Exploring Non-Invasive Methods to Improve Cognition via Sleep Manipulation

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Thesis summary

On average, we spend one-third of our lives asleep, and we have little idea why. Despite the importance of sleep to overall health, sleep has been neglected for decades and considered an inactive state in which the brain "turns off" to rest from daily activities. However, there is now compelling evidence that sleep plays a pivotal role in various domains, including learning and memory, physical and mental wellbeing. The work described in this thesis is centred around exploring non-invasive ways of manipulating sleep to enhance cognition.

Chapter 2 delves into the effects of wearing an eye mask to block out light during sleep and its implications for daily life. This simple and cost-effective manipulation resulted in enhanced reaction times and better memory encoding compared to a control condition. Such improvements are particularly advantageous in situations demanding rapid reflexes, like driving. Furthermore, the benefits can extend to academic and professional spheres, leading to enhanced performance across diverse tasks.

Chapter 3 investigates whether sleep facilitates insight problem solving. We found that offline consolidation and reorganisation of memories had a beneficial effect on insight, but this result was confounded by the influence of circadian rhythms.

Finally, **Chapter 4** explores the potential benefits of an experimental technique called targeted memory reactivation (TMR) applied during rapid eye movement (REM) sleep for arousal processing. Our manipulation resulted in a reduction of emotional reactivity, as demonstrated by objective measurements of arousal. Notably, the effect of cueing on subjective arousal responses was tied to participants'

baseline arousal levels.

In conclusion, this thesis provides valuable insights into the importance of sleep in enhancing cognitive functions and sheds light on non-invasive interventions whose implications extend far beyond the laboratory and into everyday life.

Declaration and Statements

Declaration

This thesis is the result of my own independent work, except where otherwise stated, and the views expressed are my own. Other sources are acknowledged by explicit references. The thesis has not been edited by a third party beyond what is permitted by Cardiff University's Use of Third Party Editors by Research Degree Students Procedure.

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This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is it being submitted concurrently for any other degree or award (outside of any formal collaboration agreement between the University and a partner organisation).

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List of Abbreviations

AASM American Academy of Sleep Medicine

ACC Anterior cingulate cortez

ACh Acetylcholine

ASC Active system consolidation

BDNF Brain-derived neurotrophic factor

BiOtA Broader form of the iOtA model

DH Dreem headband

EEG Electroencephalography

EMG Electromyography

EOG Electrooculography

fMRI Functional magnetic resonance imaging

FWE Family-wise error

FDR False discovery rate

GPT Generic part technique

HRD Heart rate deceleration

IADS International affective digitized sounds

IAPS International affective picture system

iOtA Information overlap to abstract

mPFC Medial prefrontal cortex

MVPA Multivariate pattern analysis

N1 Non-REM sleep stage 1

N2 Non-REM sleep stage 2

NREM Non-rapid eye movement (sleep)

OFC Orbitofrontal cortex

PAL Paired associate learning

PANAS Positive and negative affect scale

PET Positron emission topography

PGO Ponto-geniculo-occipital waves

PSG Polysomnography

PVT Psychomotor vigilance test

REM Rapid eye movement (sleep)

ROI Regions of interest

RSA Representational similarity analysis

SCN suprachiasmatic nucleus

SD Standard deviation

SEM Standard error of the mean

SFSR Sleep to Forget, Sleep to Remember

sgACC Subgenual anterior cingulate cortex

SHY Synaptic homeostasis hypothesis

SOs Slow oscillations

SSS Stanford sleepiness scale

SWA Slow wave activity

SW-Rs Sharp wave-ripples

SWS Slow wave sleep

tSOS Transcranial slow oscillation stimulation

TMR Targeted memory reactivation

TST Total sleep time

Chapter 1

General Introduction

1.1 Preface

Every night, we collectively lose consciousness. From an evolutionary perspective, sleep may seem to be the most foolish of biological phenomena, as it disconnects us from the outside world and our own bodies, leaving us vulnerable to predation while our minds wander in the most bizarre places.

It has long been unclear why we sleep. Interestingly, it's not just humans who sleep, but most living organisms, including birds, fish, flies, plants, and worms (Siegel, 2008; Zielinski et al., 2016). Given the ubiquity of sleep across different species, it's evident that it serves critical functions and offers significant benefits for the organisms. Yet, defining these precise benefits and functions remains a compelling and unresolved question.

The discovery of the electroencephalogram (EEG) enabled the recording of human brain activity in real time, thus allowing the investigation of the nature of sleep. In 1929, the German psychiatrist Hans Berger demonstrated that the low-voltage activity associated with wakefulness gradually transitions to a higher-voltage and lower-frequency rhythm when the subject falls asleep (Datta et al., 2008). Soon enough, the sleeping brain was found to be a non-homogeneous state characterised by different sleep stages and oscillatory patterns that serve various functions (Siegel, 2008; Zielinski et al., 2016). Thanks to the research that has been conducted in the last decades, we now know that sleep is not "*the biggest mistake that evolution has ever made*" (Mignot, 2008). Instead, it has been found to be restorative for our brain, body, and mind. Suggested benefits include learning and memory consolidation (Diekelmann & Born, 2010; Rasch & Born, 2013), processing of emotional information and recalibration of emotional brain circuits (Helm & Walker, 2010; Walker, 2009), regulation of metabolism, immune system, and hormones (Mignot, 2008; Zielinski et al., 2016). The work presented in this

thesis aims to enhance our understanding of the relationship between sleep and the brain, emphasising non-invasive approaches to manipulating sleep to optimise its positive effects on cognition. The focus of this research is on exploring techniques and strategies for manipulating sleep to benefit learning and memory, stimulate creativity, and alleviate the effects of negative emotions.

Sleep has been extensively demonstrated to be involved in three memory processes: encoding, consolidation, and retrieval. As compared to memory encoding and retrieval, which are best served when the brain is awake, memory consolidation benefits from the decreased level of sensory processing during sleep (Diekelmann et al., 2011; Ellenbogen et al., 2006; van der Heijden et al., 2022). Notably, during consolidation, memories are not only strengthened but also integrated into pre-existing knowledge networks, transformed, and restructured thanks to a process that involves the repeated reactivation of memory traces during sleep (Diekelmann & Born, 2010; Rasch & Born, 2013). Despite initial theories that offered a passive view of sleep and believed that it consisted of a time when the brain shuts down, it is now widely accepted that sleep is an active time for the brain. In fact, during sleep, the brain selectively reactivates memory by replaying specific patterns of neuronal activity similar to those observed during awake learning (Skaggs & McNaughton, 1996; Wilson & McNaughton, 1994). This replay appears to be critical for the transfer of information from the hippocampus to the neocortex, where it becomes integrated into pre-existing long-term memories (Bergmann et al., 2012; Maquet et al., 2000; Peigneux, 2015; Peigneux et al., 2004; Rasch & Born, 2013; Schönauer et al., 2017; Zhang et al., 2018). This process also seems to be tied to a qualitative transformation of memories and indeed, sleep has been shown to facilitate the abstraction of general rules (e.g., Durrant et al., 2011; Ellenbogen et al., 2007; Wagner et al., 2004), the integration of distinct elements into unified concepts (e.g., Lewis & Durrant, 2011) and the emergence of false memories (e.g., Payne et al., 2009). Beyond integration, memory representations can be disinte-

grated and recombined, allowing associative thinking and creativity (Cai et al., 2009; Monaghan et al., 2015; Sio et al., 2013) and the processing of emotional memory (Helm & Walker, 2010; Hutchison et al., 2021; Walker, 2009). Nowadays, many studies in both animals and humans make use of a technique referred to as targeted memory reactivation (TMR) to manipulate memory processing during sleep. TMR pairs sensory cues with a memory during awake encoding and then presents them again during sleep to bias memory consolidation (Hu et al., 2020; Oudiette & Paller, 2013; Rasch et al., 2007).

The goal of this thesis is to investigate ways of manipulating sleep to enhance cognition. In this general introduction, I will begin by giving a comprehensive summary of the present state of knowledge of sleep physiology and its oscillatory patterns. Next, I will delve into the link between sleep and memory, beginning with an exploration of memory systems and processes, followed by an introduction to the most prominent models of sleep and memory. Emphasis will be placed on the reactivation of memories during sleep. Finally, I will conclude by identifying the central questions that this thesis intends to answer.

1.2 Sleep physiology

Polysomnography is the gold standard method used to investigate the complexity of sleep physiology. It consists of a combination of electroencephalography (EEG), electrooculography (EOG), and electromyography (EMG) recordings from electrodes attached to the scalp, beside the eyes, and on the chin, respectively (Iber et al., 2007). Polysomnography recordings in humans have revealed that sleep is not uniform but consists of distinct physiological stages characterised by different oscillatory patterns (Figure 1.1).

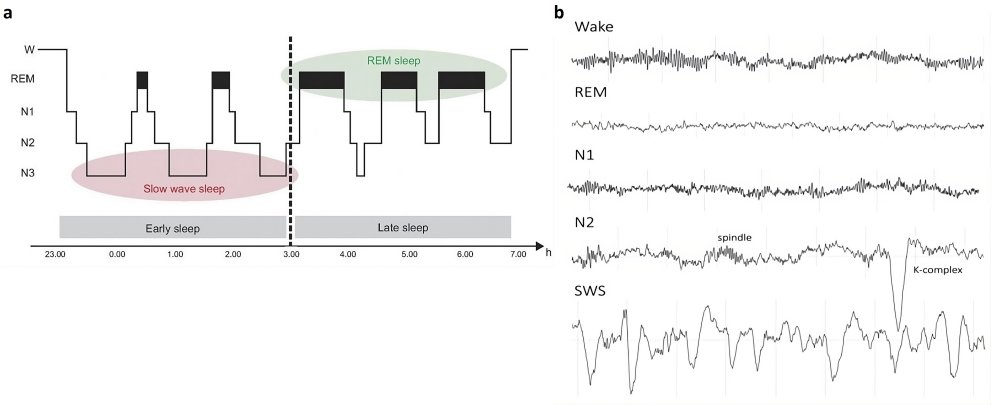


Figure 1.1: *Sleep architecture and oscillatory patterns.* **(a)** Hypnogram. Human sleep alternates in cycles between non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep. Stages 3 and 4 of NREM are jointly referred to as slow wave sleep (SWS). Earlier periods of sleep are rich in SWS, whereas later periods contain greater amounts of REM sleep. Figure adapted from Rasch and Born, 2013. **(b)** Exemplary EEG traces for wake and each of the sleep stages. K-complexes and sleep spindles are key features of stage 2 of NREM sleep, while slow oscillations and delta waves prevail during SWS.

The two major sleep stages that can be distinguished are Rapid Eye Movement (REM) sleep and Non-Rapid Eye Movement (NREM) sleep. The latter can be further subdivided into four stages: the lighter sleep stages 1 and 2, and the deeper sleep stages 3 and 4, now jointly referred to as slow wave sleep (SWS; Iber et al., 2007). NREM and REM sleep alternate or "cycle" across the night approximately every 90 minutes. Within each cycle, the ratio of NREM to REM varies throughout the night: NREM sleep predominates during the first half of the night, but as the night progresses, the length of REM periods becomes longer (see hypnogram in Figure 1.1a).

When transitioning from wakefulness to sleep, people typically spend a short period in Stage 1 of NREM sleep. This stage only accounts for up to 10% of the total sleep time (TST) and is characterised by low-amplitude mixed-frequency activity (2-7 Hz) and less than 50% of the wake-like alpha rhythm (8-13 Hz; Moser et al.,

2009; Silber et al., 2007). Sharply contoured waves called vertex sharp waves and slow rolling eye movements can also be observed (Silber et al., 2007).

Stage 1 of NREM is typically followed by Stage 2, which takes up approximately 45–55% of the TST. As shown in Figure 1.1b, sleep spindles and K-complexes are the two pronounced oscillatory events that characterise this sleep stage (however, spindles can be also found during deeper sleep stages).

Sleep spindles are waxing and waning bursts of high-frequency activity that last about 0.5 to 3 seconds. They are generated in the thalamic reticular nucleus and then propagated into cortical regions through thalamocortical projections (De Gennaro & Ferrara, 2003). Their exact frequency range is still being debated; however, spindles are generally considered to be in the 10–15 Hz range and often further divided into slow spindles ($<$ 13 Hz), which predominate in frontal cortices, and fast ($>$ 13 Hz) spindles, which predominate in centroparietal areas (Andrillon et al., 2011; De Gennaro & Ferrara, 2003; Fernandez & Lüthi, 2020; Schabus et al., 2007; Ulrich, 2016). Sleep spindles are primarily associated with memory consolidation, learning, and intellectual abilities (Fernandez & Lüthi, 2020; Ulrich, 2016). For instance, evidence of their involvement in memory consolidation comes from a study conducted by Schabus and colleagues in which participants performed a declarative word-pair association task. Overnight change, computed as the number of recalled words in the evening after learning minus the number of recalled words in the morning after the intervening night, correlated significantly with increased spindle activity (Schabus et al., 2004). Similarly, Morin and colleagues trained participants on a motor sequence task and retested their performance the following morning after a night of sleep. Both the number and duration of sleep spindles were higher in post-training sleep (Morin et al., 2008). In addition to the above-mentioned functions, sleep spindles have also been linked to plastic neuronal modifications, sleep protection against environmental disturbances, and cognitive dysfunction (Astori et al., 2013; Bergmann et al., 2008; Rasch & Born, 2013).

K-complexes represent the largest event in a healthy human EEG. They have a widespread brain topography, although their maximal amplitude is typically frontal. K-complexes consist of high amplitude waves, made up of a negative sharp wave followed by a longer-lasting positive component; a shorter positivity precedes the negative wave but it is not easily discernible by eyes (Colrain, 2005; Ioannides et al., 2019). Functionally, k-complexes are believed to serve a sleep-protecting mechanism and a "sentinel" function that (1) evaluates the salience and/or alarm of internal and external signals; (2) promotes sleep maintenance; (3) suppresses cortical arousal; (4) promotes wakefulness (Ioannides et al., 2019; Jahnke et al., 2012). Additionally, they are considered a physiological correlate of arousal, as evidenced by their association with typical signs of arousal such as increases in heart rate and blood pressure, and respiratory shifts (Forget et al., 2011).

Sleep deepens further into SWS which makes up 15-20% of TST in young adults (this percentage decreases with aging). SWS is defined by the presence of four oscillatory rhythms: slow (SOs, 0.5-1 Hz) and delta oscillations (1-4 Hz), whose combined denomination is Slow Wave Activity (SWA, 0.5-4 Hz; see Figure 1.1b), spindles (10-15 Hz) and ripples (Iber et al., 2007). SOs, in addition to their low frequency, have a large peak-to-peak amplitude of at least 75 μV and an average peak-to-peak duration of 1 s. SOs are considered to be the pacemaker of brain activity during sleep, as they comprise a DOWN or hyperpolarization state and a UP or depolarisation state that reflects synchronous alterations in the membrane potential of neocortical neurons. SOs DOWN states are associated with neuronal silence, whereas SOs UP states with vigorous wake-like neuronal firing; both states last a few hundred milliseconds (Massimini et al., 2004; Mölle et al., 2011; Nir et al., 2011). The other two prominent oscillations that characterise SWS are spindles - also present in S2 and discussed above - and sharp wave-ripples (SW-Rs). SW-Rs are composed of ripples and sharp waves. Sharp waves are fast depolarizing

events generated in the CA3 region of the hippocampus, on which ripples are superimposed. Ripples are rapid bursts of elevated (100-300 Hz) neuronal activity generated in the CA1 region of the hippocampus (Buzsáki, 1986; Rasch & Born, 2013). Evidence suggests that these waves contribute to various aspects of memory, such as memory consolidation and retrieval (Buzsáki, 1986).

SWS has been linked to both cognitive and physiological functions (Léger et al., 2018). While SWS's cognitive functions will be discussed later in more detail (see section 1.3.3), it is worth mentioning its involvement in several important physiological activities. SWS supports the immune system's response to infection by producing pro-inflammatory cytokines (Lange et al., 2010) and plays a role in clearing metabolic waste, such as β-amyloid (Léger et al., 2018). Moreover, SWS is associated with glucose regulation and the release and regulation of hormones. Regarding the former, a study conducted in young healthy adults showed that SWS deprivation resulted in a significant reduction of glucose tolerance and an increase in type 2 diabetes risk (Tasali et al., 2008). Regarding the latter, there is evidence for a reduced release of growth hormone being linked to SWS deprivation (e.g., Van Cauter et al., 2008).

