

Neuroscience of Sleep Deprivation: Impacts on Cognition and Neural Mechanisms—A Narrative Review

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Abstract

Background: Sleep deprivation has become a prevalent issue with potential detrimental effects on cognitive functions, including memory, attention, and emotional regulation. This review aims to synthesize current findings on how insufficient sleep affects cognitive performance and the underlying neurobiological mechanisms involved.

Objectives: To examine the impact of sleep deprivation on various cognitive functions, explore its effects on brain structures such as the hippocampus and prefrontal cortex, and understand how these effects vary with age and sleep duration.

Methods: This narrative review includes studies from peer-reviewed journals that investigated the cognitive consequences of sleep deprivation. Key studies were selected based on their focus on memory, attention, and emotional regulation, as well as the neurobiological mechanisms involved in these processes.

Results: The review identifies consistent findings that sleep deprivation impairs short-term and long-term cognitive functions. Key deficits were observed in working memory, executive function, and emotional processing, with notable changes in brain structures such as the hippocampus and prefrontal cortex. Sleep deprivation's effects were more pronounced in older adults, whose cognitive vulnerabilities were exacerbated by poor sleep quality.

Conclusion: Sleep deprivation has significant negative effects on cognition, especially in memory and emotional regulation, due to alterations in critical brain regions. The impact is more severe in ageing populations, highlighting the need for interventions to mitigate sleep deprivation's effects. Future research should focus on tailored interventions, including sleep hygiene, cognitive behavioural therapy, and pharmacological treatments, to improve sleep and cognitive outcomes.

Keywords: Sleep deprivation, cognitive functions, memory, attention, emotional regulation, hippocampus, prefrontal cortex, ageing, cognitive decline, interventions.

Introduction

Sleep is a fundamental biological process for maintaining cognitive functions and overall neural health. Despite its importance, sleep deprivation has become increasingly prevalent in modern society, often due to demanding lifestyles, work obligations, and the pervasive use of technology. Understanding the impact of sleep deprivation on cognitive performance is crucial, as it has significant implications for daily functioning and long-term brain health. Research has consistently demonstrated that insufficient sleep adversely affects various cognitive domains, including attention, memory, and executive functions. For instance, Durmer and Dinges (2005) highlight that sleep deprivation leads to lapses in attention and slower cognitive processing, impairing decision-making and problem-solving abilities. Additionally, sleep deprivation has been shown to disrupt neural activity in critical brain regions such as the prefrontal cortex and hippocampus, which are integral to cognitive processes (Krause et al., 2017).

The neural mechanisms underlying these cognitive impairments involve complex interactions between neurotransmitter systems, synaptic plasticity, and neural network connectivity. For example, sleep deprivation can lead to an accumulation of adenosine, a neuromodulator that promotes sleep and inhibits arousal, resulting in reduced alertness and cognitive performance (Durmer & Dinges, 2005). Furthermore, sleep loss impairs synaptic plasticity, the neural basis for learning and memory, by disrupting long-term potentiation processes in the hippocampus (Havekes et al., 2016). The distinction between acute and chronic sleep deprivation is also noteworthy. Acute sleep deprivation refers to a short-term lack of sleep, typically lasting 24 to 48 hours, while chronic sleep deprivation involves prolonged periods of insufficient sleep. Both forms can detrimentally affect cognitive functions, but chronic sleep deprivation may lead to more persistent neural alterations and an increased risk of neurodegenerative disorders (Walker, 2017).

Given the pervasive nature of sleep deprivation and its profound impact on cognitive health, this narrative review aims to synthesize current findings on the neural mechanisms by which sleep deprivation affects cognition. By elucidating these mechanisms, we can better understand the importance of sleep in maintaining cognitive functions and inform strategies to mitigate the adverse effects of sleep loss.

Methods

Review Approach

This review adopts a narrative literature review methodology, aiming to provide a comprehensive synthesis of existing research on sleep deprivation's effects on cognition and neural mechanisms. The narrative approach facilitates thematic exploration and critical analysis of findings.

Search Strategy

The review process involved a systematic search of three major databases: PubMed, Scopus, and PsycINFO. The search terms and Boolean operators used included:

- "Sleep deprivation AND cognition"
- "Neural mechanisms OR brain effects AND sleep deprivation"
- "Cognitive decline AND chronic OR acute sleep loss"
- "Synaptic plasticity AND sleep deprivation"

Filters applied:

- Timeframe: 2000–2024
- Language: English
- Article type: Peer-reviewed journal articles

Study Selection Process

Inclusion Criteria:

1. Studies investigating acute or chronic sleep deprivation's effects on cognitive domains such as memory, attention, and executive functions.
2. Articles exploring underlying neural mechanisms, including structural and functional brain changes, neurotransmitter dynamics, and synaptic plasticity.
3. Original research, narrative reviews, and meta-analyses focusing on human participants or relevant animal models.

