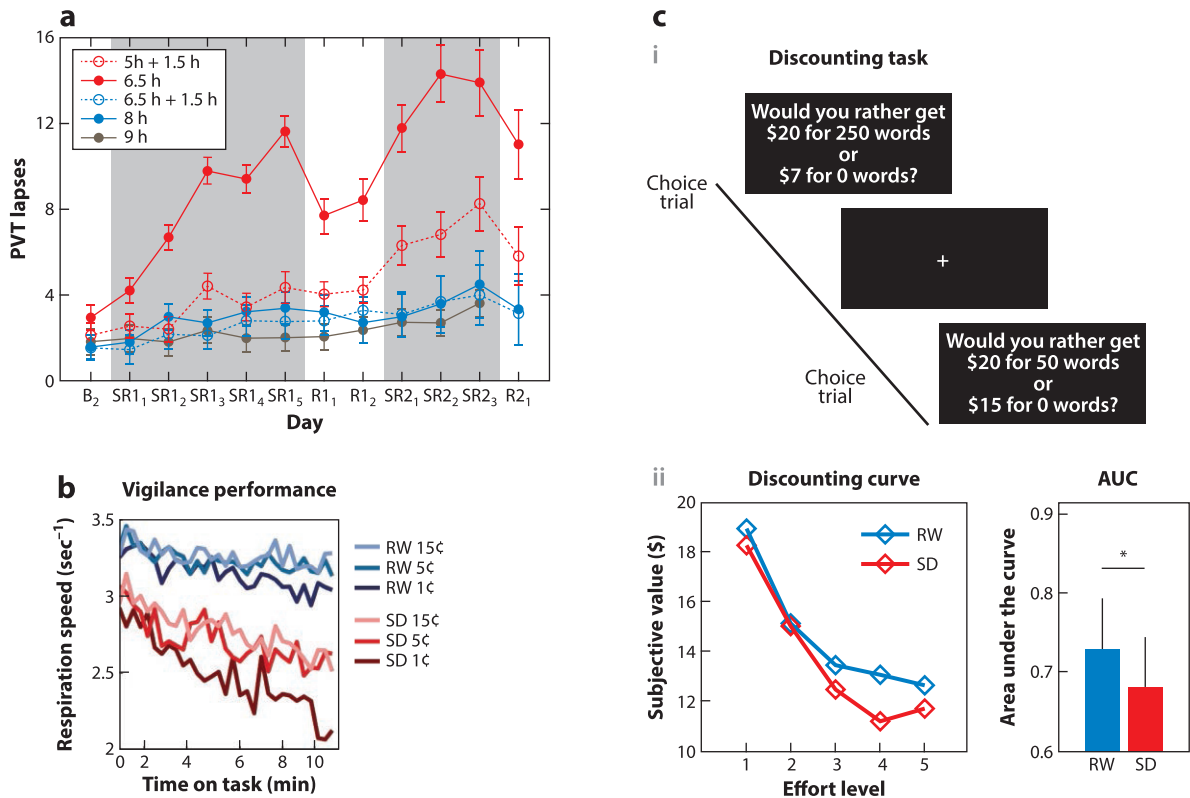
Figure 1

(*a*) Successive cycles of SR to 5 h (*dashed red line*) or 6.5 h (*solid red line*) a night resulted in increased lapses on the PVT that are compounded by a second week of restriction. When a nap is incorporated so that total opportunity is 8 h, both the continuous sleep schedule (8-h nocturnal; *solid blue line*) and split sleep schedule (6.5-h nocturnal + 1.5-h nap; *dashed blue line*) achieved similar performance on sustained attention comparable to obtaining the optimal 9 h at night (*gray line*). Panel based on data from Lo et al. (2016b, 2017, 2020). (*b*) Time-on-task effects on the PVT after normal sleep (RW) and SD, wherein the latter was modulated by reward (1, 5, or 15 cents) per fast response. Panel adapted from Massar et al. (2019a). (*c, i*) Trials in an effort discounting task with effort operationalized as backward word typing. (*c, ii*) Discounted value of a $20 reward at increasing effort levels, represented in the discounting curve (*left*) and quantified as the area under the discounting curve (*right*). Panel adapted from Libedinsky et al. (2013). Abbreviations: AUC, area under the curve; PVT, Psychomotor Vigilance Test; RW, rested wakefulness; SD, sleep deprivation; SR, sleep restriction.

preclude one's ability to self-monitor for increased errors, although awareness appears to vary across cognitive tasks (Boardman et al. 2018). Vulnerability to attentional lapses after sleep deprivation may also predict performance in visual working memory and processing speed tasks (Mathew et al. 2021).

The extensive and robust results obtained from use of the PVT have led researchers to use it as an output variable for biomathematical models of fatigue prediction in which time-of-day and the person's sleep schedule are inputs (Hursh et al. 2016). These models can reasonably predict group-level performance following multi-night PSD, but they do not sufficiently predict heterogeneous individual responses to the same schedule of sleep restriction (Flynn-Evans et al. 2020) or individual vigilance performance following three 3-day repeated cycles of sleep restriction and recovery (St. Hilaire et al. 2017).

Interindividual differences in response to sleep deprivation can be substantial. For example, there are exceptional individuals who have hardly any attentional lapses even after 48 h of TSD

(Basner et al. 2013). Rare individuals with a DEC2 mutation can habitually sleep from 4 to 6.5 h per night with minimal or no daytime sleepiness (Ashbrook et al. 2020). Recovery from sleep deprivation shows similar heterogeneity, with the duration of rebound sleep giving an indication of cumulated sleep insufficiency (Kitamura et al. 2016).

The trait-like nature of responses to sleep restriction (Van Dongen et al. 2004) motivates the search for their genetic underpinnings. Both candidate gene studies (Casale & Goel 2021, Satterfield et al. 2019) and genome wide association studies (GWAS) (Garfield 2021) have been used. Unsurprisingly, the DEC2 example notwithstanding, complex traits like sleep duration and resilience to sleep loss are affected by multiple genes whose associations may be influenced by ethnicity and even age. This leads to considerable heterogeneity in the variance accounted for by hereditability in different studies (Garfield 2021).

In mission-critical professions, even a high level of competency and favorable personality traits when well rested are no guarantee that the person will maintain vigilance after sleep deprivation (Galli et al. 2021). A clue to vulnerability to vigilance decline, however, can be obtained from observing baseline PVT performance after habitual sleep (Chua et al. 2019). Remarkably, response speed sampled at any time of day can be used to predict the likelihood of lapsing when sleep deprived (St. Hilaire et al. 2019).

When a period of sleep restriction is anticipated, for example, prior to a night shift, sleep banking achieved through elevating sleep opportunity beyond one's habitual sleep duration might mitigate performance deficits (Arnal et al. 2015, Rupp et al. 2009). The preliminary assessment of this strategy is positive, but opportunities remain for systematically studying its pragmatics and efficacy (Patterson et al. 2019).