The last sleep stage is REM sleep, which when discovered in 1953 contradicted the general impression of sleep as a passive state (Aserinsky & Kleitman, 1953). In fact, REM sleep, which accounts for 25% of TST, is also referred to as *paradoxical sleep* because it displays EEG activity that closely resembles wakefulness with oscillations predominantly within the theta (4-7 Hz) and gamma (25-80 Hz) band ranges (Iber et al., 2007; Steriade et al., 1996). Moreover, REM sleep is characterized by skeletal muscle atonia (very low muscle tone) visible in the EMG, peripheral muscle twitches, and pronounced fluctuations in temperature and cardio-respiratory rhythms (Peever & Fuller, 2017). REM sleep is composed of two different microstates, namely phasic and tonic periods. Tonic REM is considered to be a quiescent period in between periods of phasic activity charac-

terized by ponto-geniculo-occipital (PGO) waves, bursts of eye movements (EM), sawtooth waves, myoclonic twitches and periods of marked respiratory and heart rate irregularities (Simor et al., 2020). REM sleep has been shown to be involved in the formation and consolidation of memories, such as procedural (Peigneux et al., 2003), declarative (Fogel et al., 2007) and emotional (Helm & Walker, 2010) memories. Furthermore, it has also been involved in the reorganization of synaptic plasticity in the cortex (Almeida-Filho et al., 2018; Pereira & Lewis, 2020; Zhou et al., 2020). However, even though REM was discovered more than 60 years ago, evidence regarding its specific functions and mechanisms remain rather elusive although a consistent amount of evidence is provided by animal studies (e.g., Peever & Fuller, 2017; Rasch & Born, 2013; Simor et al., 2020). For instance, PGO waves, bursts of large electric potentials that originate in the pons and propagate in the lateral geniculate nucleus and occipital cortex cannot be identified on a human scalp EEG, therefore they have been extensively studied in cats, rats, and primates (Gott et al., 2017). These waves, together with theta waves, have been proposed as a mechanism of synaptic plasticity (Rasch & Born, 2013).

As previously mentioned, NREM and REM sleep cycle throughout the night, with NREM sleep being more prevalent in the early part of the night. This pattern is explained by the theoretical model of sleep and wake regulation proposed by Borbely (Borbely, 1982; Borbély et al., 2016). In this model, the interaction between the homeostatic sleep pressure (Process S) and the circadian pacemaker, an internal body clock operating on an approximately 24-hour rhythm (Process C), is key. The longer one stays awake, the more homeostatic sleep pressure accumulates, influencing the duration of SWS during the subsequent sleep period. This pressure diminishes throughout the sleep cycle, leading to a higher proportion of SWS shortly after sleep onset when the pressure is at its peak. Furthermore, these two processes are crucial in determining the quality and timing of sleep onset and offset. The influence of external stimuli, particularly light, plays a significant

role in this context: the duration and timing of light exposure can lead to either a phase advance, shifting the circadian rhythm to an earlier time, or a phase delay, shifting it to a later time. Consequently, light exposure can affect various aspects of sleep, including its duration, timing, structure, and quality. This interplay between light, sleep patterns, and circadian rhythms is not only fundamental to understanding sleep itself but also has implications for learning and memory, which will be explored in more detail in Chapter 2.

1.3 Sleep and memory

Of the many advantages conferred by sleep, this thesis will primarily examine sleep's impact on memory. To provide context, an overview of memory systems and processes will be provided. The subsequent discussion will delve into the crucial role that sleep plays in memory, citing prominent theories that support this claim.

1.3.1 Memory systems

The notion that memory is not a single entity has been acknowledged for a long time. However, the first empirical evidence to support this idea was presented by Brenda Milner in 1957 through her study of the patient H.M., who underwent a bilateral resection of the medial temporal lobe to treat intractable epilepsy. Surprisingly, after the surgery, he was still able to learn new tasks, such as hand-eye coordination, even though he had no recollection of previous learning experiences (Squire & Dede, 2015). This finding indicated that memory is not confined to a single structure but is instead composed of multiple systems that rely on different neuroanatomical structures. A comprehensive overview of the various types of memory has been reported by Henke (Henke, 2010) and it is depicted in Figure 1.2.

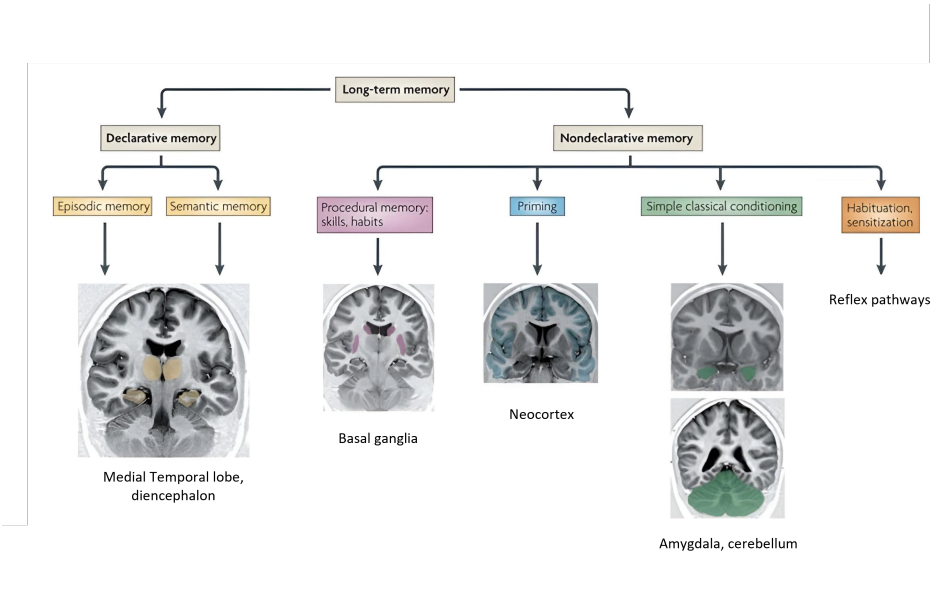


Figure 1.2: *Organisation of long-term memory systems and associated brain structures.* Modified from Henke, 2010.

The above figure illustrates the categorization of long-term memory into two primary types: declarative (explicit) and nondeclarative (implicit) memory (Henke, 2010; Squire & Dede, 2015; Squire & Zola, 1996). Declarative memory refers to the conscious recollection of information, and it can be further subdivided into memories for facts (semantic memory) and memories for events (episodic memory). Semantic memory refers to memories of information stored in the absence of contextual knowledge, whereas episodic memory is embedded in a specific spatiotemporal context. Non-declarative memories are instead linked to unconscious learning and retrieval capacities, and they can be classified into several subtypes. The first subtype, procedural memories, refers to the learning of skills, such as riding a bike or playing an instrument; the second, priming, involves performance enhancement due to prior exposure to related information; the third, conditioning, involves the association of two unrelated stimuli to learn a new response; and finally, non-associative learning refers to the attenuation or augmentation of a response towards a repeated presentation of a stimulus (Henke, 2010; Rasch & Born, 2013; Squire & Dede, 2015; Squire & Zola, 1996). The integrity of the

medial temporal lobe system, which includes the hippocampus and entorhinal, perirhinal, and parahippocampal cortices, is thought to be essential for declarative memories. In contrast, nondeclarative memories are generally considered to be hippocampus-independent (Squire & Dede, 2015; Squire & Zola, 1996).

1.3.2 Memory processes

Memory is formed over time through three distinct processes: encoding, consolidation, and retrieval. Encoding comprises the formation of new memory traces following the perception of a stimulus. These newly encoded traces are initially labile and susceptible to chance and forgetting, but they become increasingly robust and resistant to interference through consolidation. During this process, the new memory traces are integrated into pre-existing long-term memory networks (Rasch & Born, 2013).

Consolidation involves two steps: synaptic and system consolidation. The initial step is accomplished at a synaptic level within minutes or hours after learning and leads to enduring changes in synaptic connections (Kandel, 2001). Synaptic consolidation is then supplemented by system consolidation which redistributes synaptic connectivity across different brain areas (Frankland & Bontempi, 2005). These changes enable the newly encoded information to become part of long-term memory, providing a basis for later retrieval (Rasch & Born, 2013). However, two significant challenges arise: how newly learned material becomes permanently accessible without overwriting old memories, and how the brain determines what information to store or forget.

The **standard two-stage model of memories** (Marr, 1971) offered a solution to the first issue, and nowadays, it constitutes the most influential model of human memory. The model suggests that effective learning requires two complemen-

tary systems: the hippocampus and the neocortex. During wakefulness, the hippocampus acts as a fast-learning storage where new memory traces are temporarily stored. These memories are gradually transferred into the neocortex, a long-term slow-learning storage system. The model further proposes that the transfer process (from the short-term store to the long-term one) occurs slowly via repeated and spontaneous reactivation of hippocampal-cortical networks. Over time, network reactivation increases the stability and strength of cortico-cortical connections, allowing integration of the traces into pre-existing neocortical knowledge networks. Ultimately, this results in memories becoming hippocampal-independent (Frankland & Bontempi, 2005; Marr, 1971; Squire & Alvarez, 1995). These complementary memory systems allow the storage of new memories without interfering with existing ones.

With respect to the second challenge - how the brain determines what information to store or forget - it seems sensible that information in some way relevant for adapting to the environment or important for upcoming challenges will be preferred. In this context, emotions have been shown to play a significant role in labelling which information will be stored in memory and which will be forgotten (Dolan, 2002; Williams et al., 2022). Numerous studies have demonstrated that emotional stimuli are better remembered than their neutral counterparts, largely due to the modulatory role played by the amygdala in the process of hippocampal-dependent memory formation (Anderson et al., 2003; McGaugh, 2000; McGaugh & Roozendaal, 2002; Vuilleumier et al., 2001; Whalen et al., 1998). Indeed, during the initial encoding phase, the amygdala rapidly responds to emotional stimuli, often before conscious awareness, thereby enhancing attention to prioritise the processing of these stimuli. In later stages of memory formation, it modulates the effects of stress hormones in the consolidation of hippocampal-dependent memories (Diano et al., 2017; Phelps, 2004). As a result, emotionally charged events are more readily remembered.

The hippocampo-cortical information transfer of memories is a continuous process that occurs not only during wakefulness but also during offline periods including sleep. Sleep, indeed, is an ideal time window for these processes to occur as it protects memories from interference by preventing encoding of new information (Ellenbogen et al., 2006; Rasch & Born, 2013).

1.3.3 Models of sleep and memory

Although as early as 1885 Ebbinghaus published a seminal study demonstrating the effect of time on forgetting (i.e. forgetting is reduced when followed by a period of sleep), the interest in studying the relationship between sleep and memory was reignited only in the late 1980s with a variety of studies demonstrating the beneficial effects of NREM and REM sleep on memory consolidation (see Rasch & Born, 2013, for a review). A differential role of these two sleep stages in the consolidation of different types of memory was theorised by the **Dual Process Hypothesis** (Gais & Born, 2004; Rasch & Born, 2013; Smith, 2001). This account assumes that hippocampus-dependent declarative memories are linked to NREM sleep, while REM sleep benefits the consolidation of nondeclarative memories, such as procedural and emotional. The Dual process hypothesis is supported by human studies that employed the "night–half paradigm", in which participants' memory performance is compared across retention intervals including the early half (rich in NREM sleep) and the late half of the night (rich in REM sleep). However, this methodology overlooks the fact that neither the early nor the late half of the night contains one stage of sleep. Furthermore, subsequent experiments have not consistently demonstrated this distinction (e.g., Fogel et al., 2007; Huber et al., 2006; Rauchs et al., 2004), and theoretical accounts have proposed that the cyclic succession of NREM and REM sleep may constitute the key to successful overnight memory consolidation.

The **Sequential hypothesis** (Ambrosini & Giuditta, 2001; Giuditta et al., 1995) stresses this concept and assumes that during SWS, non-adaptive or irrelevant memory traces are downscaled (or eliminated), while useful memories are strengthened. Subsequently, during REM sleep, these adaptive memories are integrated with pre-existing memories. Supporting evidence for the Sequential hypothesis has been originally obtained from studies conducted with animals (e.g., Ambrosini et al., 1992; Ambrosini et al., 1995) and then confirmed in humans (e.g., Ficca et al., 2000; Mednick et al., 2003; Stickgold et al., 2000). For example, Ficca and colleagues investigated the impact of sleep cycle disorganisation on the recall of verbal material in young adults and demonstrated that morning recall was significantly affected by sleep cycle disorganisation (Ficca et al., 2000).

The **Active System Consolidation Hypothesis** (ASC, Diekelmann & Born, 2010; Rasch & Born, 2013, Figure 1.3) represents the most prominent model in the field. It originates from the Standard two-stage model of memories (see section 1.3.2) and argues that sleep is not merely a passive state but is actively involved in memory consolidation. Furthermore, central to this model is the concept that newly encoded memory representations are repeatedly reactivated during sleep, a vital process for consolidation. During encoding, labile memory traces are stored temporarily in the hippocampus. Subsequently, during SWS, these traces undergo repeated reactivation, facilitating their gradual transfer to the cortex for long-term storage (Figure 1.3A). The involvement of SWS in memory processing is well-documented (Diekelmann & Born, 2010; Rasch & Born, 2013; Walker, 2009), highlighting its importance in this model. A critical aspect of the transfer of memory traces involves the precise temporal synchronization of three key oscillations during SWS: neocortical slow oscillations, thalamo-cortical spindles, and hippocampal sharp wave ripples (Figure 1.3B). The SOs up-states trigger memory reactivations in tandem with hippocampal ripples. Ripples have been shown to occur in the troughs of spindles, which are in turn coupled with the SOs up-states.

This intricate coupling is essential for the efficient transfer of reactivated memory traces, thereby facilitating their integration into the neocortex (Rasch & Born, 2013).

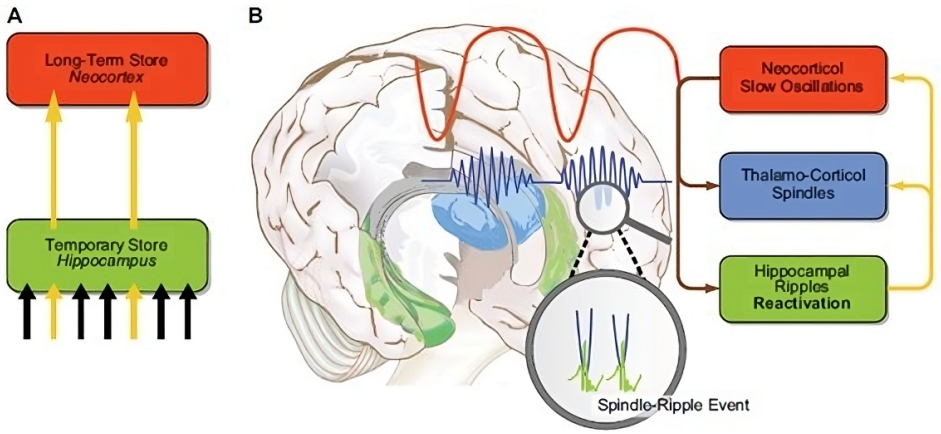


Figure 1.3: *The Active System Consolidation Hypothesis.* **(A)** Newly acquired memories are encoded into a temporary store, the hippocampus, and transferred to the long-term neocortical store during SWS. **(B)** The cortico-hippocampal dialogue is orchestrated by neocortical slow oscillations (red), thalamo-cortical spindles (blue), and hippocampal sharp-wave ripples (green). Source: Rasch and Born, 2013.