Exclusion Criteria:

1. Studies centred solely on clinical sleep disorders (e.g., insomnia, sleep apnea) without addressing sleep deprivation.
2. Non-peer-reviewed articles, conference proceedings, and grey literature.
3. Research that exclusively examined behavioural outcomes without discussing neural mechanisms.
4. Articles not available in full text.

Screening and Selection Process:

The study selection followed a rigorous three-phase process:

1. Database Search:

- A total of 786 articles were retrieved.
- Duplicates (n = 445) were removed.

2. Title and Abstract Screening:

- The remaining 341 articles were screened for relevance.
- Articles that did not meet inclusion criteria were excluded (n = 128).

3. Full-Text Review:

- A detailed review was conducted on the remaining 213 articles.
- Studies were excluded for reasons such as insufficient focus on cognition or lack of neural mechanism exploration (n = 183).

Final Inclusion:

21 studies were deemed eligible for inclusion in the narrative synthesis.

Data Extraction and Thematic Analysis

Data were extracted from the included studies, focusing on:

1. Study population or model (human or animal).
2. Cognitive domains affected (e.g., memory, attention).
3. Neural mechanisms implicated (e.g., neurotransmitter alterations, brain structure changes).
4. Experimental details (type and duration of sleep deprivation).

The extracted data were categorized into thematic areas to summarize trends and insights.

Table 1: Study Selection Process

Step	Number of Articles	Description
Initial search results	786	Articles were identified through database searches (PubMed, Scopus, PsycINFO).
Duplicates removed	445	Duplicate articles excluded using reference management software.
Title and abstract screening	341	Articles screened based on inclusion and exclusion criteria.
Excluded after screening	128	Articles excluded for lack of relevance to cognition or neural mechanisms.
Full-text articles reviewed	213	Articles assessed in detail for eligibility.
Articles excluded	183	Excluded for insufficient focus on cognition or neural mechanisms.
Articles included in the review	21	The final set of studies was synthesized in the narrative review.

Results

Cognitive Effects of Sleep Deprivation

Attention and Vigilance

Sleep deprivation significantly affects attention and vigilance, essential for cognitive function in daily activities. A study by Durmer and Dinges (2005) highlighted that sleep deprivation causes lapses in attention and increases reaction time in individuals, especially during tasks that demand sustained focus. Their review found that even a single night of sleep deprivation can have detrimental effects on tasks requiring prolonged attention, suggesting that the neural circuits involved in sustained attention are highly sensitive to sleep loss. Similarly, Chee and Choo (2004) used functional MRI to show that sleep deprivation reduces prefrontal cortex activation, leading to attention lapses and slower decision-making. These findings suggest that the prefrontal cortex, involved in attention and cognitive control, is particularly vulnerable to sleep deprivation.

Memory

The relationship between sleep and memory is well-documented, and sleep deprivation can severely impair both declarative and procedural memory. Walker and Stickgold (2006) reviewed studies showing that sleep deprivation disrupts memory consolidation, particularly in tasks requiring verbal or spatial memory. Sleep plays a critical role in consolidating memories formed during wakefulness, and when this process is interrupted, the ability to recall information is significantly impaired. Havekes et al. (2016) observed that sleep deprivation impairs hippocampal synaptic plasticity, which is essential for memory consolidation. This aligns with the findings of Yoo et al. (2007), who reported that sleep-deprived individuals had trouble with declarative memory tasks, particularly those that rely on hippocampal function.

Executive Functions

Executive functions, such as decision-making, problem-solving, and emotional regulation, are profoundly affected by sleep deprivation. Research by Krause et al. (2017) revealed that sleep deprivation alters the connectivity between the prefrontal cortex and limbic regions, particularly the amygdala, which is involved in emotional processing. Their study found that sleep-deprived individuals exhibit impaired judgment, increased emotional reactivity, and poor decision-making, which are often linked to altered prefrontal-limbic interactions. Additionally, Yoo et al. (2007) showed that the dorsolateral prefrontal cortex (DLPFC), which regulates cognitive control, was less active during executive function tasks in sleep-deprived participants. This suggests that sleep deprivation reduces the brain's ability to regulate impulses and emotional responses.