Memory

Abundant work supports the benefits of sleep on memory (Klinzing et al. 2019, Rasch & Born 2013) but in contrast to the findings of the literature on vigilance, heterogeneity in memory tasks, type of memory tested, experimental conditions, memory stage tested, and time elapsed since initial learning do not allow a ready formulation of recommendations about the optimal sleep duration for maximizing memory. For brevity, this review is confined to declarative memory, referring to consciously accessible memories of prior events or fact-based information.

The contributions of sleep to declarative memory can be separated into those related to encoding, consolidation, and retrieval. Memories generally become less accessible with the passing of time. Consolidation refers to memory stabilization without further practice, and it has been the most extensively studied memory stage (Klinzing et al. 2019, Rasch & Born 2013). Its benefits have been repeatedly observed when nocturnal sleep instead of an equivalent duration of daytime wakefulness follows learning and when testing is performed within ~12 h of initial learning.

Sleep has been reported to reduce the interference that occurs when newly learned memoranda contain elements that conflict with previously learned material (Ellenbogen et al. 2009). This active stabilization process was postulated to complement the reduced forgetting that may be a by-product of not being exposed to additional information while asleep (Jenkins & Dallenbach 1924). Recent work, however, suggests that the effect size of sleep-related protection of memories from active interference may have been overstated (Bailes et al. 2020, Pohlchen et al. 2021). This caution might even extend to claims about the magnitude of sleep's contribution to memory consolidation (Cordi & Rasch 2021a,b).

The negative impact of sleep deprivation or, conversely, the duration of benefit that sleep confers on memory consolidation may be shorter lived or smaller than previously believed. For example, while a single night of sleep deprivation clearly impaired memory retrieval, 3 further nights

of good sleep after learning alleviated the initial poorer memory recall (Schonauer et al. 2015). In another study, consolidation of declarative memory in adolescents remained unimpaired when encoding was followed by 5 consecutive nights of sleep restriction to 5 h TIB (Voderholzer et al. 2011). Temporary hippocampal buffering following TSD and relative preservation of slow-wave sleep (SWS) despite sleep restriction were proposed to explain the conserved memory in these studies. However, an alternative reason for less forgetting despite inadequate sleep is that over time, daytime memory reactivation can make up for the effects of deficient sleep. The reactivation of neural activity associated with learning in the form of hippocampal sharp wave ripples (**Figure 2**) occurs most often during SWS (Euston et al. 2007, Ji & Wilson 2007). This is a key mechanism underlying the systems consolidation of memory, whereby initially labile, hippocampal-dependent memories are stabilized through engagement of frontal and posterior parietal neocortical sites (Diekelmann & Born 2010, Himmer et al. 2019). Notably, such neural reactivation via hippocampal sharp wave ripples is not exclusive to sleep and can take place during quiet wakefulness (Joo & Frank 2018).

Spontaneous entry into offline states such as day-dreaming during wakefulness (Wamsley 2019, Wamsley & Summer 2020) or even quiet rest can facilitate memory consolidation. The benefits of such episodes can persist 1 week after learning (Dewar et al. 2012). Although this type of reactivation differs qualitatively (Zhang et al. 2018) from that occurring during non–rapid eye movement (NREM) sleep, it may still assist in sustaining memories even after sleep loss. Many details remain unclear—for example, whether reactivation outside the hippocampus is casually related to memory benefit and whether findings from rodent studies can be related to human memory performance (Findlay et al. 2020).

Retrieving learned material through testing can also improve memory performance (Roediger & Butler 2011), perhaps as a result of triggering the same kind of neural reactivation that occurs during sleep except that it takes place during wakefulness (Joo & Frank 2018). Interestingly, the memory boost associated with daytime test-related information retrieval and reactivation appears to diminish the offline benefits of sleep when participants are evaluated 1 week after initial learning (Abel et al. 2019, Antony & Paller 2018). This suggests that memories already stabilized during wakefulness may receive less benefit from sleep.

Hence, as important as sleep may be for the initial consolidation of learned material, early consolidation deficits arising from sleep deprivation/restriction may be repaired or compensated for by a combination of taking advantage of quiet restful periods, repeated testing or restudy, and catching up on lost sleep. Collectively, these findings might contribute to explaining why students who deprioritize sleep (Biggs et al. 2010, Sun et al. 2014) can still excel in standardized academic tests.

Compared to the effects on consolidation, the effects of sleep on encoding have received relatively less attention. Encoding of pictures can be affected by a single night of TSD (Yoo et al. 2007) as well as multiple nights of sleep restriction (Cousins et al. 2018). TSD may lower the quality of visual information represented in the higher visual cortex (Poh & Chee 2017). In contrast to the apparent ability of deficient consolidation to be recovered, defective encoding can have long-lasting consequences. For example, the capacity to acquire detailed factual knowledge was significantly impaired when learning took place after 4 nights of sleep restricted to 5 h per night; following comparable group performance before the sleep restriction, retrieval was poorer in the sleep-restricted group compared to the control group at 3 days and for 6 weeks after the last of multiple learning sessions (Cousins et al. 2019b). Conversely, a nap sandwiched between learning periods, compared to continuous cramming or a period of video watching, yielded superior memory for learned biological facts 1 week after initial learning (Cousins et al. 2019a). This speaks to possible long-lasting benefits of encoding with adequate sleep.
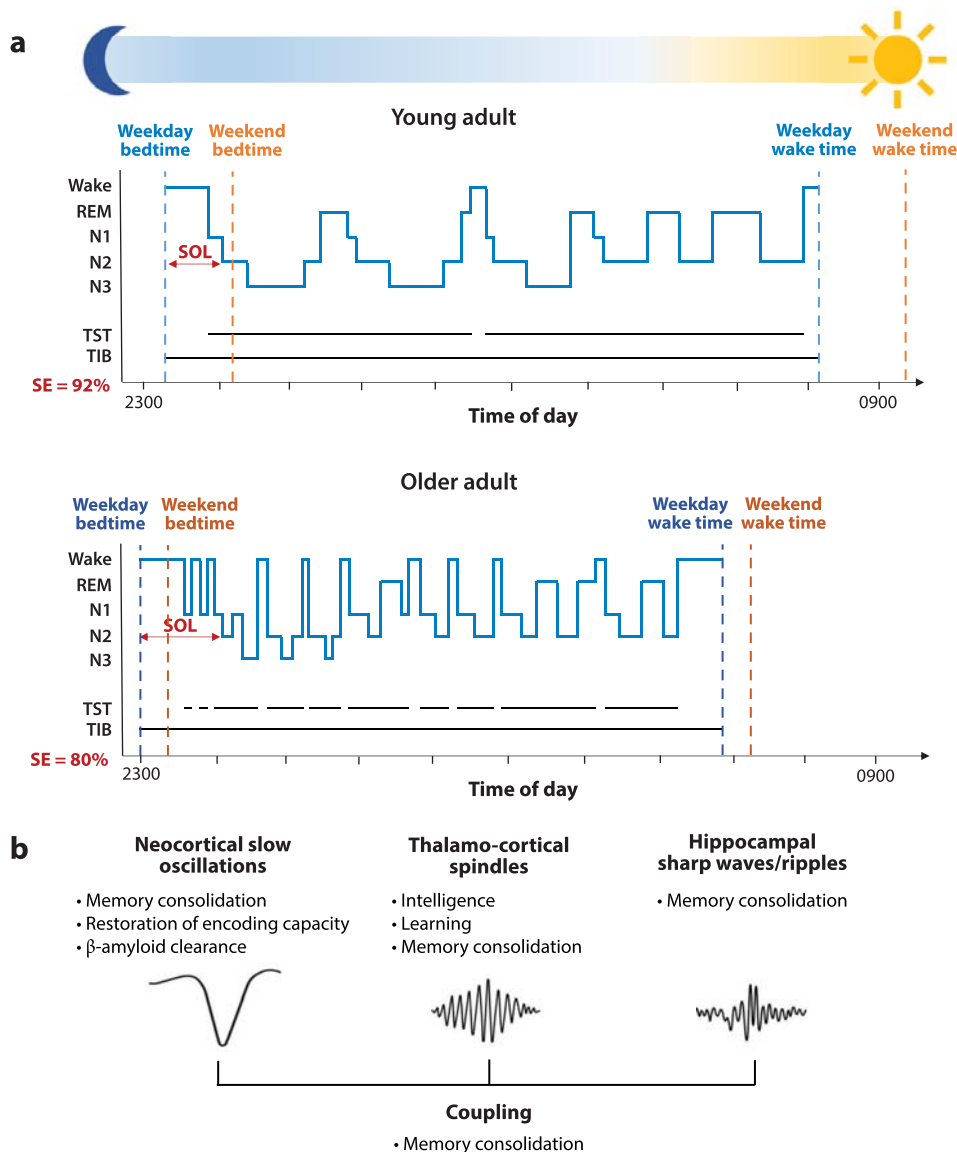
Figure 2