The hypothesis further suggests that the temporal synchronization of SWS-related oscillations not only supports memory reactivation but also leads to a qualitative reorganization of memories, involving their redistribution and transformation. Additionally, REM sleep contributes to the stabilization of these transferred memories through synaptic consolidation. Empirical evidence from various studies bolsters this hypothesis. For example, research in rodents using paradigms like fear conditioning or object recognition tasks has demonstrated the necessity of this coupling for effective consolidation (Latchoumane et al., 2017; Maingret et al., 2016). Similarly, human intracranial EEG recordings in epilepsy patients have corroborated these findings (Helfrich et al., 2019; Jiang et al., 2019). Finally, the coupling between SOs and spindles was shown to correlate with performance improvements on several memory tasks (for instance Hahn et al., 2020; Muehlroth et al., 2019; Schreiner et al., 2021).

An alternative hypothesis for the mechanisms underlying memory consolidation

during sleep has been offered by the **Synaptic Homeostasis Hypothesis** (SHY, Tononi & Cirelli, 2003, 2006, Figure 1.4). It postulates that wakefulness is accompanied by a net increase in synaptic strength that progressively saturates learning abilities. Sleep, as an antidote, promotes synaptic downscaling, renormalizing the net synaptic strength and restoring the brain's ability for future encoding (synaptic homeostasis), while maintaining certain memory traces. Further, this renormalization mechanism is proposed to occur during SWA, a hallmark of SWS. This hypothesis has been corroborated by sleep deprivation studies that demonstrated that memory performance is worse after waking than sleep (Ashton et al., 2020; Gais et al., 2006; Yang et al., 2012) and by studies that highlighted that the amount of SWA predicts memory performance after sleep (Ferrarelli et al., 2019; Huber et al., 2006). Crucially, SHY suggests that memories tagged as important are weakened less - or relatively strengthened - overnight than irrelevant memories, thus promoting the consolidation and integration of memories (Tononi & Cirelli, 2003, 2006, 2014; Wilhelm et al., 2014).

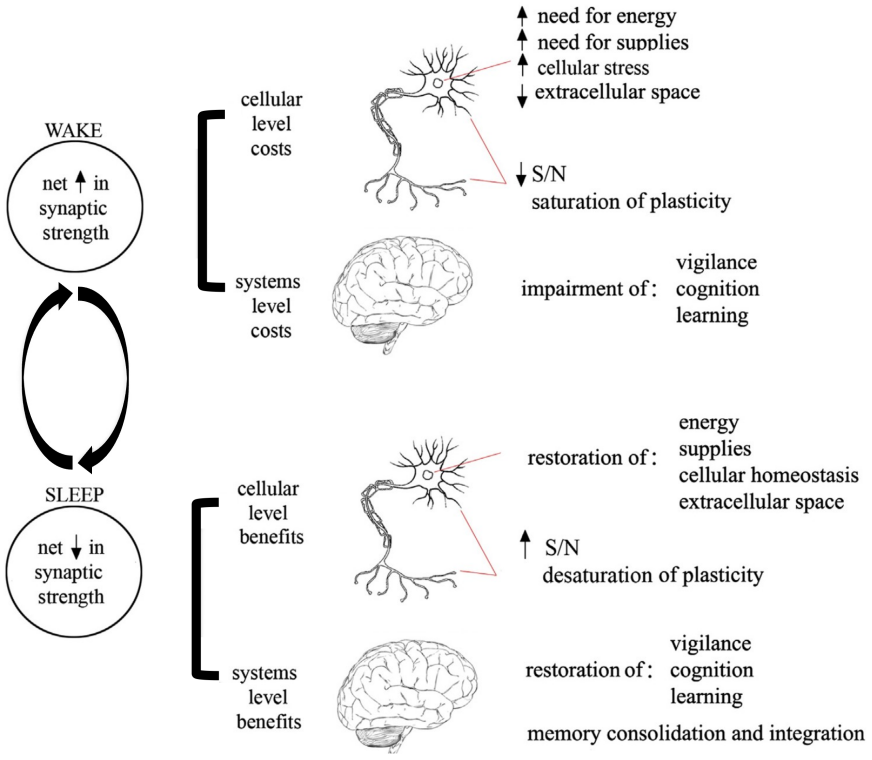


Figure 1.4: *Synaptic Homeostasis Hypothesis.* Modified from Tononi and Cirelli, 2014.

There is evidence of a more rapid transfer of information from the hippocampus to the neocortex if the new set of information to be acquired is compatible (overlaps) with an existing framework of organised knowledge, called *schema* (Tse et al., 2007; Van Kesteren, Fernández, et al., 2010; Van Kesteren, Rijpkema, et al., 2010). The **Information overlap to abstract** (iOtA) model developed by Lewis and Durrant explains the underlying mechanisms of this facilitation effect and the role sleep plays in it (Lewis & Durrant, 2011). The model states that during SWS, the replay of overlapping memories is strengthened through Hebbian plasticity, representing the core mechanism for schema formation. Synaptic interconnections between neurons that code for shared elements are strengthened and survive SWS downscaling (Abbott & Nelson, 2000; Lewis & Durrant, 2011; Tononi & Cirelli, 2003, 2006). Thereby, only newly learned information that overlaps with an existing schema and is reactivated on multiple occasions will be potentiated and incorporated into the schema. The replay of overlapping memories in SWS leads to the extraction of commonalities or 'gist' (the core of a memory), promoting both a quantitative and a qualitative reorganisation of memory representations (Durrant et al., 2011; Ellenbogen et al., 2007; Lewis & Durrant, 2011). The iOtA model is the foundation of the **Broader Form of the iOtA Model** (Lewis et al., 2018, BiOtA), which integrates REM sleep into the framework. The BiOtA model emphasizes the significance of the cyclic structure of a night's sleep, in which NREM and REM alternate. During NREM sleep, the replay of thematically related memories is enhanced, while during REM sleep, the connections between seemingly disparate concepts are recognised, resulting in the formation of new connections between concepts (Figure 1.5; Lewis et al., 2018). The interleaving of these two stages could explain the role of sleep in creativity and problem-solving.

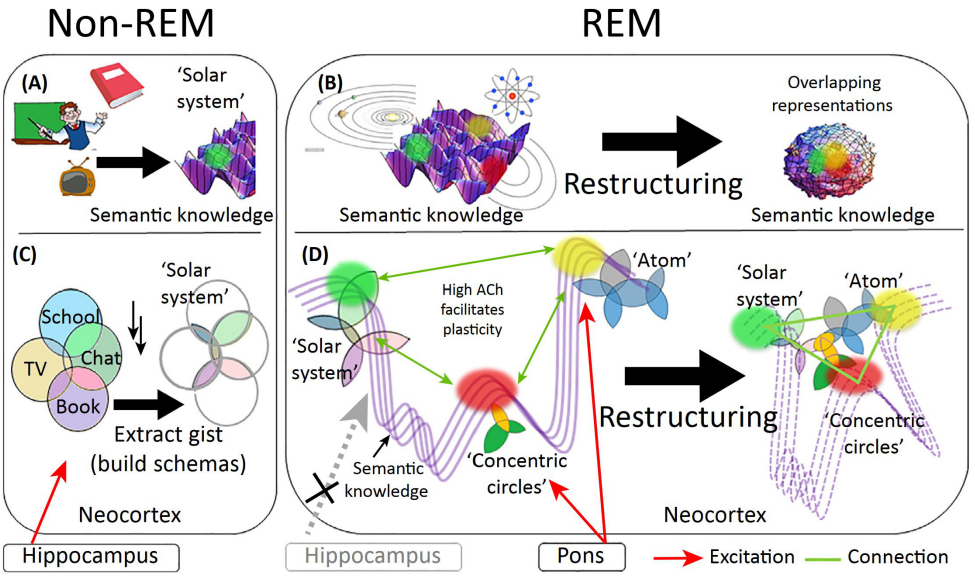


Figure 1.5: *The BiOtA model.* **A** and **B** provide a simpler representation of **C** and **D**. **(A-C)** During NREM sleep, overlapping memories are replayed in the neocortex. Areas of overlap are strengthened, leading to general abstraction or the formation of new schemas. **(B-D)** During REM sleep, connections between the hippocampus and the neocortex are lost, and PGO waves trigger activity in other schemas, allowing the detection of similarities between schemas that, once found, lead to the restructure of knowledge. Modified from Lewis et al., 2018.

Finally, as briefly mentioned in Section 1.3.2, a substantial body of research suggests that emotional memories are preferentially consolidated across sleep (Alger et al., 2018; Cairney et al., 2014; Cunningham et al., 2014; Groch et al., 2013; P. Hu et al., 2006; Nishida et al., 2009; Tempesta et al., 2015; Wagner et al., 2001; Wagner et al., 2006); however, see (Lipinska et al., 2019) that challenges this view. According to the **Sleep to Forget, Sleep to Remember Hypothesis** (SFSR), while the content (the information) of emotional memories is strengthened over time, the affective responses associated with their recall are attenuated across multiple nights of sleep (Helm & Walker, 2010; Walker, 2009). It is therefore possible that time plays a vital role in modulating sleep's impact on the visceral charge (emotional strength) of emotional memories. Moreover, the SFSR hypothesis also suggests that REM sleep, because of its unique biology, represents a particular

brain state for the consolidation and modulation of emotional memories, and a variety of studies have confirmed this hypothesis (Groch et al., 2013; Groch et al., 2015; Harrington et al., 2018; Helm & Walker, 2010; Hutchison et al., 2021; Menz et al., 2013; Menz et al., 2016; Nishida et al., 2009; Payne et al., 2012; Wagner et al., 2001; Wagner et al., 2006; Wassing et al., 2019). Indeed, during REM sleep we observe (1) increased activity in limbic and paralimbic structures, which are key brain regions involved in the formation and consolidation of emotional memories; (2) theta oscillations, which propagation in limbic and prefrontal regions are believed to modulate affective experiences in both animals and humans; (3) increased concentrations of acetylcholine (ACh) - crucial for the long-term consolidation of emotional learning - and reduced concentration of noradrenergic and serotonergic input to the cortex, associated with lower levels of stress and anxiety (see Helm & Walker, 2010; Walker, 2009, for reviews).

1.4 Memory reactivation

Before diving into different studies conducted on animals and humans on memory reactivation, it is crucial to clarify some technical terms. Genzel and colleagues provided definitions to facilitate the use of a common language among researchers (Genzel et al., 2020). As per their definitions, the term reactivation refers to the re-emergence of a previously encoded pattern at a later point in time, whereas replay directly assesses the temporal structure of the sequential information (Genzel et al., 2020). This terminology will be used throughout the thesis.

1.4.1 Animal studies

The first evidence of spontaneous memory replay during sleep is found in the rodent literature on place cells. Place cells are hippocampal CA1 pyramidal neurons that fire selectively when the animal occupies a specific location in the environment, known as place fields (Girardeau & Zugaro, 2011; O'Keefe & Dostrovsky,

1971). By following the sequence of place cells, the rat's movements from one location to another can be traced. Pavlides and Winson demonstrated that during subsequent sleeping states, hippocampal place cells used in recent awake exploration exhibited an increased firing rate compared to cells that were not involved in the pre-sleep exploration (Pavlides & Winson, 1989). In the seminal study by Wilson and McNaughton, the activity of pairs of hippocampal place cells was recorded during both a spatial navigation task in a maze and during the SWS period that preceded and followed the task (Wilson & McNaughton, 1994). Notably, during the SWS period that followed the task, the same place cells that fired during exploratory behaviour fired together, indicating that information acquired during active behaviour is re-expressed in hippocampal circuits during sleep. The order of neuronal firing observed during wakefulness was preserved during sleep reactivation, albeit in a compressed temporal manner (Wilson & McNaughton, 1994).

Reactivation during sleep has also been observed in various brain regions and species, thereby supporting the Active System Consolidation Hypothesis (see section 1.3.3). For instance, visual (Ji & Wilson, 2007), parietal (Qin et al., 1997), prefrontal (Benchenane et al., 2010; Euston et al., 2007; Johnson et al., 2010; Peyrache et al., 2009) and sensorimotor cortices (Hoffman & McNaughton, 2002) have all shown reactivation. Evidence of reactivation and replay during REM sleep is substantially less extensive compared to NREM, however the occurrence of these phenomena in rodents is supported by place cell recordings (Louie & Wilson, 2001; Poe et al., 2000), appetitive conditioning (Maho & Hennevin, 2002) and cell recording from the primary motor cortex (Eckert et al., 2020). Interestingly, while replay during NREM sleep occurs in a temporally compressed form (Lee & Wilson, 2002), REM sleep replay is temporally structured at a timescale closer to that seen during wakefulness (Louie & Wilson, 2001). Just like replay during sleep, wake replay is triggered by SW-Rs however, the order during awake replay is reversed compared to that seen during sleep (Foster & Wilson, 2006).

1.4.2 Human studies

Studies investigating memory reactivation during sleep in humans are limited due to the low temporal and spatial resolution of non-invasive techniques compared to electrophysiological recordings (Schreiner & Staudigl, 2020). Early attempts to reveal memory reactivation during sleep in humans, investigated whether brain regions activated during memory encoding show corresponding activity during subsequent sleep (Bergmann et al., 2012; Maquet et al., 2000; Peigneux et al., 2004; Yotsumoto et al., 2009). For instance, using simultaneous EEG-fMRI recordings Bergmann and colleagues observed that participants who learned face-scene associations exhibited increased activity in both hippocampal and neocortical areas compared to those who performed a visuomotor control task. The increased neural activation was temporally coupled with increased spindle amplitude and correlated with pre-sleep behavioural performance, indicating the involvement of spindles in reactivation-like patterns (Bergmann et al., 2012). Another study employed positron emission topography (PET) to investigate the effects of training on a probabilistic serial reaction time task. Findings indicated that brain areas activated during the task in wakefulness were similarly active during REM after the training, thus supporting the hypothesis that there is an experience-dependent re-activation of specific brain areas during post-training REM sleep (Maquet et al., 2000). The advent of multivariate pattern analysis (MVPA; Haxby et al., 2001) and representational similarity analysis (RSA; Schönauer et al., 2017) helped tackle the issue of whether the re-expression of encoding related activity reflects the content of the learned task. In other words, studies that used these techniques aimed to measure replay of stimulus-related activity patterns (Deuker et al., 2013; Liu et al., 2019; Schönauer et al., 2017; Sterpenich et al., 2014; Zhang et al., 2018). For instance, Schönauer and colleagues used MVPA to decode EEG activity during sleep to determine whether participants viewed faces or houses during a declarative task performed the day before. They showed that the memory con-

tent was reprocessed during both NREM and REM sleep and that reactivation of declarative material during NREM sleep was associated with a greater memory performance (Schönauer et al., 2017). Furthermore, combining intracranial EEG electrodes with RSA in epilepsy patients, Zhang and colleagues identified that stimulus-specific activity spontaneously re-occurred during waking rest and sleep, but only ripple-triggered replay during NREM sleep was associated with memory consolidation (Zhang et al., 2018).

These studies support the evidence that the spontaneous reactivation of prior learned material during sleep constitutes a plausible mechanism supporting sleep-based memory consolidation. However, only methods that can directly manipulate memory reactivation during sleep provide evidence for a causal role of sleep in memory consolidation. Targeted Memory Reactivation (TMR) is a technique that emerged to directly address this issue.

1.4.3 Targeted Memory Reactivation (TMR)

TMR involves associating learning materials used in a task during awake learning with a contextual cue, like a sound or an odour. These stimuli are then unobtrusively re-presented during sleep, usually during specific sleep stages, to bias the spontaneous memory reactivation process towards the cued stimuli. Performance change scores between reactivated and non-reactivated items are then compared during a post-sleep test. The aim of this technique is to selectively improve memory consolidation of the cued items and thereby increase performance on those items in subsequent memory tests (Andrillon et al., 2011; Hu et al., 2020; Rasch et al., 2007). Early attempts with the use of TMR date back to the end of the 1980s (Oudiette & Paller, 2013), however, this procedure was experimentally demonstrated for the first time by Rasch and colleagues in 2007 (Rasch et al., 2007). In this seminal study, olfactory stimuli were used to cue declarative memory during sleep. Participants were trained on a two-dimensional memory task

involving object locations while smelling the scent of a rose. During the subsequent night, the same odour was presented again during SWS periods without disrupting participants' sleep. Declarative memory improvement was measured the next day by comparing the recall performance of participants who did or did not receive the rose-scented air during sleep. Those who received the TMR procedure demonstrated enhanced recall performance for the cued stimuli compared to a control group. Additionally, functional magnetic resonance imaging (fMRI) revealed a higher hippocampal activation for those object-location pairs that were re-exposed to the odour during SWS (Oudiette & Paller, 2013; Rasch et al., 2007). However, it remained unclear from this study whether TMR during sleep has the ability to selectively reactivate and strengthen specific memories formed during a learning episode.