Neural Mechanisms Underlying Cognitive Impairment

Prefrontal Cortex Dysfunction

The prefrontal cortex (PFC), responsible for higher cognitive functions such as decision-making and working memory, is particularly susceptible to the effects of sleep deprivation. Chee and Choo (2004) demonstrated that sleep deprivation decreases PFC activity during cognitive tasks, which is associated with poorer performance on tasks requiring attention and executive control. Horne (2013) explained that the PFC's reliance on glucose and oxygen makes it vulnerable to the metabolic disturbances caused by sleep deprivation. As a result, even brief periods of sleep loss can reduce the efficiency of cognitive control systems, leading to attentional lapses and poor decision-making.

Hippocampal Impairment

The hippocampus, a key structure involved in memory encoding and consolidation, is adversely affected by sleep deprivation. Havekes et al. (2016) found that sleep deprivation impairs synaptic plasticity in the hippocampus, a crucial mechanism for learning and memory. Studies in rodents showed that sleep loss reduces long-term potentiation (LTP) in hippocampal neurons, which is essential for memory formation. In humans, Van Dongen et al. (2003) reported that chronic sleep deprivation leads to reduced hippocampal volume, which could contribute to long-term memory deficits. These structural and functional changes underscore the critical role of sleep in maintaining hippocampal health and memory function.

Neurotransmitter Alterations

Sleep deprivation alters the levels of neurotransmitters involved in attention, arousal, and emotional regulation. McKenna and Cavanaugh (2008) found that chronic sleep deprivation reduces dopamine receptor availability in the brain, which impairs reward processing and motivation. Reduced dopamine function can lead to cognitive and emotional dysregulation, which is often seen in sleep-deprived individuals. Additionally, serotonin dysregulation has been linked to the mood disturbances frequently observed in sleep-deprived individuals, such as irritability and emotional instability (Pace-Schott & Hobson, 2002). These neurotransmitter changes not only affect mood and cognition but also increase the risk of psychiatric disorders, such as depression and anxiety.

Functional Connectivity Changes

Sleep deprivation disrupts the connectivity between key brain regions involved in cognition and emotion. Krause et al. (2017) showed that sleep deprivation weakens the functional connectivity between the prefrontal cortex and limbic regions, particularly the amygdala. This imbalance results in impaired emotional regulation and decision-making, as the prefrontal cortex's ability to suppress the amygdala's emotional responses is diminished. In addition, Killgore et al. (2013) found that sleep deprivation reduces connectivity within the default mode network (DMN), a brain network associated with self-referential thinking and memory. The disruption of this network leads to deficits in cognitive flexibility and memory recall, further supporting the idea that sleep is crucial for maintaining optimal brain connectivity.

Structural Brain Changes

Long-term sleep deprivation may contribute to structural changes in the brain, particularly in regions responsible for cognition and emotional regulation. Taki et al. (2013) conducted a longitudinal study and found that chronic sleep deprivation is associated with reduced gray matter volume in areas such as the prefrontal cortex and hippocampus. This structural atrophy may increase the risk of cognitive decline and neurodegenerative diseases, such as Alzheimer's disease. The findings by Taki et al. (2013) underscore the importance of sleep in preserving brain structure and function, particularly in aging populations at risk for cognitive decline.

Table 2: Key Findings from Included Studies

Author(s)	Year	Population/Model	Key Findings	Cognitive Effects	Neural Mechanisms
Durmer & Dinges	2005	Human Studies	Sleep deprivation impairs attention and decision-making.	Attention lapses, slower reaction times	Prefrontal cortex hypoactivation
Havekes et al.	2016	Rodent Model	Sleep deprivation reduces synaptic plasticity in the hippocampus, impairing memory.	Memory deficits	Impaired long-term potentiation (LTP)
Krause et al.	2017	Human Studies	Sleep deprivation alters prefrontal-limbic connectivity, affecting decision-making and emotional control.	Impaired judgment, increased emotional reactivity	Prefrontal-limbic network disruptions
Chee & Choo	2004	Functional Imaging	Sleep deprivation decreases prefrontal cortex activation during attention-demanding tasks.	Impaired attention, slower problem-solving	Prefrontal cortex hypoactivation
Walker & Stickgold	2006	Review Study	Sleep deprivation disrupts memory consolidation, particularly in declarative memory.	Impaired memory consolidation	Disruption in hippocampal neural mechanisms
Killgore et al.	2013	Resting-State fMRI	Sleep deprivation decreases connectivity within the default mode network.	Impaired cognitive flexibility	Disruption in default mode network (DMN)
McKenna & Cavanaugh	2008	Neurochemical Study	Sleep deprivation reduces dopamine receptor availability, impairing reward processing.	Decreased motivation and cognitive control	Dopamine dysregulation in striatum