(*a*) Hypnograms illustrating age-related changes in sleep macrostructure whereby N3 and REM sleep are reduced. Longer sleep latency and greater fragmentation contribute to lower SE (calculated as TST/TIB × 100). Circadian clock timing advances with age contribute to the shift toward earlier sleep times. Diminished differences between weekday and weekend sleep follow the loss of fixed work schedules. (*b*) Sleep oscillations, their putative origins, and their links to memory and cognition. Abbreviations: REM, rapid eye movement; SE, sleep efficiency; SOL, sleep onset latency; TIB, time in bed; TST, total sleep time.

Work to date has mostly evaluated how item memory, rather than memory for facts and structured material whose mastery builds on existing knowledge frameworks, benefits from sleep (Lewis & Durrant 2011). Real-world learning involves transformation of learned material through the addition of novel elements and, sometimes, the removal of obsolete or incorrect information.

Such learning would require the reactivation of interleaved old and new memories. Preliminary evidence that sleep benefits both the initial development and later transformation of structured memoranda has been found using a task engaging transitive inference of picture sequences (Golkashani et al. 2022).

Risky Decision Making

Of the different domains of decision making following sleep loss, risky decisions have been the best studied in both laboratory experiments and surveys (Womack et al. 2013). In the experimental approach, a participant's true preferences are uncovered by observing decisions made during gambles involving monetary gains and/or losses under conditions of uncertainty (Platt & Huettel 2008). These studies are based on theory-inspired, often complex designs but involve relatively small sample sizes. Findings have been mixed with regard to risk taking in such gambling tasks (Killgore et al. 2006, Maric et al. 2017, Menz et al. 2012, Salfi et al. 2020, Venkatraman et al. 2007).

The survey approach inquires whether a person with poorer habitual sleep is more prone to engage in risky behaviors—for example, if they are more likely to consume alcohol or violate road safety (Mantua et al. 2020). Studies using this approach have been more consistent than experimental studies in suggesting a negative association between sleep duration and/or quality and risk-taking tendency (Short & Weber 2018). Although they allow for more diverse sampling and involve many more participants than experimental studies, they do not distinguish whether inadequate or poor quality sleep is a cause or consequence, or whether an independent thrill-seeking personality is contributory (Paiva et al. 2016, Rusnac et al. 2019).

Impulsivity has been related to risky decision making. In decision-making parlance, impulsivity refers to a tendency to accept a smaller but more immediate reward instead of a larger but delayed one. This delay discounting is assessed through repeated decisions on two such offers involving different pairs of offers. Delay discounting does not increase with sleep deprivation (Demos et al. 2016, Libedinsky et al. 2013) (**Figure 1c**). This is quite remarkable, because it indicates a preserved ability to perform value computations while sleep deprived. In total, the existing evidence does not point to a consistent change in risk taking after sleep deprivation, although there is some evidence to support lower quality of decisions (Menz et al. 2012).

Executive Function and Complex Cognitive Processes

Executive function, broadly defined as a set of abilities involving the integration and manipulation of information as well as the inhibition of prepotent responses, is often studied in laboratory experiments using tasks that isolate specific aspects of this ability. These studies have found that sleep deprivation impairs inhibitory control (Chuah et al. 2006) as well as the continuous updating of a temporary storage of information, wherein both speed and accuracy are impacted (Lim & Dinges 2010). Other studies using strategic games involving planning and reasoning (Glass et al. 2011, Killgore et al. 2009) have also shown negative effects of sleep loss. However, findings in this domain are less consistent than findings on simple attention, with other studies showing absent or less pronounced effects (Sagaspe et al. 2006). This has led some to suggest that the effects on executive function may be primarily driven by the deterioration in attentional aspects of the task rather than in the ability to manipulate information per se (Mathew et al. 2021).

Complex cognition is a more accurate reflection of the combination of cognitive processes needed in occupations in which sleep loss is common—e.g., health care workers, first responders, and the military. Two meta-analyses have summarized that the effects of sleep loss on complex cognition are smaller compared to the effects on more elementary cognitive processes like vigilance (Lim & Dinges 2010, Wickens et al. 2015). A different view was taken in a systematic review that

concluded that complex cognition is indeed affected, but only when cognitive demands require flexibility, such as task-switching, rather than being stable (Smithies et al. 2021). This converges with a report finding that working-memory capacity determines the extent to which interruptions and multitasking demands increase occupational errors committed while sleep deprived (Westbrook et al. 2018). Studies examining the effects of sleep loss in occupational settings are harder to control and allow for less detailed characterization of why failures arise. However, observational studies have reported higher likelihood of medical errors (Trockel et al. 2020, Whelehan et al. 2020) and work injuries (Uehli et al. 2014) when individuals are sleep deprived. Naps to supplement nocturnal sleep may boost productivity and well-being in such settings (Bessone et al. 2021).