Rudoy and colleagues (Rudoy et al., 2009) addressed the specificity issues by using auditory cues instead of sounds. Participants learned semantic associations between images and sounds (e.g., cat/meow) in specific locations. During the TMR procedure delivered during SWS, half of the items were cued by representing the sound of the corresponding objects. Post-sleep results showed higher accuracy for the items that were cued during sleep, suggesting that specific memories can be targeted and strengthened during sleep (Rudoy et al., 2009).

These findings have been further supported by animal studies. Bendor and Wilson trained four rats on an auditory-spatial association task in which sounds (sound L or R) were associated with reward locations: rats received a food pellet reward at the left-end side of a track for sound L and at the right-end side for sound R. In addition, control sounds not associated with the behavioural task were also played. During subsequent sleep, auditory cues were represented during NREM sleep, and place cell activity in the CA1 region of the hippocampus was recorded during the task and during sleep. After comparing firing rates for each acoustic stimulus during NREM periods, they observed that both task-related cues (sound L and R) biased the content of replay events. Sound L resulted in a higher firing

rate of individual place cells and ensembles of place cells with place fields on the left side, while sound R had the same effect on the right side (Bendor & Wilson, 2012).

TMR has been applied during both NREM (N2 and SWS) and REM sleep however, to date, a relatively low number of studies examined the effect of TMR during REM sleep. The majority of studies applied TMR during SWS to boost performance on declarative memory tasks. Beyond spatial location (Diekelmann et al., 2012; Diekelmann et al., 2011; Rasch et al., 2007; Rudoy et al., 2009), TMR studies have shown a benefit for spatial navigation (Shimizu et al., 2018), vocabulary learning (Schreiner & Rasch, 2015), associative learning tasks (Cairney et al., 2018; Cairney et al., 2017), word recall (Fuentemilla et al., 2013). Additionally, evidence shows that SWS TMR can improve non-declarative memories such as procedural skills (Antony et al., 2013; Cousins et al., 2014; Cousins et al., 2016; Schönauer et al., 2013) and emotional memories (Cairney et al., 2014; Hu et al., 2020; Lehmann et al., 2016).

TMR during N2 has been mainly employed with motor skill learning tasks (Laventure et al., 2016; Laventure et al., 2018) due to the well-known role played by sleep spindles in the consolidation of motor memories traces (Fogel & Smith, 2011; Morin et al., 2008). Not many TMR studies focused on REM sleep. Early studies conducted with animals, by Hennevin and Hars, reported significant performance improvement in rats on an active avoidance conditioning task after receiving ear shocks as a cue during post-learning REM sleep (Hars et al., 1985; Hennevin & Hars, 1987). Early attempts in humans also demonstrated enhanced memory after auditory stimulation during REM on a Morse code task (Guerrien et al., 1989) and a complex logic task (Smith & Weeden, 1990). On the contrary, more recent attempts have reported negative REM sleep-declarative and procedural memory effects (Laventure et al., 2016; Rasch et al., 2007) and a positive REM-emotional memory effect (Hutchison et al., 2021; Schwartz et al., 2022; Wassing et al., 2019).

Today's research takes advantage of artificial intelligence methods to develop automated sleep stage scoring and to perform TMR in participants' own homes, thus allowing real-life applications. Recently, Whitmore and colleagues developed a TMR system called "SleepStim" that works with a smartphone and a smartwatch used to play sounds and record movement and heart rate parameters, respectively (Whitmore et al., 2022). They tested whether at-home TMR, delivered via the SleepStim system during N3, replicates the spatial-memory benefit observed in laboratory settings. Across two experiments, they found a stronger TMR effect using a relatively low auditory cue intensity (Whitmore et al., 2022). Furthermore, TMR manipulations can be extended to clinical settings and used in clinical psychotherapy. Some studies explored the potential of TMR to weaken fear memories (Hauner et al., 2013; Oudiette et al., 2014) and to reduce negative valence of stimuli (Hutchison et al., 2021; Rihm & Rasch, 2015), which could be used to treat emotion and memory-related disorders, such as depression and PTSD. For example, a clinical reduction in nightmare frequency and more positive dream emotions have been demonstrated in adults with nightmare disorder (ND) after exposing them to TMR during REM sleep for 14 days in combination with imagery rehearsal therapy (Schwartz et al., 2022).

1.4.4 Research objectives

This thesis comprises three experimental chapters that investigate the beneficial effects of sleep manipulation on cognition.

Chapter 2 aimed to examine whether blocking natural light during nighttime sleep with the use of an eye mask benefits memory and alertness. To this end, we compared participants' performance on a cognitive battery while wearing an eye mask or a control mask during sleep. Additionally, we utilised a wearable EEG device to track sleep architecture, as we were interested in looking at the impact

of the eye mask manipulation on sleep parameters.

Chapter 3 explored the role of sleep in consolidating the effects of a cognitive training, thereby overcoming functional fixedness, a cognitive obstacle that prevents people from thinking outside the box and reaching insight. Participants were first exposed to a training session and then their performance was compared after a period of nocturnal sleep or daytime wakefulness.

In **Chapter 4**, the focus switched to assessing the potential of TMR during REM sleep to disarm the effects of negative emotions. We examined the effect of cueing on subjective and objective measurement of arousal. To this end, we employed subjective ratings of arousal, functional MRI, and heart rate deceleration.

Chapter 2

Wearing an eye mask during overnight sleep improves episodic learning and alertness

2.1 Abstract

Ambient light can influence sleep structure and timing. We explored how wearing an eye mask to block light during overnight sleep impacts memory and alertness, changes that could benefit everyday tasks like studying or driving. In Experiment 1, ninety-four 18–35-year-olds wore an eye mask while they slept every night for a week and underwent a control condition in which light was not blocked for another week. Five habituation nights were followed by a cognitive battery on the sixth and seventh days. This revealed superior episodic encoding and an improvement on alertness when using the mask. In Experiment 2, thirty-five 18–35-year-olds used a wearable device to monitor sleep with and without the mask. This replicated the encoding benefit and showed that it was predicted by time spent in slow-wave sleep. Our findings suggest that wearing an eye mask during overnight sleep can improve episodic encoding and alertness the next day.

2.2 Introduction

Sleep stands as a cornerstone of overall health due to its vital engagement in a multitude of physiological functions and cognitive processes that sustain well-being, including immune control, energy conservation, homeostatic restoration, and memory processing (Diekelmann & Born, 2010; Killgore, 2010; Lange et al., 2010). The strong association between sleep and health emphasizes the need for a thorough comprehension of the mechanisms that regulate our sleep-wake cycles. In this context, the two-process model of sleep regulation emerges as a fundamental framework (Borbely, 1982; Borbély et al., 2016). This model establishes that sleep relies on both circadian rhythms and homeostatic process. The homeostatic *process S* accumulates with increasing time spent awake and dissipates during sleep; the biological circadian pacemaker *process C*, refers to an endogenous body clock entrained to approximately 24 hours. Taken together, these processes determine

the quality and the timing of sleep onset and offset (Borbely, 1982; Borbély et al., 2016).

In mammals, the circadian pacemaker is regulated by the suprachiasmatic nucleus (SCN) of the anterior hypothalamus, responsible for regulating circadian cycles of nearly all physiological functions, such as body temperature, hormonal activity, and the sleep-wake cycles (Bass & Takahashi, 2010). Environmental cues, also known as zeitgebers, play a crucial role in modulating the circadian clocks and synchronizing the SCN to light-dark cycles. Among these cues, light holds paramount significance, as it directly reaches the SCN via intrinsically photosensitive retinal ganglion cells. Indeed, both the duration and the timing of light exposure affect the SCN, leading to a phase advance, where the circadian rhythm shifts to an earlier time, or a phase delay, causing a shift to a later time (Bjorvatn & Pallesen, 2009; Blume et al., 2019; Wams et al., 2017).

Numerous studies have highlighted the significant impact of light exposure on various aspects of sleep, including its duration, timing, structure and quality (Badia et al., 1991; Bjorvatn & Pallesen, 2009; Blume et al., 2019; Cho et al., 2013; Dijk et al., 1989; Dijk et al., 1987; Park et al., 2019; Siraji et al., 2023; Wams et al., 2017). For instance, in a controlled laboratory study, participants exposed to bright light from 06:00 to 09:00 over three consecutive days experienced a noticeable reduction in sleep duration, particularly in rapid-eye movement (REM) sleep, while slow-wave sleep (SWS) remained largely unaffected (Dijk et al., 1989; Dijk et al., 1987). In contrast, a non-intervention field study conducted by Wams and colleagues indicated that early morning light exposure didn't impact overall sleep duration but did increase SWS duration at the expense of REM sleep (Wams et al., 2017). Similarly, when participants were exposed to artificial 40 lux light during the night to simulate bedside light, no differences in NREM and REM duration were found. However, there were alterations in power spectral density, including reduced slow wave activity (SWA) and spindle frequency bands in NREM epochs,

and reduced theta activity during REM (Cho et al., 2013). Exploring sleep quality, Boubekri and colleagues investigated the effects of daylight exposure on the productivity and well-being of office workers. Their findings indicated increased sleep duration and improved sleep quality, along with higher levels of physical activity and an enhanced quality of life for workers in workspaces with windows (Boubekri et al., 2014). In intensive care units, where patients are exposed to high light levels, non-pharmacological interventions like using an eye mask during the night have notably enhanced sleep quality (Bani Younis et al., 2019; Locihová et al., 2018). Beyond sleep, light also exerts a significant influence on cognitive functions. Vandewalle and colleagues found that exposure to a monochromatic blue light enhanced working memory performance in an auditory 2-back task where participants were instructed to determine whether the current consonant matched the one presented two stimuli earlier in the sequence (Vandewalle et al., 2007). Similarly, Alkozei and colleagues reported improved memory retention on a verbal memory task when participants were exposed to this type of light (Alkozei et al., 2017). Furthermore, evening light exposure decreased alertness the following day (Chang et al., 2015), while blocking evening light improved alertness the next day (Knufinke et al., 2019). Given the extensive evidence indicating that light can impact sleep and cognition, and considering that sleep is vital for effective cognitive functioning (Diekelmann & Born, 2010; Rasch & Born, 2013; Walker, 2009), our study was designed to explore the potential effects of wearing an eye mask during periods characterized by heightened natural light in the early morning. We specifically chose to conduct our research during the summer months, driven by the expectation that the eye mask might be particularly advantageous when dawn breaks exceptionally early, such as around 5:00 a.m. in Cardiff, United Kingdom. Our underlying hypothesis was that blocking ambient light during the summer period could serve as a protective measure for sleep, ultimately leading to improvements in cognition. With this aim in mind, we ran a within-subject design during the summer of 2018 and 2019 (Experiment 1) and a replication study

in the summer of 2020 (Experiment 2). Specifically, we hypothesised that the eye mask would yield enhancement in declarative memory, vigilant attention, and procedural memory, all of which are known to be sleep sensitive (Lim & Dinges, 2008; Loganathan, 2014; Van Der Werf et al., 2011; Walker et al., 2002; Yoo et al., 2007).

2.3 Materials and Methods

2.3.1 Participants

All participants were healthy volunteers, with no history of drug/alcohol abuse, psychological, neurological, and sleep disorders. We selected participants who reported no hypersensitive skin or contact allergies and no problems falling asleep with open shutters and wearing both an eye mask and a wearable EEG device (Dreem headband, DH, Arnal et al., 2020). Participants agreed to abstain from alcohol and caffeine throughout the experiment. Additionally, the online screening ensured that they had not worn an eye mask for sleep before and they agreed not to nap on the days of the experiment. The sample size of Experiment 1 was determined using a power calculation based on a pilot study (n = 8) on the Paired associate learning (PAL) task and based on a paired-sample t-test (G*Power Version 3.1.9.6; Faul et al., 2009). This pilot predicted 80% power to detect a medium-size effect (Cohen's d = 0.3) with 88 subjects and a conventional α of 0.05. Ninety-four native English speakers (59F, age range: 18–35 years, M = 21.07, SD = 2.74) took part in the study. Of these, five were excluded due to voluntary withdrawal, so our final dataset included 89 participants (54F, M = 20.98, SD = 2.68). Due to technical failures when executing the tasks, a further six participants were excluded from the PAL, four were excluded from the Psychomotor Vigilance Test (PVT), and three from the motor-skill learning (MSL) analysis.

Experiment 2 was undertaken by 37 native English and Italian speakers (29F, age range: 18–35 years, M = 23.03, SD = 3.52). Of these, four were excluded due to difficulty falling asleep before 05:00 a.m. (n = 1), sudden notification of working commitments (n = 1), and voluntary withdrawal (n = 2). Our final dataset therefore included 33 participants (25F, M = 23.09, SD = 3.57). Sample size was predetermined using a formal power analysis for correlation analysis. A sample size of 29 was needed to detect a correlation coefficient of 0.5 with a conventional α of 0.05 and 80% power. The number recruited slightly exceeded the number needed.

All participants gave informed consent for the experiments, which were approved by the Ethics Committee of the School of Psychology at Cardiff University, and received monetary compensation for their participation.

2.3.2 Study design and procedure

The study design of both experiments is outlined in Figure 2.2.

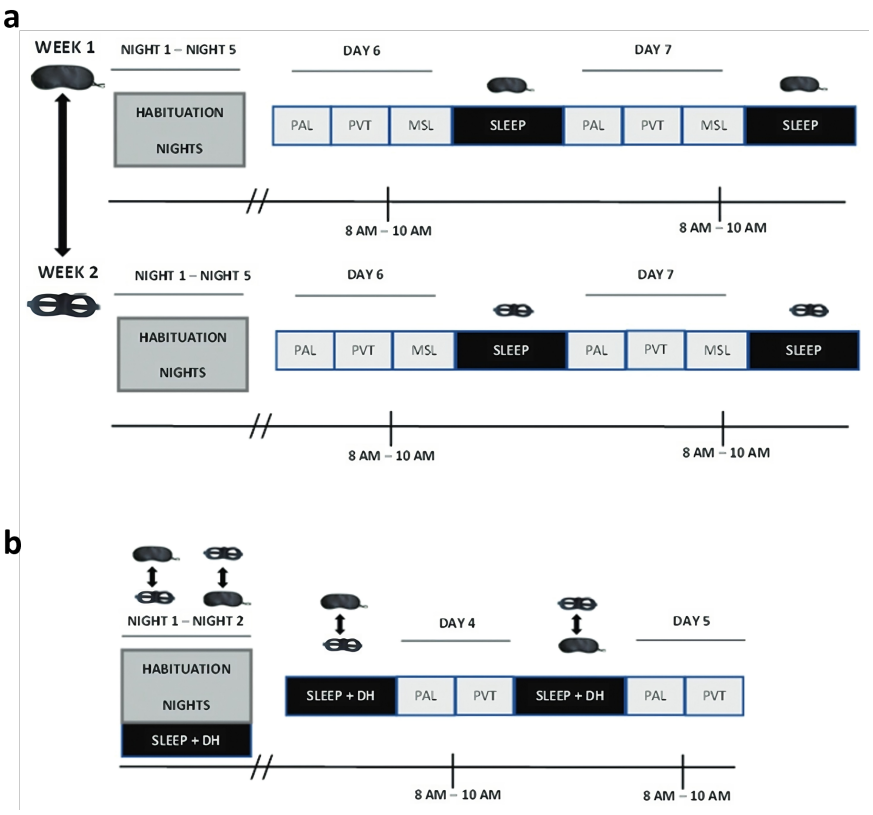


Figure 2.1: *Study design.* **(a)** Experiment 1 consisted of 2 consecutive weeks in which, in a counterbalanced order, ambient light was blocked with an eye mask during sleep for 1 week, or not blocked with a control mask for the other week. Night 1–Night 5: participants slept at home wearing a mask (eye mask or control). Day 6–Day 7: participants performed the PAL, the PVT, and the MSL task. **(b)** Experiment 2 consisted of 5 days, 2 habituation nights, and 2 experimental days. For the entire study duration, participants slept with an eye mask or a control mask (counterbalanced order) together with the DH. In the morning of Days 4 and 5, participants completed the PAL and the PVT.