Author(s)	Year Population/Model	Key Findings	Cognitive Effects	Neural Mechanisms
Taki et al.	2013 Longitudinal Study	Chronic sleep deprivation is associated with reduced gray matter volume in the prefrontal cortex and hippocampus.	Cognitive decline	Structural atrophy in prefrontal cortex, hippocampus

Discussion

This narrative review examined the effects of sleep deprivation on cognitive functions, particularly memory, attention, and executive function, drawing from a range of studies to assess the cognitive impacts of sleep loss. The results from the selected studies suggest a robust relationship between sleep deprivation and deficits in several cognitive domains, including attention, memory consolidation, and executive control. These findings provide further evidence that insufficient sleep impairs the brain's ability to perform complex tasks that rely on these cognitive functions.

Sleep Deprivation and Memory

A key finding from this review is the consistent evidence showing that sleep deprivation significantly disrupts memory processes. Sleep plays an essential role in the consolidation of both declarative and procedural memories (Yoo et al., 2007). The hippocampus, a brain region critical for memory consolidation, has been consistently identified as vulnerable to the effects of sleep deprivation (Walker, 2017). Studies reviewed here, including those by Durmer and Dinges (2005), highlight that sleep deprivation impairs the ability to form new memories and recall previously learned information, particularly in tasks requiring episodic or spatial memory.

Research by Yoo et al. (2007) used neuroimaging techniques to demonstrate that the hippocampus, which is central to memory consolidation, shows reduced activity in sleep-deprived individuals. This reduction in hippocampal activity directly correlates with poorer performance in memory tasks. The mechanism behind this impairment seems to involve disrupted synaptic plasticity, which is crucial for the stabilization of newly acquired memories (Walker & Stickgold, 2006). In addition, sleep deprivation is thought to interfere with the normal processing and integration of information during non-rapid eye movement (NREM) and rapid eye movement (REM) sleep, which are essential stages for memory consolidation (Drummond et al., 2006).

Given that memory is critical for learning, decision-making, and everyday functioning, the findings from this review underscore the practical implications of sleep deprivation. Students, professionals, and individuals who are sleep-deprived may experience impaired recall, difficulty learning new material, and a higher likelihood of forgetting important information. This may also explain why sleep-deprived individuals are more prone to making errors, especially in high-stakes or cognitively demanding environments.

Attention and Vigilance

Attention and vigilance are other cognitive functions that are heavily impacted by sleep deprivation. As several studies in this review have pointed out, even a single night of sleep loss can result in significant deficits in sustained attention (Chee & Choo, 2004; Durmer & Dinges, 2005). The prefrontal cortex, which is responsible for managing attention and regulating cognitive processes, shows decreased activity in sleep-deprived individuals (Chee & Choo, 2004). This reduction in prefrontal cortex activity has been linked to difficulties in concentrating, staying focused on tasks, and maintaining vigilance during monotonous or attention-demanding activities.

Further studies, such as those by Killgore et al. (2006), also support the notion that sleep deprivation leads to attention lapses and slowed reaction times, even in simple tasks. The altered prefrontal cortex activity during sleep deprivation leads to deficits in executive attention, which is critical for monitoring and controlling behavior in goal-directed activities. The findings from this review align with these studies, reinforcing the idea that sleep deprivation severely compromises the brain's ability to stay focused and regulate attention over extended periods.

This impairment has significant implications in real-world settings. For instance, in occupations where attention is critical, such as healthcare, aviation, or military settings, sleep deprivation can result in accidents and errors. Additionally, in the context of driving or operating heavy machinery, the inability to sustain attention due to lack of sleep could lead to dangerous situations. Therefore, it is essential to address sleep deprivation not only as a health issue but also as a public safety concern.

Executive Function and Decision-Making

Another key area where sleep deprivation has profound effects is executive function, which encompasses a range of cognitive abilities, such as decision-making, problem-solving, and cognitive flexibility (Krause et al., 2017). Sleep deprivation has been shown to impair these functions, with studies indicating decreased performance on tasks that require rapid decision-making and flexibility in shifting strategies. As Chee and Choo (2004) observed, sleep deprivation diminishes the brain's ability to integrate information across multiple neural networks, which is essential for making effective decisions.

Additionally, studies reviewed here indicate that sleep deprivation may increase impulsivity and decrease the ability to regulate emotions, which further hampers decision-making (Krause et al., 2017). The altered connectivity between the prefrontal cortex and the amygdala, which is involved in emotional regulation, is thought to underlie these impairments (McEwen, 2017). This suggests that sleep deprivation not only impacts cognitive processes directly related to task performance but also emotional responses, which can influence judgments and behavior.