SLEEP STRUCTURE AND COGNITION

EEG is the reference measure of sleep, so its associations with cognition merit review. EEG informs about sleep macrostructure, which refers to the duration and arrangement of different sleep stages, as well as its microstructure, which refers to the quantification of spindles, slow-wave activity (SWA), and microarousals (**Figure 2**). NREM begins with lighter stages (N1, N2) before deepening into SWS (N3) and then entering rapid-eye-movement (REM) sleep. This cycle repeats about 4–5 times each night in healthy young adults.

Prolonged wakefulness results in an increase in slow-wave EEG power (Cajochen et al. 1999, Finelli et al. 2000). This marker of homeostatic sleep pressure dissipates during sleep in accordance with how much it was elevated during wakefulness. There are stable interindividual differences in sleep EEG (Tucker et al. 2007), whereby spectral power is trait-like across baseline recordings (De Gennaro et al. 2005) and following sleep deprivation (Chua et al. 2014, Ong et al. 2017). These observations raise the question of whether baseline sleep EEG informs about sleep need or cognitive vulnerability to sleep deprivation, akin to how baseline PVT performance informs about vulnerability to vigilance decline upon sleep deprivation. However, empirical data indicate that baseline sleep EEG is not informative about either (Galli et al. 2021).

The homeostatic regulation of sleep might lead us to expect that a person requiring more sleep will have higher slow-wave EEG power than someone needing less sleep, if both stay awake for the same duration. Although we do not know the answer to this specific question, habitual short sleepers (<6 h TIB nightly) who stay awake longer consistently express more slow-wave power in both waking and post-sleep EEGs (Aeschbach et al. 1996, 2001) compared to long sleepers (>9 h TIB). However, surprisingly, while asleep both groups do not differ in total duration of SWS or recovery kinetics, although short sleepers have a shorter sleep latency and higher amounts of SWS. These points suggest that habitual short sleepers consistently live under higher levels of sleep pressure compared to long sleepers. Hence, while monitoring the upward trend within an individual's EEG spectral power over several recordings is a physiological marker for extended wakefulness and possibly cognitive fatigue, a single EEG does not inform us about an individual's habitual sleep duration or about their propensity for vigilance decline following sleep deprivation [with one exception provided by Maric et al. (2017)]. Cross-sectional EEG measures also accounted for less than 5% of the variance in self-reported daytime sleepiness within a large community-based sample (Lok & Zeitzer 2021).

SLOW OSCILLATIONS AND SLEEP SPINDLES: THEIR MODULATION AND RELEVANCE TO MEMORY

Reactivation of spatial memories during SWS, cued by using odor (Rasch et al. 2007) or sounds (Rudoy et al. 2009), can improve subsequent retrieval. Slow oscillations (large amplitude 0.5–1 Hz

waves), a subcomponent of SWS, are strongly associated with sleep-related memory consolidation (Diekelmann & Born 2010, Klinzing et al. 2019). These oscillations occur in N2 but are more prominent in N3. Nested within slow oscillations are sleep spindles (Staresina et al. 2015). These 1- to 3-s bursts of waxing-and-waning 10–15 Hz oscillations are the hallmark of light sleep (N2) but are also present, albeit visually obscured, in N3. Studies seeking to quantify associations between sleep and cognition use measures related to particular EEG features, like the amplitude or power of slow waves (particularly slow oscillations) and fast spindle density (spindles per minute). The coupling or time-locking of slow oscillations with fast spindles (12–15 Hz) is thought to be critical for post-learning memory consolidation (Molle et al. 2011, Muehlroth et al. 2019). Such coupling weakens with ageing (Helfrich et al. 2018), contributing to why the benefit of sleep on memory might be stronger in young persons (Gui et al. 2017). Young persons also have an abundance of high-amplitude slow oscillations together with a longer N3. In contrast, older adults have lower-amplitude slow oscillations and shorter N3 (Feinberg & Campbell 2003, Ohayon et al. 2004) alongside less well-coupled slow oscillations (Helfrich et al. 2018, Muehlroth et al. 2020). These age-related changes are accentuated in those whose cognition has declined (Backhaus et al. 2007, Mander et al. 2015). Finally, using noise to interfere with SWS impacts memory encoding–related brain activation (Van Der Werf et al. 2009).

Associations between reduced SWS and poorer memory suggest that stimulating slow oscillations might be of benefit (Wilckens et al. 2018). Boosting sleep slow oscillations using transcranial electrical, transcranial magnetic, or phase-locked acoustic stimulation is achievable, but only with careful attention to multiple parameters (Feher et al. 2021). For example, improperly delivered or mistimed stimulation can suppress SWA instead of boosting it (Leger et al. 2018). Acoustic stimulation, the most promising and practicable technology, has generated mixed results for improving memory—for example, increasing memory for word pairs (Ngo et al. 2013) but not consistently for pictures (Ong et al. 2018) or face recognition (Leminen et al. 2017). A meta-analysis of 11 studies involving healthy persons found an overall small positive effect size (Hedge's $g = 0.25$) of acoustic stimulation on boosting episodic memory (Wunderlin et al. 2021). Discovering the optimal combination of stimulation parameters (number of clicks, continuity, click timing), condition (nap, nighttime sleep), and demographics (younger or older age, neuro-psychiatric conditions) requires studying far more participants than existing studies do (Harrington & Cairney 2021, Wunderlin et al. 2021).

In young adults, the positive correlation of N3 duration or SWA with declarative memory performance was shown in multiple studies with small sample sizes ($n \sim 10$–30) (Rasch & Born 2013). However, this was not replicated either at the between-individual (Ackermann et al. 2015) or within-individual (Cordi & Rasch 2021b) level with large sample sizes ($n > 100$). Having more large-amplitude slow oscillations and longer SWS may be favorable for older adults' memory. However, it remains an open question whether boosting slow oscillations (or spindles) in healthy persons is scalable, is beneficial to memory function, or lowers the risk of late-life cognitive decline.

Having an abundance of sleep spindles, specifically fast spindles (12–15 Hz), in adults correlates with higher intelligence with a small but consistent effect size (Ujma et al. 2020). This sleep microstructural feature has trait-like amplitude, power, and density over multiple nights of recording in a given person (Markovic et al. 2018, Purcell et al. 2017, Werth et al. 1997). Trait-likeness notwithstanding, spindles have been reported to increase following learning (Gais et al. 2002). Correlations between an increase in spindles following learning and better declarative memory have been reported (Schabus et al. 2008), but other work suggests that these increases may simply reflect brain structural features and thalamo-cortical connectivity in persons possessing innately higher learning capabilities (Lustenberger et al. 2012). Spindle power can be boosted along with slow oscillations in experiments designed to enhance the latter using brain stimulation

(Wunderlin et al. 2021). However, such augmentation may be insufficient to boost memory (Henin et al. 2019). Incrementing fast spindle density with the hypnotic Zolpidem was associated with improved memory for learned word pairs following nocturnal sleep (Zhang et al. 2020a) and a nap (Mednick et al. 2013) in young adults. Despite this set of findings, the pharmacological approach to augmenting sleep architecture for cognitive improvement in healthy persons has yielded mixed findings and shown potential side effects, and it is generally not preferred. It should also be noted that in healthy adults, neither SWA nor spindles are positively correlated with the subjective perception of sleep depth (Stephan et al. 2021).