Experiment 1 was conducted over two summers (end of June–end of September) in 2018 and 2019. We chose the summer months because we suspected that the eye mask would be more helpful when dawn occurred early (as early as 05:00 am at midsummer in Cardiff, United Kingdom). The 2018 study involved two consecutive weeks in a counterbalanced order, in which ambient light was blocked with an eye mask during sleep for the experimental week and not blocked for the control week. Each week consisted of 5 habituation nights, followed by 2 consecu-

tive testing days (Day 6 and Day 7, respectively). During the habituation nights, participants were instructed to sleep at home (wearing an eye mask or control) and to maintain their regular sleep–wake habits. On Days 6 and 7, participants arrived at the sleep laboratory at CUBRIC between 08:00 a.m. and 10:00 a.m. and performed three cognitive tasks: PAL, PVT, and MSL. The 2019 study was identical to the 2018 study, except that in the control condition, participants wore a modified eye mask with two big holes manually cut over each eye, with nothing covering the eye region, such that it did not block the light. This was done to control for any discomfort caused by wearing a mask. Computer-based tasks were executed using Matlab 2016 or 2017 (The MathWorks Inc., Natick, MA).

Experiment 2 was conducted over the summer of 2020 and consisted of four nights (two habituation and two experimental), in which participants were asked to sleep at home with the DH and an eye mask or a modified mask with holes, in a counterbalanced order. Participants were given a digital light meter (Aoputtriver AP-881E, Digital-Handheld-Temperature), and instructed to place it on the pillow and to report light intensity as soon as they woke up each morning. They did this for the entire duration of the study. The first two habituation nights were used to accustom participants to sleeping while wearing both the DH and one of the masks. Between 08:00 and 10:00 a.m. on Days 4 and 5, subjects performed the learning part of the PAL and the PVT. Tasks were executed online using PsychoPy3 Experiment Runner (v2020.1.3; Peirce et al., 2019).

From now on, we will refer to the two conditions as *eye mask* for the normal sleep mask and *control* for both no mask (2018 participants) and the modified mask with holes over the eyes (2019/2020 participants). In both experiments, an online sleep diary was completed every morning, and self-reported alertness was measured with the Stanford Sleepiness Scale (SSS, Hoddes et al., 1973) on the morning of each experimental day. Participants were asked to sleep with open

shutters/curtains for the entire duration of the study.

2.3.3 Experimental Tasks

2.3.3.1 Paired Associate Learning Task (PAL)

Declarative memory was assessed with the PAL task. On the first testing day (Day 6 of both weeks), participants were first instructed to learn 80 semantically related pairs of English nouns presented on a screen for 3500ms with an interstimulus interval (ISI) of 1000ms. We had two different lists of word-pairs, counterbalanced between subjects. The learning session was followed by an immediate cued recall test, in which subjects were presented with the first noun of every pair in a random order and asked to recall the associated noun by typing it into a computer keyboard. Unlimited time was given to type an answer, and word-pairs were repeatedly presented until the subject reached 60% accuracy. After each response, the correct answer was displayed for 2s, allowing the subject to relearn the pair if necessary. Followed by 10 minutes of PVT, a final cued recall without feedback was presented and used to assess participants' pre-sleep scores. Approximately 24 hours later, a delayed recall without feedback took place and it was used to calculate the post-sleep score. We calculated: (i) learning performance as the number of correctly recalled pairs in the final cued recall (pre-sleep score); (ii) absolute consolidation performance as the number of correctly recalled words in the delayed recall minus the final cued recall (post-sleep score – pre-sleep score).

2.3.3.2 Psychomotor Vigilance Test (PVT)

A 10-minute PVT performed on both testing days required to focus on a fixation cross and to respond (and stop by pressing the space bar on the keyboard), as quickly as possible, to a millisecond counter that randomly appeared between 2 and 10s. When the counter was stopped, reaction times (in ms) remained on the screen for 1s and served as feedback. If the space key was not pressed within

2000ms, an onscreen message reminded participants to pay attention. Responses below 100ms (false starts) and above 500ms (attention lapses) were excluded from the analysis before the average score from the remaining trials was calculated (Basner & Dinges, 2011).

2.3.3.3 Motor-skill learning task (MSL)

The MSL required subjects to tap a fixed five-digit sequence (e.g., 4-1-3-2-4) using their non-dominant hand, pressing four numeric keys on a computer keyboard as quickly and accurately as possible. On the first testing day of both weeks (Day 6), the pre-sleep session had participants repeat the numeric sequence across 12 blocks of trials, each lasting 30 seconds, with a 30-second ISI. Before beginning the task, participants completed a short 30-second practice round. On the second testing day of both weeks (Day 7), the post-sleep session followed the same procedure. However, the last three blocks of 30 seconds each featured a different control sequence to determine if the overnight improvement was sequence-specific. We employed two sequences for this task, balancing their order across subjects. Pre-sleep performance was assessed by averaging the correctly tapped sequences in the last three blocks, while post-sleep performance was determined by averaging the first three blocks. Performance improvement was calculated by determining the difference between the pre-sleep and post-sleep scores, representing the absolute overnight change.

2.3.4 Wearable EEG device: Dreem headband

In Experiment 2, sleep macro-architecture was recorded using the DH that automatically records, stores, and analyses physiological data (Arnal et al., 2020). The DH comprises five dry-EEG electrodes: O1, O2, FpZ, F7, and F8. The signal is recorded at a sampling frequency of 250 Hz with a 0.4–35 Hz bandpass filter. The DH enabled participants to sleep in their own environment instead of in a labo-

ratory setting, thereby increasing sleep quality and comfort levels. Recent validation of the DH's automatic sleep stage classification, when compared to standard polysomnography (PSG), demonstrated that the automatic algorithm can reliably perform sleep staging (Arnal et al., 2020). We examined the time spent in each sleep stage during the two experimental nights (nights 3 and 4). Relationships between behavioral measures and sleep were assessed using Pearson's correlations or Spearman's Rho if Shapiro–Wilk tests indicated a non-normal distribution. All statistical tests were two-tailed and considered significant at $p < .05$. Analyses were conducted in R (version 4.0.2, R Core Team, 2020). Results are presented as mean ± SEM. Four participants did not initiate the DH recording correctly, resulting in a lack of sleep data collection. Therefore, sleep macrostructure analysis was based on N = 29 participants.

2.4 Data analysis

2.4.1 Behavioural analysis

We conducted a linear mixed-effects (LME) analysis using the *lme4* package in R. In all models, we incorporated fixed effects for *MaskType* (two levels: eye mask, control mask) and *YearOfExperiment* to account for variations in the control conditions across years. Additionally, we introduced an interaction term between *MaskType* and *YearOfExperiment* to investigate if the effect of *MaskType* on the tasks varied based on the specific control condition of each year. Participants were included in the model as random intercepts.

Full model: $DV \sim \ MaskType * YearOfExperiment + 1|participants.$

To determine statistical significance, we utilized likelihood ratio tests (LRTs). We compared the full model to a reduced model omitting the interaction term and to

another model that only considered *MaskType* as a fixed effect.

Reduced 1: $DV \sim \ MaskType + YearOfExperiment + 1|participants.$

Reduced 2: $DV \sim \ MaskType + 1|participants.$

We based our results on the model that LRTs deemed the best fit for each specific task. A detailed comparison of these models for all tasks can be found in Table 2.2 in the Supplementary Material. Additionally, in the Result section of each task, the final model employed is delineated. Significance threshold was set at 0.05. For all models, visual inspection of residual plots was used to assess the model assumptions of linearity, homoscedasticity, and normality of the residuals. Effect sizes were computed using *lsr* package (Navarro, 2015). All figures were created using *ggplot2* R-package (Wickham, 2009). Descriptive statistic of the tasks for both experiments is reported in Table 2.1 in Supplementary Material.
All data and research materials have been made publicly available in Open Science Framework (OSF) and can be accessed at DOI 10.17605/OSF.IO/Q4P9V.

2.4.2 Questionnaires

The SSS was used to provide a self-reported indication of sleepiness. Participants rated their current state on a seven-point Likert scale, where 1 represents the most alert and 7 represents the least alert (Hoddes et al., 1973). A sleep diary gathered information about units of alcohol and caffeine consumed, sleep duration, and the regularity of the sleep–wake cycle. In Experiment 2, we assessed the comfort of the masks and the DH on a five-point Likert scale, ranging from 1: "Very uncomfortable" to 5: "Very comfortable". Similarly, self-rating of sleep quality was measured on a Likert scale, ranging from 1: "Very poor" to 5: "Very good". Paired-sample t-tests evaluated whether sleep quality differed after using the eye mask compared to the control. When the assumption of normality was violated,

we conducted non-parametric Wilcoxon signed-rank tests. All tests were two-tailed, and we set the significance threshold at $p < .05$ for all analyses. Effect sizes were computed using the *rcompanion* and *lsr* packages (Mangiafico, 2020; Navarro, 2015).

2.5 Results

2.5.1 Experiment 1

2.5.1.1 Paired associate learning task

We first assessed whether wearing the eye mask affected learning performance on the word-pair associate task. Including solely *MaskType* in our LME ($PALlearning \sim MaskType+1|participants$) significantly improved model fit (see Table 2.2 in Supplementary Material). This showed significantly better learning after wearing the eye mask compared to the control (eye mask: 65.06 ± 0.69 vs control: 63.87 ± 0.67; $\beta = -1.19$, CI = 0.18 - 2.21, p = 0.02, d = 0.19; Figure 2.2a). An additional LME model, which we fit to examine whether our experimental intervention had an impact on overnight declarative memory consolidation, revealed no effect of the eye mask on overnight change in memory performance (see Table 2.3 in Supplementary Material).

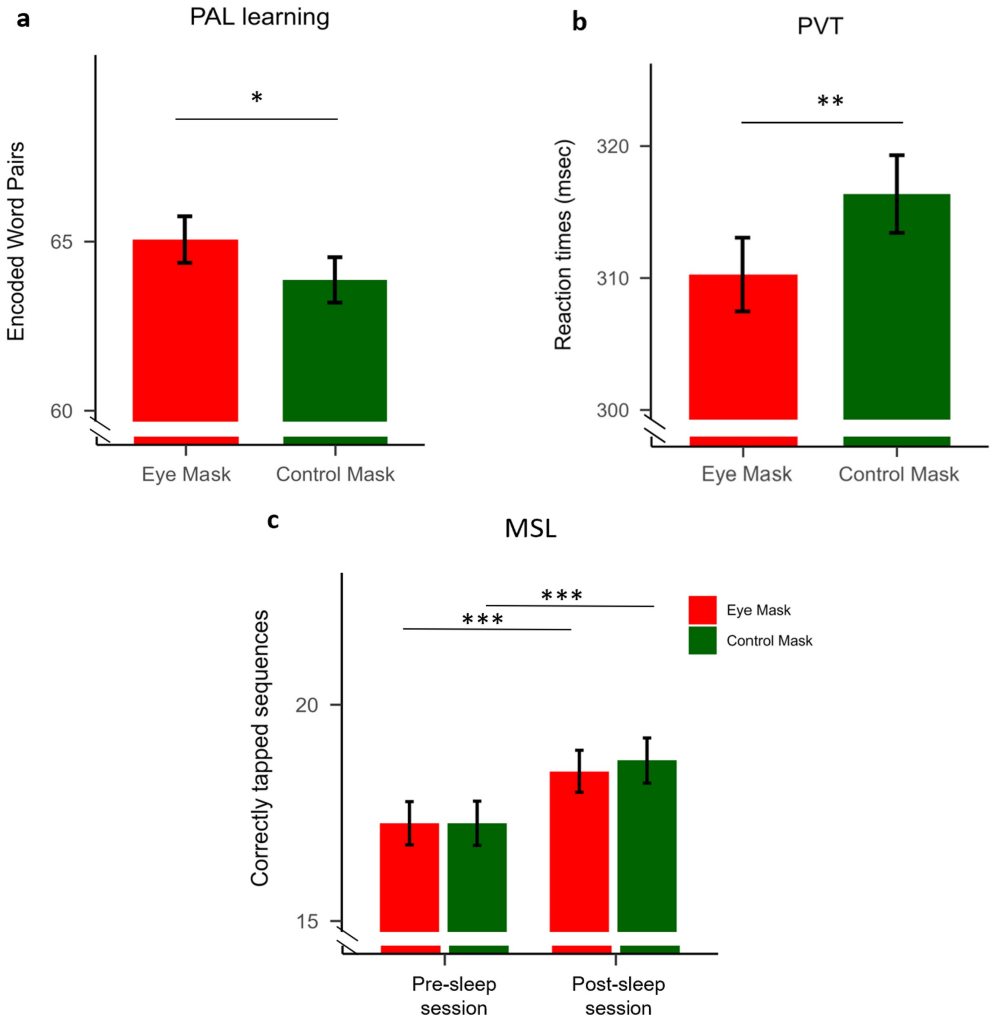


Figure 2.2: *Behavioral results.* Boxplots for **(a)** learning performance on the PAL, **(b)** reaction times on PVT, and **(c)** number of correctly tapped sequences on the MSL task. Mean and standard errors of the mean are indicated. *p< .05, **p<.01, ***p<.001.

2.5.1.2 Psychomotor vigilance test test

We next assessed the impact of wearing the eye mask on the psychomotor vigilance task. PVT responses from the two testing days were combined in an LME, which tested for differences in reaction time after wearing the eye mask as compared to the control. This analysis revealed that blocking ambient light had a significant impact on reaction times ($PVT \sim MaskType + 1|participants$, see Table 2.2

in Supplementary Material). Participants responded faster after wearing the eye mask (eye mask: 310.26 ± 2.79 vs. control: 316.37 ± 2.94; β = -6.10, p = .0.007, d = 0.16; Figure 2.2b, Table 2.3 in Supplementary Material).

2.5.1.3 Motor-skill learning

We examined motor-skill learning by fitting a linear mixed-effects model to the number of correctly tapped sequences with fixed effects for *MaskType* (eye mask and control), *Day* (Day 6 and Day 7), and their interaction, as well as random effects for participants ($MSL \sim MaskType * Day + 1|participants$). This showed no effect of the mask ($\beta = -0.00$, p = 1.000), but a significant main effect for Day (β= 1.45, p $<$ .001), indicating that participants performed the task faster after sleep, irrespective of whether they were in the mask or control condition. There was no interaction between *MaskType* and *Day* (β = 0.25, p = .597), indicating that our intervention did not modulate performance on this task (Figure 2.2c). Examination of the absolute overnight change in performance revealed no differences between the two types of masks (Table 2.3 in Supplementary Material).

2.5.1.4 Questionnaires

The LRT on the SSS, performed on both testing days combined, revealed no effect of *MaskType* on self-reported alertness ($\chi^2_1 = 3.11$, p = .078; eye mask: 2.22 ± 0.06 vs. control: 2.34 ± 0.06). Moreover, the eye mask had no impact on the actual number of hours that participants reported sleeping since a Wilcoxon signed-rank test on the total number of hours slept across the week (as indexed by the sleep diary) revealed no differences between conditions (eye mask: 8.24 ± 0.09 vs control: 8.26 ± 0.11, Z = -0.27, p = 0.78; N = 79). Notably, 10 participants were excluded from this analysis due to poor compliance in completing the sleep diary.

2.5.2 Experiment 2

In Experiment 2, we sought to build on Experiment 1 by adding objective measurements of time spent in each sleep stage through the use of the DH and measurements of light intensity. However, the eye mask manipulation did not induce any changes in the sleep macrostructure, as reported in Table 2.4 in Supplementary Material. Additionally, the inclusion of light intensity in our mixed model showed no evidence of it modulating any of our behavioral measures. For consistency, we collected similar behavioral and questionnaire data as in Experiment 1. This led to a significant result in the PAL, which is reported below. However, no other significant findings emerged (see Table 2.3 and *Supplementary Results (Experiment 2)* in Supplementary Material).