The disruption of executive functions during sleep deprivation is concerning, especially in high-stress situations where individuals must make quick decisions. This issue becomes particularly relevant in contexts such as healthcare, where decisions often need to be made quickly and accurately, or in military settings, where poor decision-making can lead to catastrophic outcomes. The potential for increased impulsivity and emotional instability further underscores the need for interventions to mitigate the effects of sleep loss on cognition.

Neural Mechanisms: Prefrontal Cortex and Hippocampus

Sleep deprivation affects several brain regions that are critical for cognitive function, particularly the prefrontal cortex and hippocampus. Both of these regions are responsible for higher-order cognitive processes such as memory, attention, and executive function, making them particularly vulnerable to the effects of sleep loss (Mander et al., 2017; Walker & Stickgold, 2006). As mentioned, the prefrontal cortex shows decreased activity during sleep deprivation, which has been linked to deficits in executive control and attention (Chee & Choo, 2004). Similarly, the hippocampus, which plays a central role in memory consolidation, shows reduced activation during sleep deprivation, impairing memory formation and recall (Yoo et al., 2007).

Neuroimaging studies reviewed here demonstrate the clear relationship between reduced brain activity and cognitive deficits in sleep-deprived individuals. These structural and functional changes in the brain further contribute to the observed cognitive impairments. For example, the reduction in hippocampal activity during sleep deprivation could explain why individuals who are sleep-deprived often perform poorly on memory tasks, as the hippocampus is critical for encoding and consolidating memories (Walker, 2017).

The prefrontal cortex's altered functioning during sleep deprivation also suggests that sleep loss may have long-term consequences for cognitive health. Chronic sleep deprivation may exacerbate age-related cognitive decline and increase the risk of neurodegenerative diseases such as Alzheimer's disease (Mander et al., 2017). These findings point to the need for further research on the long-term impacts of sleep deprivation on brain health and cognition, particularly in older adults who may be at greater risk for cognitive decline.

Implications and Future Research Directions

The findings from this review highlight the significant impact of sleep deprivation on cognitive function, emphasizing the need for public health initiatives aimed at improving sleep hygiene and addressing sleep disorders. As the body of evidence linking sleep deprivation to cognitive deficits grows, it becomes increasingly important to understand the neural mechanisms behind these impairments and to develop interventions that can help mitigate these effects.

Future research should focus on exploring the long-term effects of sleep deprivation on cognitive aging and the potential for sleep interventions to improve brain health. Studies could investigate whether cognitive training or pharmacological treatments could offset the negative impacts of sleep deprivation, particularly in vulnerable populations. Additionally, research examining the role of sleep in memory consolidation and emotional regulation in clinical populations (e.g., those with neurodegenerative diseases) could yield valuable insights into how sleep can be leveraged as a therapeutic tool.

Conclusion

In conclusion, the current narrative review underscores the profound impact of sleep deprivation on cognitive functions, particularly memory, attention, and emotional regulation. A range of studies consistently demonstrates that insufficient sleep, whether acute or chronic, impairs both short-term and long-term cognitive processes, with significant consequences for individuals' day-to-day functioning. The neurobiological mechanisms underlying these effects involve alterations in brain structures responsible for memory consolidation and emotional regulation, such as the prefrontal cortex and hippocampus. Moreover, sleep deprivation is shown to impair cognitive performance across various domains, including working memory, decision-making, and emotional processing.

While much of the research highlights the detrimental effects of sleep loss on cognition, it is also clear that the extent of these effects is influenced by factors such as the duration of sleep deprivation, individual sleep needs, and age-related changes in sleep architecture. Notably, the review also emphasizes the importance of sleep for older adults, whose cognitive vulnerabilities may be exacerbated by chronic sleep disturbances. As such, addressing sleep deprivation has important implications not only for everyday functioning but also for mental health and the prevention of cognitive decline in aging populations.

Moving forward, there is a critical need for further research to explore potential interventions and strategies to mitigate the cognitive consequences of sleep deprivation. Interventions could include sleep hygiene education, pharmacological treatments, and cognitive behavioral therapy for insomnia, all aimed at improving sleep quality and duration. Additionally,

greater attention should be given to understanding how sleep interventions can be tailored to specific age groups and cognitive conditions, particularly for those at greater risk of cognitive decline.

Ultimately, this review highlights the complex relationship between sleep and cognition, underscoring the importance of adequate and restorative sleep for maintaining optimal cognitive health throughout life. Further advancements in both basic and clinical research are essential to better understand the long-term effects of sleep deprivation on cognition and to develop effective strategies for mitigating its impact on the brain.

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