In sum, while ongoing research on augmenting sleep oscillations continues, the baseline characteristics of sleep oscillations appear to be strongly affected by heredity and age. While they can be modulated, robust evidence for the functional benefit of doing so remains to be convincingly demonstrated in field settings.

IMAGING MARKERS OF ATTENTIVE BEHAVIOR FOLLOWING SLEEP DEPRIVATION

Functional magnetic resonance imaging (fMRI) studies on healthy adults undergoing a single night of TSD reveal multiple cortical areas that show diminished activation (Krause et al. 2017) when visual attention, visual short-term memory, or working memory is evaluated. Collectively, fMRI studies show that sleep deprivation affects more than prefrontal function, as was previously suggested (Harrison et al. 2000, Muzur et al. 2002). TSD reduces the engagement of areas involved in top-down control of attention in frontoparietal cortices, which has downstream effects on extrastriate visual areas that process higher-order visual information (Chee et al. 2008, Tomasi et al. 2009). The extent to which activation downshifts across well-rested and sleep-deprived conditions has been shown to correlate with the drop in behavioral performance across these conditions (Chee & Tan 2010). These findings were corroborated in a fluorodeoxyglucose–positron emission tomography (FDG-PET) study showing that a downshift in cerebral glucose metabolism in a medial frontal area correlated with the extent of throughput decline in an arithmetic task (Xu et al. 2016). The consistency with which tasks requiring attention show reduced frontoparietal activation in the sleep-deprived state (Ma et al. 2015) corresponds with electrophysiological evidence of local sleep in these areas, where cortical columns sporadically enter an off state, compromising attentive behavior after prolonged wakefulness (Vyazovskiy et al. 2011). Recruitment of greater thalamic activation might reduce lapses in the sleep-deprived state, and if this fails lapses increase (Chee & Tan 2010, Tomasi et al. 2009). Reduced disengagement of the default mode network during stimulus presentation (Chee & Chuah 2007, Czisch et al. 2012, Tomasi et al. 2009) also occurs, albeit less robustly across different studies. Beyond delayed or absent responses, fMRI has revealed poorer target tracking (Tomasi et al. 2009), lowered capacity to process visual information peripheral to what lies in central focus (Kong et al. 2011), a slower rate of visual processing (Kong et al. 2014), and deficient suppression of visual distractors (Kong et al. 2012) not evident from classical assays of sleep-deprived behavior.

Functional connectivity studies examine interregional coherence of spontaneous fMRI signal fluctuations. Averaged over ~10 min, these studies show a pattern of reduced integration of networks that are typically engaged (e.g., dorsal attention network) or disengaged (the default mode network) while one is performing a demanding cognitive task as well as decreased segregation of brain regions whose resting state signals are anticorrelated with one another (De Havas et al. 2012, Yeo et al. 2015). When functional connectivity is assessed across sliding windows of tens of seconds, a mixture of functional connectivity patterns corresponding to high or low arousal states emerges. The respective predominance of these patterns loosely follows the temporal course of

attentive behavior (Wang et al. 2016). Further, individuals showing a relatively higher proportion of the high-arousal connectivity pattern when well rested are less likely to show vigilance decline after sleep deprivation (Patanaik et al. 2018). These findings provide neurophysiological evidence in support of the trait-like nature of behavioral responses to overnight TSD. As with task-based fMRI studies, larger samples will be necessary to evaluate the operational utility of these assays.

Faltering or fluctuating vigilance or arousal is a concern in fMRI studies, as it alters connectivity sufficiently to affect the interpretation of resting-state studies (Goodale et al. 2021, Liu & Falahpour 2020). Relatedly, it is becoming increasingly apparent that fMRI signals during periods of fluctuating vigilance are linked to changes in respiration depth and/or heart rate at the onset and offset of microsleeps and subsequent awakenings (Soon et al. 2021). As such, the interpretation of fMRI findings related to sleep deprivation need to take into account the neuro-vascular nature of physiological changes in this state (Duyn et al. 2020). In sum, fMRI studies, subject to caveats, are informative about the physiology accompanying attention/vigilance changes but do not inform about sleep adequacy.

SLEEP AND COGNITION IN ADOLESCENTS

Sleep curtailment in adolescents is prevalent in many societies (Paruthi et al. 2016). Endogenous contributors to later bedtimes include the maturational delay in circadian phase and a slower buildup of homeostatic sleep pressure. Exogenous factors include increased academic pressures, greater autonomy, and opportunities to socialize. More than 60% of teens in urban societies go to bed after midnight on school nights. A growing number of persons voluntarily delay their bedtime beyond an initially planned bedtime (Kroese et al. 2014). When engrossed in activities such as watching TV or browsing social media, it may be difficult to disengage from these pastimes and go to bed (Chung et al. 2020, Exelmans & Van den Bulck 2016). This phenomenon, known as bedtime procrastination, can be seen as a failure of self-regulation, as activities that are rewarding in the short term are favored over obtaining sufficient sleep, despite the known negative consequences on the following day (Kroese et al. 2014, Massar & Chee 2019). Late bedtimes, together with the resistance to delaying school start times, significantly curtail the amount of nocturnal sleep a student can obtain, contributing to a perfect storm of short, ill-timed, and inadequate sleep (Crowley et al. 2018).

Earlier research suggested that teenagers may be more resistant to sleep restriction than adults (de Bruin et al. 2017). It is likely that the cognitive tasks used in some earlier studies were not sufficiently sensitive or the sleep restriction was too mild. Work using similar tasks to those used in adults found decrements in vigilance following a single night of 5 h TIB of sleep in 10-year-old girls (Peters et al. 2009), 4 nights of 7.5 h TIB sleep in 9- to 14-year-old children (Campbell et al. 2018), and any sleep duration less than 8 h TIB over 24 h in 15- to 19-year-old adolescents (Lo et al. 2016b, 2020). Executive function, speed of processing, short-term memory, and declarative memory are also affected, albeit to a lesser degree. Positive mood is consistently affected by shortened sleep in adolescents (Short et al. 2020) and may have greater functional impact on students than impairment of cognitive function.