2.5.2.1 Paired associate learning task

In our assessment of mask vs control on word-pair encoding, the LRT revealed that the inclusion of *MaskType* in the model provided a better fit for the data (χ^2_1 = 3.91; p = 0.04, Table 2.2 in Supplementary Material). Thus, in keeping with Experiment 1, learning performance was better after wearing the eye mask than the control (eye mask: 69.9 ± 1.89 vs control: 67.7 ± 1.80; β = 2.18, p = 0.04, d = 0.22; Figure 2.3a, Table 2.3 in Supplementary Material).

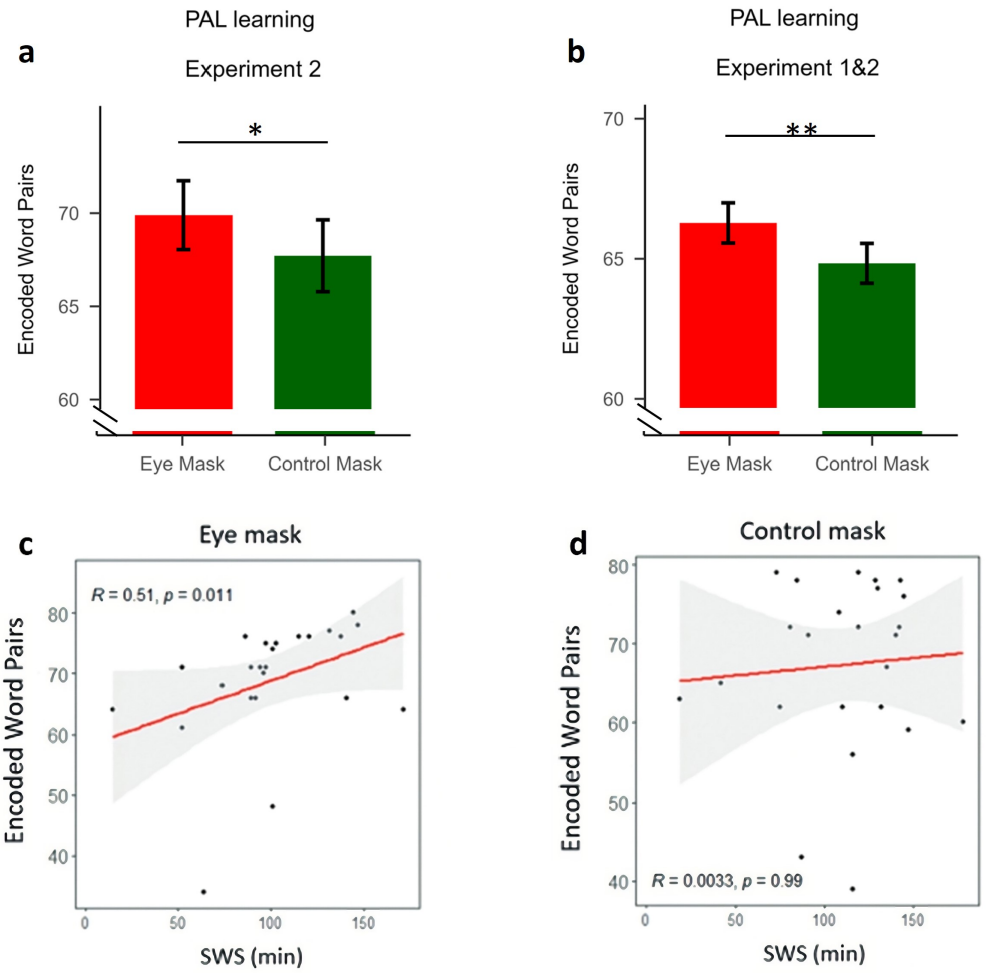


Figure 2.3: *Results of Experiment 2 and combined 1 & 2* **(a)** Experiment 2. PAL results (N = 28). Boxplots for learning performance on the PAL after a night of sleep wearing the eye mask or the control mask. **(b)** Combined results of the encoding performance on the PAL from Experiments 1 and 2 (N = 112). **p < .01; *p < .05. **(c)** Significant Spearman's (rank) correlation between the time spent in SWS (minutes) and the learning performance on the word pairs after a night wearing the eye mask. Note that when N = 3 outliers were removed, the correlation was still significant (rs = 0.44, p = .04). **(d)** Spearman's (rank) correlation between time spent in SWS (minutes) and learning performance on the word pairs after a night wearing the control mask.

To examine the overall dataset, we combined the PAL results related to the learning performance from both Experiment 1 and Experiment 2 (N = 112): $PALlearning \sim MaskType + 1|participants$. This indicated that the inclusion of the eye mask effect improved model fit ($\chi^2_1 = 9.01$; p = .0.002). Overall, the use of

the eye mask had a positive effect upon subsequent learning (eye mask: 66.6 ± 1.5 vs control: 65.1 ± 1.5; $\beta = 1.44$, p = 0.002, d = 0.19; Figure 2.3b, Table 2.3 in Supplementary Material). Given these results, we conclude that wearing the eye mask was beneficial for declarative memory encoding the next day.

In light of previous studies demonstrating that SWS plays a major role in subsequent encoding (Antonenko et al., 2013; Van Der Werf et al., 2009; Van Der Werf et al., 2011; Yoo et al., 2007), we tested for correlations between the learning of hippocampus-dependent memory and SWS time. Learning performance after a night wearing the eye mask was positively correlated with SWS time (rs = 0.51, p = 0.01; Figure 2.3c), whereas there was no such correlation after a night wearing the control mask (rs = 0.00, p = 0.99; Figure 2.3d). No other correlations were significant (all $p > .05$, Tabel 2.4 in Supplementary Material).

2.5.2.2 Questionnaires

Sleep diary data revealed no differences in the number of hours slept while wearing the eye mask (7.15 ± 16.66) or the control mask (7.18 ± 16.82; $t(23) = -0.11$, p = .914, N = 24). Likewise, there was no significant difference in self-rating of sleep quality (eye mask: 3.13 ± 0.19 vs control: 2.84 ± 0.16; $Z = -1.53$, p = .131, N = 31). Participants rated the control mask as more uncomfortable than the eye mask (eye mask: 3.10 ± 0.17 vs control: 2.40 ± 0.12; $Z = -2.86$, p = .005, N = 30), but this did not impact the comfort of the DH with mask (eye mask: 2.83 ± 0.18 vs control: 2.83 ± 0.17; Z = 0.00, p = 1.000, N = 30).

2.6 Discussion

Our results demonstrate that wearing an eye mask during overnight sleep to block out early morning light can enhance both new learning and alertness the following day, while procedural memories remain unaffected.

Previous literature has primarily focused on the role of sleep in memory consolidation (Born et al., 2006; Diekelmann & Born, 2010; Rasch & Born, 2013), with fewer studies examining its impact on next-day learning of hippocampus-dependent memories. Research in this area has shown that SWA - a hallmark of slow-wave sleep – is associated with the encoding of declarative material (Antonenko et al., 2013; Ong et al., 2018; Van Der Werf et al., 2009; Van Der Werf et al., 2011). These studies align with the Synaptic Homeostasis hypothesis, which suggests that SWA promotes the global down-scaling of synapses that have become saturated during preceding periods of wakefulness, thus restoring the capacity for encoding new information (Tononi & Cirelli, 2003, 2006). Indeed, enhancing SWA via transcranial slow oscillation stimulation (tSOS) during an afternoon nap improved subsequent memory encoding of pictures, word pairs, and word lists (Antonenko et al., 2013), while suppressing SWA via acoustic stimulation resulted in impaired encoding (Van Der Werf et al., 2009). In our study, the memory enhancement associated with the use of an eye mask was positively correlated with the time spent in SWS. Based on the available literature, we thus speculate that the eye mask may have increased SWA, even though we couldn't directly measure it due to the minimal nature of our recording method and despite the fact that our analysis of sleep macrostructure showed no differences between mask and control. Our speculation is grounded in the principles of the Active System Consolidation and the Synaptic Homeostasis Hypothesis. The former posits that the temporal synchronization of various brain rhythms during sleep is crucial for facilitating communication between the hippocampus and the neocortex, thereby playing a key role in sleep-associated memory processing (Diekelmann & Born, 2010; Rasch & Born, 2013; Walker, 2009). Furthermore, neural oscillations implicated in memory consolidation have also been implicated in preparing the hippocampus for new learning experiences, thus indicating that the processes of memory consolidation and new learning might share overlapping neural mechanisms (Van Der Werf et al., 2009; Van Der Werf et al., 2011). On the other hand, the Synaptic Homeostasis

Hypothesis emphasizes the necessity of sleep, and particularly SWA, for synaptic renormalization. This process is essential for maintaining synaptic plasticity, which is crucial for efficient learning on the following day information (Tononi & Cirelli, 2003, 2006). In line with this, the study by Van Der Werf and colleagues demonstrated that a selective reduction in SWA led to impaired encoding and reduced hippocampal activation, all without affecting sleep architecture or duration (Van Der Werf et al., 2009; Van Der Werf et al., 2011). This evidence suggests that the hypothesised enhancement of SWA facilitated by the use of an eye mask in our study could occur independently of any noticeable alterations in the overall structure of sleep.

In terms of vigilance, the current findings suggest that wearing an eye mask positively improved behavioural alertness. Specifically, participants responded faster in the PVT after a night of sleep with the eye mask. The PVT is a widely used measure of behavioural alertness and sustained attention, with negligible practice and aptitude effects over repeated administrations (Basner & Dinges, 2011; Lim & Dinges, 2008). Particularly in studies aimed at mitigating the effects of sleep deprivation, the PVT is used to gauge the effects of light exposure on alertness. However, these studies have generally focused on how increasing light exposure in the morning could counteract the deleterious effects of sleep deprivation (Comtet et al., 2019; Münch et al., 2017; Phipps-Nelson et al., 2003). The improvement in PVT performance observed in our study merits consideration because of the crucial role behavioural alertness plays in many real-world tasks, ranging from driving to other activities that require rapid responses (Dorrian et al., 2004), and because of the ecological setting in which our study was conducted. In fact, our participants slept in the comfort of their own homes, were not sleep-deprived, and no manipulation of natural light was applied.

Turning to the motor-skill learning task, consistent with the literature, our study

demonstrated the expected improvement after a night of sleep. Indeed, participants significantly improved on this task after a retention period of sleep (Walker et al., 2002). This overnight learning gain has previously been shown to correlate with the amount of Stage 2 sleep obtained, particularly in the last quarter of the night (Walker et al., 2002). However, despite this overnight enhancement, the use of an eye mask does not appear to provide further benefit to this task. Notably, the studies conducted by Van der Welf and Antonenko also examined the effect of SWA on procedural memories and showed that manipulating SWA, either through suppression (Van Der Werf et al., 2011) or augmentation (Antonenko et al., 2013), had no noticeable impact on procedural memory performance. This has led to the hypothesis that the effects of SWA might be task-specific, particularly benefiting encoding in hippocampus-dependent memories. This observation potentially supports our speculation about the eye mask's impact on SWA, given that our manipulation enhanced declarative learning while leaving procedural memories unaffected. However, this hypothesis remains speculative and warrants further investigation with the use of polysomnography.

In terms of self-reported sleep quality, as assessed through sleep diaries, we found no significant benefits of the eye mask in either experiment. It's noteworthy that despite participants in Experiment 2 reporting that sleeping with the control mask was less comfortable compared to the eye mask, this did not impact self-reported sleep quality or other sleep parameters. However, it's important to mention that in our second experiment, we did not find a beneficial effect of the eye mask on the PVT. While Experiment 2 was underpowered, contributing to non-significant results, it raises the question of whether factors such as participant discomfort with the control mask might have selectively affected PVT performance but not declarative memory. An adequately powered study focusing on PVT performance would be beneficial for resolving the inconsistencies observed in our second experiment.

Overall, our findings suggest that a simple manipulation—using an eye mask during sleep—can lead to superior memory performance and higher alertness the next day. These findings have broad implications, especially in educational and cultural contexts where effective encoding and rapid response to external stimuli are essential. Given the current climate of life-hacking, sleep monitoring, and cognitive enhancers, the eye mask emerges as a simple, cost-effective, and noninvasive tool to maximize the benefits of a night's sleep.

2.7 Supplementary Material

Table 2.1: *Descriptive statistic of the experimental tasks.*

Experiment 1					
DAY 6					
		Mean	Median	95% CI	SEM
PAL	Eye mask	65.06	65	63.69 – 66.43	0.69
	Control	63.87	64	62.53 – 65.20	0.67
PVT	Eye mask	311.58	307.87	303.28 – 319.87	4.17
	Control	314.13	310	306.06 – 322.20	4.06
MSL	Eye mask	17.27	17	16.27 – 18.26	0.5
	Control	17.27	16.5	16.25 – 18.29	0.51
DAY 7					
PAL	Eye mask	63.73	63	62.32 – 65.15	0.71

	Control	62.97	64	61.48 – 64.47	0.75
PVT	Eye mask	308.95	303.2	301.51 – 316.39	3.74
	Control	318.6	313.46	310.11 – 327.10	4.27
MSL	Eye mask	18.46	18.83	17.51 – 19.42	0.48
	Control	18.71	17.83	17.69 – 19.74	0.52
		Absolute Overnight Change			
PAL	Eye mask	-1.32	-1	-2.13 – -0.52	0.40
	Control	-0.89	-1	-1.74 – -0.03	0.43
MSL	Eye mask	1.20	1.50	0.62 – 1.77	0.29
	Control	1.45	1.34	0.98 – 1.91	0.23
		Experiment 2			
PAL	Eye mask	69.89	71.50	66.10 – 73.68	1.85
	Control	67.71	71	63.76 – 71.67	1.93
PVT	Eye mask	319.64	319.55	303.88 – 335.40	7.70
	Control	326.97	325.97	313.23 – 340.72	6.722

Note: PAL = Paired associate learning task. PVT = Psychomotor vigilance test. MSL = Motor-skill learning task. CI = confidence interval, SEM = standard error of the mean.

Table 2.2: *Model comparisons.*

Experiment 1

	AIC	BIC	Chisq	Df	Pr(>Chisq)
PAL learning					
Reduced 2	1024.00	1036.45			
Reduced 1	1024.03	1039.59	1.97	1	0.160
Full Model	1025.71	1044.38	0.32	1	0.572
PAL overnight change					
Reduced 2	908.77	921.22			
Reduced 1	910.76	926.32	0.00	1	0.958
Full Model	909.30	927.97	3.46	1	0.062
PVT					
Reduced 2	3227.89	3243.20			
Reduced 1	3229.33	3248.47	0.56	1	0.453
Full Model	3231.17	3254.14	0.16	1	0.693
MSL					
Reduced2.MSL	1756.3	1779.4			
Reduced1.MSL	1754.6	1781.5	3.7105	1	0.054
FullModel.MSL	1758.7	1797.1	1.8759	3	0.598
MSL overnight change					
Reduced 2	799.00	811.59			
Reduced 1	800.97	816.71	0.0296	1	0.863
Full Model	801.65	820.53	1.3233	1	0.250
Experiment 2					
PAL learning					
Reduced 3	391.00	397.08			
Reduced 2	398.09	397.19	3.912	1	**0.047**

PVT					
Reduced 3	557.61	563.68			
Reduced 2	556.87	564.97	2.7404	1	0.097
Experiment 1 & 2					
PAL learning					
Reduced 3	1434.6	1444.8			
Reduced 2	1427.6	1441.2	9.0105	1	**0.002**

Note: In all tasks, except for the MSL, the models are specified as follows:

Reduced 2 = $MaskType + 1|participants$;

Reduced 1 = $MaskType + YearOfExperiment + 1|participants$;

Full Model = $MaskType * YearOfExperiment + 1|participants$.

In the MSL: Reduced2.MSL = $MaskType * Day + 1|participants$;

Reduced1.MSL = $MaskType * Day + YearOfExperiment + 1|participants$;

FullModel.MSL = $MaskType * Day * YearOfExperiment + 1|participants$. Finally, in Experiment 2, Reduced 3 is related to a model with no fixed effects. AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) are both measures of the relative quality of statistical models. Chisq = Chi-squared, test statistic for the LRT. PAL = Paired associate learning task. PVT = Psychomotor vigilance test. MSL = Motor-skill learning task.

Table 2.3: *LME models outputs*

	Experiment 1		
Predictors	Estimates	CI	*p*
PAL learning			
Intercept	63.87	62.53 – 65.20	**<0.001**
Eye Mask	1.19	0.18 – 2.21	**0.02**
PAL overnight change			
Intercept	-0.89	-1.71 – -0.07	**0.034**
Eye Mask	-0.43	-1.37 – 0.50	0.360
PVT			
Intercept	316.37	309.04 – 323.69	**<0.001**
Eye Mask	-6.10	-10.51 – -1.70	**0.007**
MSL			
Intercept	17.27	16.28 – 18.25	**<0.001**
Eye Mask	0.00	-0.65 – 0.65	1.000
Day7	1.45	0.79 – 2.10	**<0.001**
Eye Mask x Day7	-0.25	-1.17 – 0.67	0.597
MSL overnight change			
Intercept	1.45	0.93 – 1.96	**<0.001**
Eye Mask	-0.25	-0.94 – 0.44	0.477
	Experiment 2		
PAL learning			

Intercept	67.71	64.00 – 71.43	<**0.001**
Eye Mask	2.18	0.05 – 4.31	**0.046**
PVT			
Intercept	326.90	311.82 – 341.98	<**0.001**
Eye Mask	-9.13	-19.93 – 1.67	0.096
Experiment 1&2			
PAL learning			
Intercept	64.84	63.44 – 66.24	<**0.001**
Eye Mask	1.44	0.51 – 2.37	**0.002**

Table 2.4: *Sleep parameters (mean±SEM) in minutes and pairwise comparisons.*

Sleep Measures	Eye Mask	Control Mask	Test statistic	p-value	Effect Sizes
TST	451.52±14.03	459.76±18.05	-0.60	0.55	0.11
Onset	15.83±2.11	14.72±2.60	-0.47*	0.638	0.08
N2	185.34±8.24	179.07±11.46	0.612	0.545	0.11
N3	99.10±6.18	107.96±6.48	-1.61	0.119	0.29
REM	123.00±10.20	133.96±7.92	-1.143	0.263	0.21
Wake	28.24±4.28	24.03±2.74	-0.25*	0.804	0.04
Awakenings	2.14±0.39	2.03±0.32	0.35	0.729	0.06

Note: Test statistics for paired-samples t-test unless indicated by * which corresponds to the Wilcoxon signed-rank test. TST = total sleep time; N2 = non-rapid eye movement sleep stage 2; N3 = non-rapid eye movement sleep stage 3; REM = rapid eye-movement sleep. Awakenings are related to the number of awakenings.

2.7.1 Supplemental Results (Experiment 2)

Experiment 2 was conducted in order to look at the impact of the eye mask manipulation on sleep parameters. For consistency, we also collected PAL, PVT and questionnaire data as in Experiment 1. However, because a power calc for PVT based on the results of Experiment 1 suggested an n of approximately 390 for 80% power, and this was not a feasible target for an experiment using the Dreem headbands, we did not expect a significant result for this task.

2.7.1.1 Psychomotor Vigilance Test (PVT)

When we examined sustained attention, the LRT revealed no significant effect of the mask ($\chi^2_1 = 1.82$; p = 0.17), suggesting no specific effect of the eye mask on reaction times ($\beta = -7.33$, p = 0.18; Table 2.3). Furthermore, analysis of the association between sleep parameters and measure of behavioural alertness revealed no significant correlation (all $p > 0.05$). Notably, the experiment was severely underpowered for examination of the PVT.

Chapter 3

Sleep and Functional Fixedness

3.1 Abstract

Creative ideas and problem-solving can result from a leap of insight in which a situation or event is suddenly reinterpreted in a novel way. However, mental fixation can limit cognitive ability and constrain thought. Sleep has been proposed to facilitate insight by supporting the restructuring of memory elements, thus allowing a qualitative change of the memory representation. The current experiment examined the role of sleep in overcoming such mental obstacles to reach insight. Twenty-eight participants underwent initial training and were tested on insight problems. After a period of nocturnal sleep or daytime wakefulness, participants attempted to solve other insight problems and performed a listing feature task. The sleep group displayed greater improvement in solving insight problems; however, this result was confounded by the influence of circadian rhythms, as performance was observed to be superior in the morning compared to the evening. Thus, while the sleep-related improvement was notable, its interpretation is complicated by the concurrent impact of time of day.

3.2 Introduction

In today's rapidly changing and increasingly complex world, creativity has emerged as a crucial skill in high demand. While the rapid development of artificial intelligence (AI) has transformed many aspects of our lives, it has also raised concerns about the impact of automation on human jobs, skills, and creativity. Although AI can perform many routine and repetitive tasks faster and more accurately than humans, it is still limited in its ability to generate truly novel and creative ideas.

Creative thinking involves the production and generation of a product, idea, or problem solution that is both novel (or unusual) and appropriate (or useful) (Runco & Jaeger, 2012). This can occur through immediate intuition or insight, as first de-

scribed by Gestalt psychologists (Gilhooly, 2016; Weisberg, 2006). Insight is commonly associated with an 'Aha!' moment, resulting from an unexpected awareness of a problem solution, accompanied by surprise and positive emotional responses (Kounios & Beeman, 2014). Reaching insight requires the ability to think beyond conventional means, explore innovative solutions, and think "outside the box". However, this process can be challenging, as our pre-existing knowledge and experience often impede our ability to do so (Storm et al., 2020). One such cognitive obstacle is functional fixedness, which limits our potential to identify alternative functions for tools or objects due to prior functional knowledge. This bias affects our ability to reach insight and creates cognitive impasses, making it difficult to think creatively and find innovative solutions to new challenges (Duncker, 1945; McCaffrey, 2012b; McCaffrey & Krishnamurty, 2015; Munoz-Rubke et al., 2018). One classic example of functional fixedness is the candle problem developed by Duncker (Duncker, 1945). In this problem, subjects are presented with a candle, a book of matches, and a box of tacks, and are instructed to attach the candle to a wall. To successfully solve the problem, the tack box must be used as a platform on which to place the candle. However, when subjects are primed with the box's typical function—a container full of tacks—rather than an empty box, they are less likely to see the problem solution (Duncker, 1945). In other words, subjects are more prone to functional fixedness.

Functional fixedness is a widespread phenomenon, and its effects have been observed in individuals across different age groups and cultural backgrounds. For instance, German and Defeyter (2000) assessed the performance of younger and older children attempting to complete a different version of Duncker's candle problem that required children to use an object for a purpose other than its conventional function. The authors found that older children performed more slowly than younger ones when primed for functional fixedness (German & Defeyter, 2000). This cognitive bias can hinder creativity and limit innovation in a wide range of

settings, from individual problem-solving to organizational strategy and societal progress. Thus, it is crucial to overcome functional fixedness to achieve insightful outcomes.

Research has indicated that when confronted with a particularly challenging problem, taking a break from the task can be an effective approach to generate creative solutions. The period during which a problem is set aside, termed incubation, allows unconscious processes to restructure associations between critical elements of the problems, resulting in the generation of novel and non-obvious solutions (Gilhooly, 2016; Kounios & Beeman, 2014; Sio & Ormerod, 2009). Insight problem-solving seems to benefit from this incubation period, which has been frequently associated with significant discoveries throughout history, including Albert Einstein's theory of relativity and Charles Darwin's theory of evolution (Kounios & Beeman, 2014). However, incubation alone might not be enough to avoid mental fixation on a problem (Storm et al., 2020). To promote the reorganization of mental representations in a novel fashion, previous studies have suggested that an incubation period during sleep may be particularly beneficial (Cai et al., 2009; Sanders et al., 2019; Sio et al., 2013; Wagner et al., 2004). Sleep after encoding promotes the consolidation of initially labile memory traces through a dialogue between the hippocampus and the neocortex (Diekelmann & Born, 2010; Rasch & Born, 2013). During this process, the newly learned traces are strengthened and gradually integrated into pre-existing memory networks (Tamminen et al., 2010). Research over the past years has suggested that sleep does not only facilitate the *quantitative* strengthening of memory traces, but also promotes the *qualitative* reorganization of memories, allowing for the abstraction of regularities in learned materials and insightful behaviour (Cai et al., 2009; Diekelmann & Born, 2010; Durrant et al., 2011; Ellenbogen et al., 2007; Monaghan et al., 2015; Sio & Ormerod, 2009; Wagner et al., 2004). For example, participants who slept after exposure to a series of tones in a probabilistically determined sequential structure

performed better in recognizing a new sequence that followed the same statistical pattern compared to those who remained awake (Durrant et al., 2011). In Wagner and colleagues' seminal study (Wagner et al., 2004), participants were tested on a modified version of the Number Reduction Task, which involved transforming an eight-digit string into a new string following specific rules. Participants' response speed on the task improved with practice. However, the task was designed such that an abrupt performance improvement could occur with the discovery of a hidden shortcut rule. In a subsequent delayed test performed after 8 hours of nocturnal sleep, participants were more likely to use the shortcut compared to those who were awake at night or during the day. This finding demonstrated that participants gained knowledge of the hidden rule while asleep (Wagner et al., 2004). Similarly, in another experiment, participants' performance on a creative problem-solving task improved after an incubation period involving REM sleep (Cai et al., 2009). Nevertheless, some studies have failed to find a beneficial effect of sleep on insight (Brodt et al., 2018; Hołda et al., 2020; Landmann et al., 2016; Schönauer & Pöhlchen, 2018). For instance, the study conducted by Schönauer and colleagues revealed that taking a nap did not enhance the ability to solve magic tricks and classical insight problems when compared to spending an equivalent amount of time awake (Schönauer & Pöhlchen, 2018). This finding was echoed in another study that observed that a nap did not lead to any improvement in riddle-solving abilities compared to a period of wakefulness (Brodt et al., 2018). Finally, another experiment by Hołda and colleagues utilized a murder mystery video game to assess the impact of sleep on problem-solving and also concluded no beneficial effects of sleep (Hołda et al., 2020).

In light of the challenges posed by functional fixedness and the potential benefits of an incubation period during sleep, overcoming functional fixedness is a crucial first step in promoting insightful problem-solving. To address this, McCaffrey recommended that individuals focus on unnoticed or obscure features that may

be present in the initial setting of a problem. By directing attention toward these often-overlooked elements, individuals may be better equipped to identify alternative functions and solutions, ultimately facilitating the process of reaching an insight (McCaffrey, 2012a; McCaffrey & Krishnamurty, 2015).

Specifically, McCaffrey provided participants with a cognitive training session known as the Generic Parts Technique (GPT). This technique involves breaking down an object into its fundamental components and defining each element based on its material, shape, and size. The ultimate goal of the GPT is to counteract functional fixedness, helping individuals identify overlooked object features that are necessary to solve insight problems (McCaffrey, 2012a). To illustrate this concept, McCaffrey used the example of a candle. Typically, we associate the candle as an item designed for illumination. However, when we apply the GPT, we break down the candle into its basic attributes. In doing so, we might realize that the candle's wick, which is essentially a piece of string, can serve other purposes beyond just lighting a candle, such as tying your shoes.

In this study, we set out to investigate whether sleep can serve as a mechanism to consolidate the effects of the GPT, ultimately facilitating creative insight in problem-solving. To this end, participants underwent the GPT followed by a set of insight problems to solve. After a 12-hour retention interval, which included either overnight sleep or daytime wakefulness, participants were asked to solve a second set of insight problems and to perform a listing feature task that relied on the features targeted by the GPT for their solutions. To determine whether sleep played a role in consolidating the training, thereby potentially enhancing the facilitation of insight problem-solving, we compared participants' performance across the two incubation periods. We hypothesized that an incubation interval that included sleep would contribute to overcoming mental fixity and would preferentially enhance participants' performance on insight problem-solving.

3.3 Materials and Methods

3.3.1 Participants

Fifty-three healthy volunteers (40 females, age range: 18–35 years, mean ± SD: 24.57 ± 3.92) participated in an online study approved by the Ethics Committee of the School of Psychology at Cardiff University. Participants were recruited from both the UK (33 participants, 26 females, mean ± SD: 22.03 ± 4.12) and Italy (20 participants, 14 females, mean ± SD: 25.60 ± 2.68) via online advertising on social media. Interested individuals were redirected to an online eligibility screening questionnaire. The online screening ensured that only native English or Italian speakers between the ages of 18 and 35 were included, as sleep quality has been shown to decline after the age of approximately 35. We also required participants to be habitual non-smokers with normal or corrected-to-normal vision and no previous history of physical, psychological, neurological, or sleep disorders. None of the participants reported taking any medication or substances affecting sleep quality. Further exclusion criteria included daytime napping habits, irregular sleep-wake rhythms, and night shift work. Additionally, participants were asked to abstain from alcohol for 24 hours prior to the study and from caffeine or other psychologically active foods for 12 hours before the study began. We also ensured that those recruited agreed not to engage in extreme physical exercise on the days of the experiment.

Out of 53 participants, data from 25 were discarded: 24 participants did not successfully complete the GPT training (see section 3.3.3 for GPT criteria), and data from one participant were excluded due to a script error. Consequently, the dataset included 28 participants (20 females, mean ± SD: 23.78 ± 3.89), with 14 subjects in the sleep group (10 females, mean ± SD: 22.71 ± 3.10; UK: 7 participants, 6 females, mean ± SD: 20.14 ± 1.21; Italy: 7 participants, 4 females,

mean ± SD: 25.28 ± 1.98) and 14 subjects in the wake group (10 females, mean ± SD: 24.86 ± 4.40; UK: 6 participants, 4 females, mean ± SD: 24.83 ± 6.31; Italy: 8 participants, 6 females, mean ± SD: 24.87 ± 2.75). All participants provided written informed consent and received monetary compensation for their participation.

3.3.2 Experimental tasks

3.3.2.1 Generic Part Technique (GPT)

The GPT is a technique developed by McCaffrey (2012) that aims to counteract functional fixedness. It identifies four essential features that are necessary to solve insight problems involving concrete objects: material, shape, size, and parts (McCaffrey, 2012a). The technique involves breaking down an object (e.g., scissors) into subparts (e.g., blades) and creating function-free descriptions of each subpart that only refer to the object's essential features (e.g., a long triangular piece of metal with a pointy-end). This step is crucial as it allows individuals to replace the commonly associated function of an object (e.g., to cut) with a function-free description, which can uncover alternative uses for an object (e.g., scissors' blades can be used as a screwdriver).

To implement the GPT, subjects need to repeatedly ask themselves two key questions every time an object is broken into its component parts: *"Can this be decomposed further?"* and *"Does this description imply a use?"*. Following this procedure, subjects create a parts diagram. The description at the bottom level is solely based on the material, shape, size, and parts of objects and does not imply any use (see Figure 3.6 in the Supplementary Material; McCaffrey, 2012a, 2012b). The GPT has been successfully demonstrated to provide individuals with a systematic approach to counteract functional fixedness in insight problems involving concrete objects (McCaffrey, 2012a, 2012b; McCaffrey & Krishnamurty, 2015).

3.3.2.2 Insight problems

Eight insight problems that require the identification of the material, shape, size, and parts of objects were presented in this study. These problems include the tower problem (Isaak & Just, 1995), the candle problem (Duncker, 1945), the circuit problem (Glucksberg et al., 1968), the two-rings problem, the stuck-truck problem, the wristwatch problem, the hot-coals problem, and the desk-lamp problem (McCaffrey, 2018). The desk-lamp problem was modified from its original version as it required knowledge about a US plug. All problems and solutions are reported in the Supplementary Material.

To solve these problems, subjects needed to uncover the feature types targeted by the GPT. Participants were instructed to solve each problem within eight minutes, which has been previously established as an adequate amount of time to produce and write an answer (McCaffrey, 2012a, 2012b). They were asked to provide no more than two solutions for each problem. While they could move on to the next problem, they were not allowed to return to the previous one. Before each problem, a reminder was given about the use of the GPT technique.