Starting school later to lengthen nocturnal sleep is supported by scientific evidence (Bowers & Moyer 2017) and endorsed by professional bodies (Watson et al. 2017). Concerns that the provision for later awakening will be eroded by students merely sleeping later are unfounded. Evidence for sustained benefits 9 months following the implementation of later start times (Lo et al. 2018) and for altered sleep behavior during COVID-19-related lockdowns indicates that while students will go to bed later if allowed to wake later, they will ultimately get more sleep (Becker & Gregory 2020, Lim et al. 2021).

In societies resistant to starting school later, adopting a split sleep schedule involving a shorter nocturnal sleep period (6.5 h) combined with a mid-afternoon nap (1.5 h) has been shown to yield vigilance, working memory, executive function, processing speed performance, and mood comparable to those of students who received 8 h of nocturnal sleep (Lo et al. 2020). Long-term memory for facts organized in multiple flash cards was also comparable across the two ways of obtaining a total of 8 h of sleep over 24 h. Interestingly, afternoon naps were feasible, even for nonhabitual nappers, were efficient on the average (85% sleep efficiency), and did not interfere significantly with nocturnal sleep (Leong et al. 2021, Ong et al. 2017).

A third of adolescents in the United States between 13 and 17 years of age reported being awake at night because of stress. In adolescents (Maskevich et al. 2020) and young adults (Beck et al. 2022), pre-sleep stress elevates heart rate and can increase sleep latency by increasing arousal. The latter is accompanied by reduced SWS and sleep spindles in the sleep EEG (Ackermann et al. 2019). Anticipation of stressful events the following day can also result in increased apprehension in young adults (Kecklund & Akerstedt 2004), as revealed by decreased SWS in the hours preceding awakening. Reactivation of mental constructs relating to the anticipated stressful events during sleep could underlie such increased physiological arousal. Conversely, cueing a participant with relaxing words during sleep can improve sleep quality and increase both SWA and spindles without affecting sleep microstructure (Beck et al. 2021). Problem-focused coping that dwells on managing or altering the problem causing stress may also reduce pre-sleep arousal during vacation time, although not during term time (Maskevich et al. 2020). Needing to complete homework is a major contributor to both stress and late bedtimes (Yeo et al. 2019). Trait vulnerabilities to stress-related disturbance of sleep (Drake et al. 2004) tend to get unmasked in adolescence and elevate the risk of insomnia later in life. Early identification of adolescents at risk and early intervention, based on an understanding of the risk factors that trigger and sustain abnormal stress reactivity, could help lessen the burden of insomnia and mental disorders in later life (de Zambotti et al. 2018).

SLEEP AND COGNITION IN OLDER ADULTS

In contrast to younger persons, who often do not obtain enough sleep because of exogenous factors, older adults (arbitrarily ~60 years old and beyond) tend to get sleep that is shorter, less continuous, and less efficient—falling from 85% from <55 years of age to ~79% at >70 years—as a result of endogenous factors (Mander et al. 2017, Ohayon et al. 2004). It takes longer to fall asleep and SWS is reduced, from around 11% in men below 55 years to 5.5% in 70-year-old men (Redline et al. 2004).

The amplitude of the circadian rhythm is reduced (Hood & Amir 2017), possibly due to dysfunctional neurons in the hypothalamic master clock and their reduced neurogenesis (Kostin et al. 2020). Following from this, older adults tend to experience difficulty falling and staying asleep at night (Dijk et al. 2001) while showing an increased tendency to nap in the day (Ohayon 1999, Owusu et al. 2019). An increase in unplanned naps is more common in persons with medical comorbidities (Foley et al. 2007, Vitiello 2009). Naps of ~60 min or longer are associated with a higher risk of poorer cognitive performance (Leng et al. 2019, Owusu et al. 2019), but shorter durations (~30–60 min) appear to be beneficial for cognition (Li et al. 2017, Owusu et al. 2019) and cardiovascular health (Hausler et al. 2019).

Beyond this broad characterization of sleep in older persons, there exist significant interindividual differences such that some cognitively healthy persons show little sleep impairment (Vitiello 2009), while others exhibit a reduction in daytime sleep propensity (Dijk et al. 2010). Balancing out the negative biological effects of aging on sleep, retirement, at least in Northern Europeans, affords the flexibility to accommodate later wake-up timing and daytime naps, and this has been

shown to modestly increase sleep duration in addition to reducing premature awakening and non-restorative sleep (Myllyntausta & Stenholm 2018). Japanese retirees, on the other hand, do not tend to wake up later after retirement (Jonasdottir et al. 2021). Overall, intraindividual variability in sleep timing tends to be lower among older adults (Bei et al. 2016).

Experimental studies reveal that compared to young adults, older adults have a slower buildup of sleep pressure (Klerman & Dijk 2008) and/or tolerate it better. As a result, although showing slower responses to reaction-time sensitive tasks at baseline compared to their younger counterparts, older adults have an attenuated response to sleep deprivation involving less slowing and less increase in lapses in vigilance (Blatter et al. 2006, Duffy et al. 2009).

The benefit of sleep on memory consolidation may be reduced with advancing age even in healthy adults (Scullin 2017). Specifically, the positive association between SWS and memory evident in young adults is diminished in older adults. Conversely, wake after sleep onset (WASO) has a stronger association with poorer memory in older adults compared to young adults (Hokett et al. 2021). Collectively, these findings have been derived from sleep measurement methodologies ranging from self-reported sleep to actigraphy and PSG. Self-reported sleep is often linked to overestimation of sleep duration and underestimation of sleep disruption in older persons. Faulty recall and/or inadequate perception of nighttime awakenings associated with some self-reports make it important to collect objective measurements of sleep. Actigraphy measures normed in young adults need to be carefully assessed in older adults who may be awake but lie still for extended periods, resulting in an overestimation of sleep duration. PSG is sensitive to WASO and informs about sleep structure. Sleep–memory associations in older persons are stronger in studies using this modality compared to self-reports (Hokett et al. 2021).

Sleep microstructural features relevant to cognition deteriorate with age. Slow-wave (Landolt & Borbely 2001, Munch et al. 2004) and spindle (De Gennaro & Ferrara 2003) power both reduce from mid-age onward. Cortical thinning of the association cortex in healthy older adults may underlie lower slow-wave amplitude and density (Dube et al. 2015) by impairing the genesis of sleep oscillations. Medial frontal gray matter volume reduction, in particular, was found to correlate with reduced prefrontal SWA and, in turn, poorer verbal memory (Mander et al. 2013; but see Fjell et al. 2021). These findings suggest that sleep changes even in healthy older adults could have structural underpinnings that restrict the amount and quality of sleep that might be obtained.

Disturbed or inadequate sleep is a risk factor for Alzheimer's disease (AD) (Yaffe et al. 2014), where abnormal accumulation of β-amyloid and tau proteins in the brain contributes to neurodegeneration (Cedernaes et al. 2017). The removal of neural waste products such as β-amyloid is enhanced during sleep, compared to wakefulness, through channels that drain into cerebrospinal fluid (CSF) spaces adjacent to brain tissue (Xie et al. 2013). A night of TSD (Ooms et al. 2014) or selective interruption of SWS (Ju et al. 2017) both result in reduced CSF clearance of β-amyloid. Habitual self-reported sleep duration of 6 h or less was associated with higher levels of a PET imaging marker for brain β-amyloid in community-dwelling older adults (Spira et al. 2013). However, a recent longitudinal study suggests a more nuanced picture, whereby total sleep time, SWA in the sleep EEG, and time in REM sleep as well as NREM sleep were found to have a nonlinear, inverted-U relationship with cognition over the years (Lucey et al. 2021). This suggests that there is an optimal middle range of sleep measures where cognitive scores are stable. Epidemiological studies across the globe have found that both short and long sleep durations (7 h TIB being the reference) elevate risk of dementia. Long sleep of 9 h or greater (risk ratio ∼2) is actually the more problematic of the two (Jike et al. 2018). This optimal middle range of sleep duration has also been observed for cross-sectional cognition (Xu et al. 2011), longitudinal cognitive change (Ferrie et al. 2011), and overall mortality (Tamakoshi et al. 2004).

A meta-analysis of epidemiological studies concluded that individuals with sleep problems have an ~1.5 times higher risk of AD and that about 15% of cases might be preventable with interventions to reduce sleep problems or treat sleep disorders (Bubu et al. 2017). However, such interventions are complicated by a bidirectional relationship between sleep and AD pathology (Wang et al. 2016, Yaffe et al. 2014). Changes in sleep quality and efficiency precede the appearance of symptoms by years and track both the decline in cognitive function and the development of pathology (Ju et al. 2014), suggesting that lifestyle changes or interventions to improve sleep might be helpful. However, ageing itself causes loss of cells within hypothalamic nuclei that maintain sleep and protect against sleep fragmentation (Lim et al. 2014), so it is unclear whether such interventions would be beneficial.

Poor self-reported sleep has been related to unfavorable brain structural changes in cross-sectional studies, but there has been no consistency in the specific sleep parameter showing association and the brain regions affected (Lo et al. 2014b, Sexton et al. 2014, Spira et al. 2013). As reviewed earlier, it is also unclear whether deliberately manipulating sleep microstructure is helpful. In sum, while it is clear that sleep and cognition both deteriorate in most older adults and that sleep disorders compound these issues, actionable advice about what it means to sleep better and how to do it for dementia prevention is difficult, leading to its omission as a potential intervention (Livingston et al. 2020).

MEASURING AND IMPROVING SLEEP AND COGNITION USING TECHNOLOGY AND BIG DATA

Translating the multiple theories about sleep and cognition derived from small-scale, carefully controlled experiments into tangible benefits will gain from the integration of data streams from smartphones, wearable devices, and computers that have become ubiquitous in urban societies, with over 90% penetration in most cities. Large-scale smartphone-delivered questionnaires and social media–based or app-based characterization of self-reported sleep patterns inform about sleep norms as well as shifts in duration, timing, and quality across the life span (**Figure 3**). There have been useful additions, documenting for example delayed sleep timing in relation to sunset times (Walch et al. 2016) or the linkage between spending a long time in bed having difficulty initiating sleep (Kocevska et al. 2021). Many questionnaires have been used to characterize sleep during the COVID-19 pandemic (Cellini et al. 2020, Huang & Zhao 2020).

Here, it is useful to caution that large numbers do not equate to representativeness. For example, the UK Biobank, which recruited 500,000 participants from the United Kingdom, involves participants who are significantly healthier than those of nationally representative data sources (Fry et al. 2017). Fortunately, high-quality, nationally representative (Low et al. 2019) or inclusive population phenotyping studies (Arges et al. 2020) with evaluations of sleep and cognition are emerging. Apps polling self-perceived well-being and mood as well as those delivering short online cognitive tests afford the collection of longitudinal data on the influence of sleep on next-day behavior in field settings. Innovative deployment of these could help resolve whether the timing of sleep after learning affects long-term retention, or how to customize advice on when and how long to take naps at different ages to optimize cognitive function (Mantua & Simonelli 2019).

Consumer wearable devices provide increasingly accurate measures of sleep behavior that currently rival more expensive research actigraphs (Chee et al. 2021, Chinoy et al. 2021, de Zambotti et al. 2020). Initially based on activity measurement, these devices have expanded to use photo-plethysmography (to measure heart rate), temperature, and even skin conductance sensors. Sensor technology is fairly mature, but algorithms are constantly advancing. Some manufacturers have incorporated machine learning into the training of their algorithms (Altini & Kinnunen 2021).
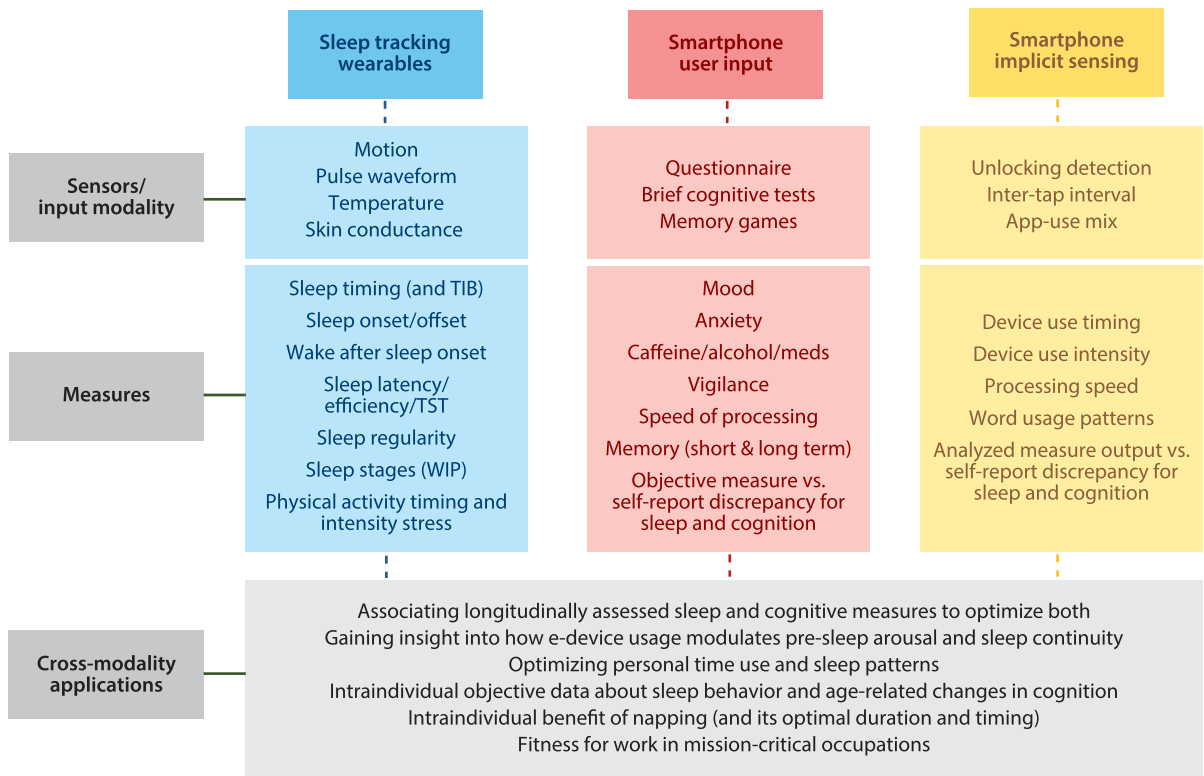
Figure 3

Advancements in sleep-tracking wearables, app-based assessments, and implicit sensing via smartphones provide opportunities for sleep, cognitive, and behavioral measurements that contribute to the optimization of human well-being and performance. Abbreviations: TIB, time in bed; TST, total sleep time; WIP, work in progress.

This might also improve nap detection, a current gap in many systems. With enlarged and more diverse (by age and race) PSG-validated training data, sleep staging using additional sensor data and contextual information has shifted from being a novelty to a tool researchers can use to collect data at scale. The additional sensors can also be used to infer stress levels (Sano & Picard 2013) and to correlate sleep history with cognitive performance. The criticism that these devices are black boxes with proprietary algorithms unsuited for high-quality longitudinal studies will eventually be overcome by the provision of minimally processed data that qualified users can access and analyze. With well over 100 million devices in the market around the world, manufacturers, researchers, and clinicians need to be able to adapt the communication of sleep metrics and their norms to end users. This will require careful validation studies (Depner et al. 2020) that include age (Galland et al. 2018), race, and health status (Moreno-Pino et al. 2019) in diverse populations.

Long-term monitoring of typing patterns of computer users conducting web searches has been shown to yield data about how real-world performance varies across the day and how it is influenced by chronotype and prior sleep, in close agreement with small-scale laboratory studies (Althoff et al. 2017). Analyzing the interval between successive search characters typed and the interval between the display of a search result and the response to it was informative that sleeping 1 hour later than usual, but not earlier than usual, affected next-day performance speed. Porting such keystroke analyses to smartphones, another group found that this technique could detect

median sleep onset times and wake-up times that highly correlated with actigraphy ($R^2 = 0.72$). They also found that elevated device interactions during periods of low physical activity and around wake time predicted a lower likelihood of having undisturbed nocturnal sleep (Borger et al. 2019). Such assessment of behavior is unobtrusive and does not depend on user input beyond the habitual use of a device, overcoming a known disadvantage of app-based approaches whereby users tend to disengage after a few weeks (Onnela 2021). Long-term user engagement will be critical in assessing cognition when nights of poor quality or shortened sleep are interleaved with nights of recovery sleep (Simpson et al. 2016).

Integrating device interactions with contextual information affords additional inferences. For example, in over 80% of nights, information obtained from a sleep wearable device, tappigraphy, and sleep diaries was concordant, providing redundancy in sleep measurement. However, the analysis of discordant minority reports enabled the detection of three distinct phenotypic groups: a younger group who had heavy smartphone usage in the pre-sleep and immediate post-awakening period and also late and shorter sleep; a second group who slept earlier, made sparing use of their smartphones, and slept longer on average; and a third, older group who had heavy phone use but woke up early, briefly used their phones, and then went back to sleep, with total sleep time comparable with that of the second group (Massar et al. 2021). Grouping individuals into cohorts with similar behavioral characteristics has been shown to be promising for encouraging change in sleep behavior inspired by social comparison and increased awareness of sleep habits (Daskalova et al. 2018). Participants also find it useful to have secondary and primary weekly goals and to receive nonjudgmental reminders. The development of advice tailored to features that appeal to different users (Munson & Consolvo 2012) benefits user retention.

LIMITATIONS OF THIS REVIEW

We focused on selected aspects of sleep and cognition in healthy participants who are most likely to benefit from improving sleep, highlighting newer articles or reviews on established findings while bringing to attention several new articles that challenge some older findings. We omitted discussing insomnia (Van Someren 2021), obstructive sleep apnea, and other sleep and psychiatric disorders that can contribute to cognitive outcomes. We also omitted discussing the evolving role of fluid biomarkers in determining sleep adequacy or circadian misalignment (Mullington et al. 2016). We refer the reader to other studies for insights into the affective and emotional influences of sleep (e.g., Ben Simon et al. 2020).

OPPORTUNITIES FOR FUTURE RESEARCH ON SLEEP AND COGNITION

Social engineering, already expertly deployed by marketeers, will be critical to maintain data contribution by a representative sample over the extended periods needed to answer questions such as whether improving sleep habits in young adults can forestall the development of cognitive decline and dementia. Although we have presented a generally positive view of napping, there remain significant uncertainties that only large-scale longitudinal studies can address. For example, do older adults nap more often because retirement enables them to do so, or is the increase driven more by lowered amplitude of circadian rhythms? What is the optimal timing and duration of naps for different persons and across ages? What are the underlying reasons for which long sleepers have poorer cognitive and health outcomes?

Many persons state that they are unable to obtain sufficient sleep on account of having insufficient time. Digital time use tools that autonomously collect data on how we use time can, like sleep trackers, create awareness of how we compare with others on using limited time efficiently,

perform better, and get to bed earlier (Hysing et al. 2016). The interrelationships between social media use, sleep, and mental well-being are another topic of interest (Kelly et al. 2018).

Insufficient sleep often accompanies shift workers, who encounter disrupted sleep patterns and elevated risk for accidents and multiple chronic diseases (Kecklund & Axelsson 2016). Ad hoc or gig work can also compromise sleep through expanded pathways for extended-hour delivery of goods and services. Unsurprisingly, polyphasic sleep, the practice of distributing multiple short sleep episodes across the 24-h day, has gained popularity. Although leading sleep experts have strongly advised against it (Weaver et al. 2021), objective data would strengthen the case against trendy but harmful sleep patterns. Overall, it has become a challenge for workers to self-regulate sleep without a legislative push. In order to treat persons manifesting cognitive features of inadequate sleep in the manner we handle unacceptable levels of drug and alcohol intoxication (Dawson et al. 2021), trustworthy assays of sleep and cognition are necessary.

Finally, most of the existing literature on sleep including recommendations arises from a few influential labs in the United States and Europe. New digital tools and frameworks should enable researchers from a more diverse pool of scientists across the globe to gather data on sleep and cognition at a higher level of quality and detail, akin to how smartphone cameras have transformed photography for billions. This will undoubtedly herald a new era in optimizing sleep and cognition.

DISCLOSURE STATEMENT

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