3.3.2.3 Feature-listing task

As previously outlined, the GPT technique reveals the four key features (material, shape, size, and parts of objects) necessary for solving insight problems. The feature-listing task aimed to investigate how many of these types of features participants could identify.

During this task, participants were instructed to list all possible features, properties, and associations of ten objects. The first five objects presented were unrelated to the insight problems (bike, bin, chair, scissors, umbrella). These were followed by four objects (candle, rope, truck, watch) that contained the key features for

solving the insight problems. The last object was a lamp, which did not possess the crucial feature but had been previously encountered by participants when solving the problems. A reminder to use the GPT technique was provided at the top of each object, and participants had four minutes to work on each one. They were permitted to move on to the next object before time expired but were not allowed to go back to a previous one. Before starting the feature-listing task, participants were shown an example using the features of a coffee cup (McCaffrey, 2012a, see Supplementary Material).

3.3.3 Procedures

The study used a between-subject design consisting of two sessions performed 12 hours apart (Figure 3.1). Participants were randomly assigned to either the sleep or wake group. For the wake group, the first session was conducted between 9 a.m. and 10 a.m., with the second session taking place between 9 p.m. and 10 p.m. on the same day. Conversely, the sleep group underwent the first session between 9 p.m. and 10 p.m., with the second session being held between 9 a.m. and 10 a.m. the following day.

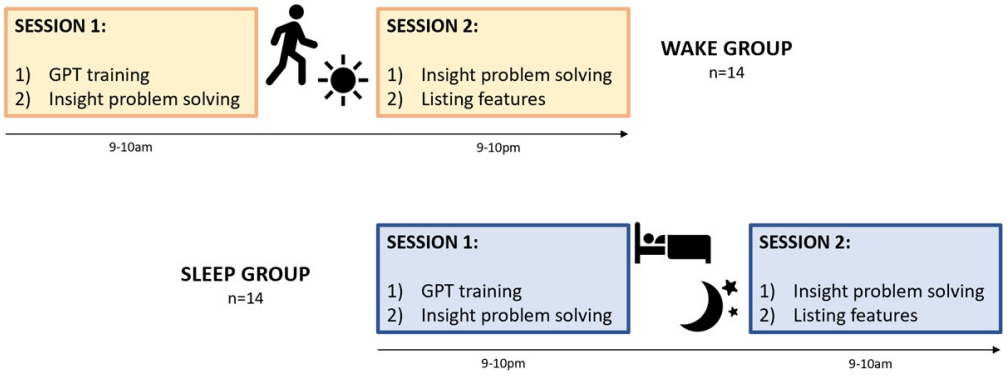


Figure 3.1: *Experimental procedure.* Participants were randomly allocated to either a wake or a sleep group. During Session 1, both groups were asked to perform the Generic Part Technique (GPT) and solve four insight problems. After a 12-hour retention interval, which included either daytime wake or overnight sleep, Session 2 was conducted. In the second session, participants from both groups were asked to solve an additional four insight problems and perform a listing feature task.

In Session 1, participants first completed the Stanford Sleepiness Scale (SSS, Hoddes et al., 1973) to assess their present level of alertness. Then, following the procedure adopted by McCaffrey (2012), the GPT's general purpose and instructions were presented, followed by the example of a tree-part diagram of a bell (McCaffrey, 2012a). Participants then attempted to use the technique with three different objects: a ladder, a kettle, and an arrow. A reminder with the two main questions of the GPT (*"Can this be decomposed further?"* and then, *"Does this description imply a use?"*) was always present on the screen. All participants received feedback with an appropriate answer for each part diagram. No time limit was imposed on completing the training. As reported by McCaffrey (2012), the training was considered successfully completed when (a) all parts of the objects were listed and (b) the final descriptions did not imply any uses. Only one mistake was allowed on each part diagram, either one missed part or one description implying the use of an object. This method ensured that participants gained a systematic approach to avoid overlooking obscure features of the objects. As a

second and last step in Session 1, participants attempted to solve four insight problems and rated the usefulness of the GPT and the level of effort applied while performing the task using a Likert-scale assessment (1: “Did not work hard at all” to 10: “Worked as hard as I possibly could”) (McCaffrey, 2012a).

Session 2 included four insight problems and a feature-listing task, preceded by the administration of the SSS questionnaire (Hoddes et al., 1973). As in Session 1, the Likert-scale assessments were conducted at the end of Session 2 to evaluate the usefulness of the GPT and the level of effort applied. In both sessions, participants were asked to indicate their familiarity with the insight problems presented, so that those problems were not included in the final analysis. Insight problems were presented in the same order in both sessions but counterbalanced across participants. All tasks were executed online using PsychoPy3 Experiment Runner (v2020.1.3; Peirce et al., 2019).

3.4 Data Analysis

The analysis presented in this section pertains only to participants who successfully completed the GPT training. We assessed the correctness of solutions for the eight insight problems by determining whether participants identified and utilized the key features of the problems. To calculate the time taken to solve each problem, we divided the average time required to solve the problem by the number of correct responses. For the feature-listing task, each listed feature was categorized as either "Material", "Shape", "Size", or "Part", following the categorization scheme from McCaffrey (McCaffrey, 2012a). The total number of each type of feature across all objects was calculated to determine the total feature-listing score. Three independent scorers, who were blinded to the experimental conditions, conducted the scoring.

Statistical analyses were conducted using IBM© SPSS© Statistics (version 25, IBM Corp, Armonk, NY, 2017) and R (version 4.0.2; R Core Team, 2020). Separate two-way mixed-method analyses of variance (ANOVAs) were used to evaluate the effects of group and session. Significant two-way interactions between the within and between subjects factors were further explored using a simple main effects analysis. By contrast, for non-significant two-way interactions, we determined whether the main effects were significant (Fox, 2016). The homogeneity and sphericity assumptions were satisfied for all ANOVAs. The normality assumption was violated in one of the sub-groups, as assessed by a significant Shapiro-Wilk test. Although ANOVA is known to be robust to the violation of the normality assumption (Blanca et al., 2017; Gelman & Hill, 2007), throughout the scientific literature there are divergent opinions (Osborne & Waters, 2002; Warton et al., 2016). Therefore, we also ran a two-way mixed ANOVA using robust estimators with the *WRS2* package and the *bwtrim* function that computes the two-way mixed ANOVA in trimmed means (Mair & Wilcox, 2020). Effect sizes were reported as partial eta squared η_p^2.

Between-conditions analysis were conducted using independent-samples T test. When the assumption of normality was violated, as assessed by a significant Shapiro-Wilk test and confirmed through visual inspection of the Normal Q-Q plots, the non-parametric Mann-Whitney U was conducted instead. To account for multiple comparisons, the false discovery rate (FDR) correction (Benjamini & Hochberg, 1995) was applied, thus controlling for the expected proportion of falsely rejected hypotheses. All figures were created in R using *ggplot2* package and *raincloud plot* (Allen et al., 2019; Wickham, 2009). All tests were two-tailed with a statistical significance level set at $p<0.05$. All data are shown as Mean $\pm$ Standard error of the mean (SEM) unless otherwise specified.

3.5 Results

3.5.1 Questionnaires

Mann-Whitney U Test revealed no differences between groups in alertness during the first session, measured with the SSS (sleep group: M = 2.78, SE = 0.19; wake group: M = 2.64, SE = 0.40; comparison of groups: U = 84, Z = -0.68, p = 0.493, r = 0.13). A similar pattern was found in session 2 (sleep group: M = 2.86, SE = 0.29; wake group: M = 2.64, SE = 0.37; comparison of groups: U = 85, Z = 190, p = 0.537, r = 0.12).

3.5.2 Insight problems

Two participants (one in the sleep group and one in the wake group) indicated that they were familiar with 2 insight problems (the tower and the candle problem), therefore we didn't take into account these answers when analysing subjects' data. Behavioral results are presented in Table 3.1.

Table 3.1: *Descriptive statistic of the Insight Problems.* Descriptive statistic of sleep and wake groups for the insight problems on the first and the second test sessions. CI = confidence interval, SEM = standard error of the mean.

Session 1					
		Mean	Meadian	SD	SE
Sleep Group	Insight Problems Solved	1.93	2.00	1.35 - 2.50	0.27
	Time to reach solution	3.22	2.28	2.01 - 4.42	0.55
Wake Group	Insight Problems Solved	2.64	3.00	2.11 - 3.18	0.25
	Time to reach solution	3.22	3.11	2.34 - 4.31	0.46
Session 2					
Sleep Group	Insight Problems Solved	2.71	3.00	2.14 - 3.29	0.26
	Time to reach solution	4.10	4.45	3.01 - 5.19	0.50
Wake Group	Insight Problems Solved	1.86	2.00	1.36 - 2.36	0.23
	Time to reach solution	2.26	2.04	1.54 - 2.98	0.33

Our analysis initially focused on testing the effect of sleep on the number of insight problems solved and on the time required to solve each problem. We conducted two separate two-way mixed ANOVAs with the within-subjects factor of Session (Session 1 versus Session 2) and the between-subjects factor of Group (sleep versus wake). For the insight problems, the analysis revealed a significant interaction between Session and Group ($F(1,26) = 9.62$, $p = 0.005$, $\eta_p^2 = 0.27$). Further exploration through simple main effect analysis of the groups showed no difference between groups in the first test session ($F(1,26) = 3.85$, $p = 0.061$, $\eta_p^2 = 0.13$), but there was a statistically significant difference in the number of insight problems solved between groups in the second test session ($F(1,26) = 5.92$, $p = 0.022$, $\eta_p^2 = 0.19$). Specifically, the sleep group exhibited superior performance in the second session compared to the wake group (Mean difference Sleep-Wake group = 0.86, SE = 0.35, 95% CI = [0.13, 1.59]) (Figure 3.2a).

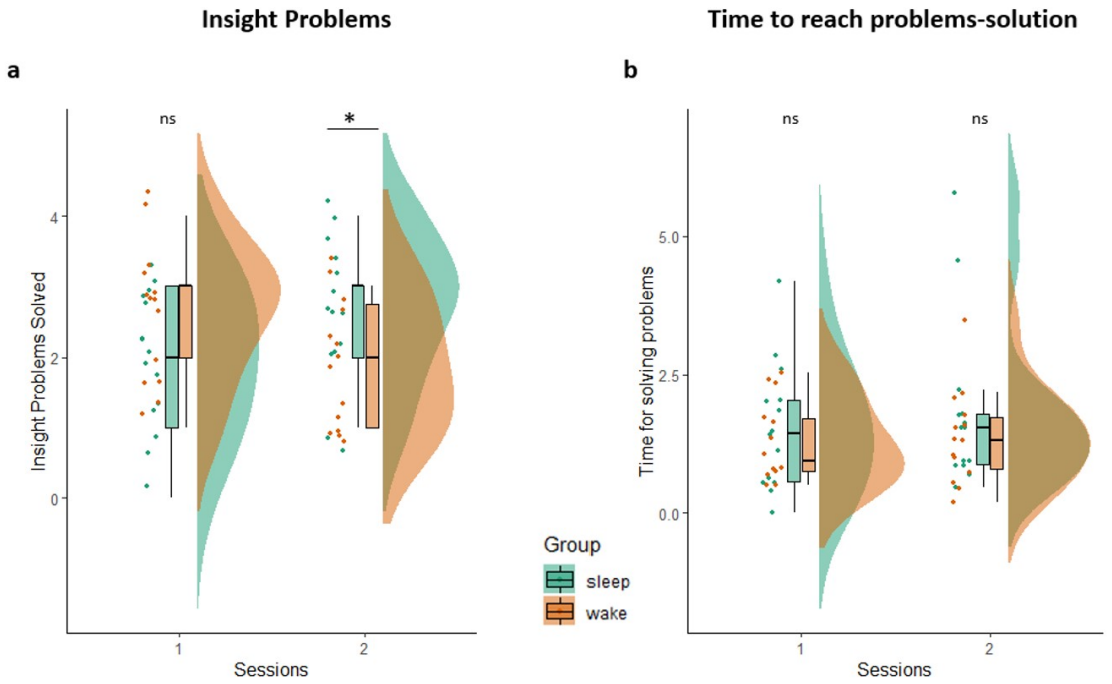


Figure 3.2: *Behavioural results.* **a)** Performance on insight problems of sleep (green) and wake (orange) groups on the first and the second test sessions. **b)** Time needed for solving insight problems on the first and the second test sessions for both the sleep (green) and the wake (orange) groups. Boxplots show the median (inner thick horizontal line), the 25th and 75th percentiles (the bottom and the top of the box), the maximum and the minimum of the data (whiskers). *p$<$ 0.05. ns: non-significant.

The investigation into the time required to solve the insight problems yielded no statistically significant interaction between session and group ($F(1,26) = 0.11$, $p = 0.742$, $\eta_p^2 = 0.00$) and no main effects of sessions ($F(1,26) = 0.43$, $p = 0.516$, $\eta_p^2 = 0.02$) or groups ($F(1,26) = 1.35$, $p = 0.255$, $\eta_p^2 = 0.05$). Given the violation of the normality assumption for residuals, we conducted a robust ANOVA. This robust analysis also confirmed the absence of a significant interaction between session and group ($F(1,17) = 0.06$, $p = 0.80$) and no main effect of either session ($F(1,17) = 0.03$, $p = 0.87$) or group ($F(1,17) = 0.39$, $p = 0.54$) (Figure 3.2b).

In order to test for time of day confounds, we conducted an ANOVA with within-

participant factor *Time of Day* (morning or evening) and between-participant factor *Session*. The dependent variable in this analysis was the number of insight problems solved. We found a significant main effect of time of day ($F(1,52) = 9.62$, $p = .003$), revealing a difference in participants' performance based on whether the session took place in the morning or evening. Specifically, participants performed significantly better in the morning compared to the evening session (Morning: 2.68±0.18; Evening: 1.89±0.17). No significant effect of session ($F(1,52) = .000$, $p = 1.000$) and no significant interaction was found ($F(1,52) = 0.08$, $p = .779$). These findings suggest that time of day plays a role in influencing the performance on insight problems.

3.5.3 Listing features

Overall, the sleep group listed significantly more features related to the material (sleep group: $M = 25.28$, $SE = 2.81$, wake group: $M = 13.21$, $SE = 2.62$, comparison of groups: $t(26) = 3.14$, $p = 0.004$) and part (sleep group: $M = 41.64$, $SE = 3.22$, wake group: $M = 25.93$, $SE = 4.23$, comparison of groups: $t(26) = 2.95$, $p = 0.006$) categories compared to the wake group. Although the sleep group descriptively listed more features related to the shape and size categories, this difference did not reach statistical significance (shape: $t(26) = 1.73$, $p = 0.095$; size: $U = 65$, $Z = -1.53$, $p = 0.131$, Table 3.2). Importantly, none of these comparisons maintained significance after undergoing multiple corrections ($p_{\text{adj}} > 0.05$ for all comparisons).

Table 3.2: *Descriptive statistic of the listing-feature task.* Descriptive statistic (mean ± standard error of the mean, SEM) of sleep and wake groups for the listing-feature task on the second test sessions and pairwise comparisons. Statistical test used: independent-samples t-test (t-test) or Mann-Whitney U test (U-test). Both the uncorrected and FDR-corrected p-values are reported.

Features	Sleep group	Wake group				
			Statistical test	Test statistic	p-value	p_{adj}
Material	25.28 ± 2.81	13.21±2.62	t-test	3.14	.004	0.13
Part	41.64 ± 3.22	25.93±4.23	t-test	2.95	.006	0.13
Shape	13.07 ± 1.86	8.93±1.51	t-test	1.73	.095	0.13
Size	6.36 ± 1.51	3.14±0.74	U-test	-1.53	.131	0.13

3.5.4 Post-sessions questionnaire

A 5-point Likert scale was used to assess the usefulness of the training in solving insight problems and to determine whether participants utilized the training when attempting to solve the problems. Both groups rated the training as moderately beneficial and indicated that they employed the technique while approaching the insight problems (Table 3.3). An evaluation of the level of effort, using a 10-point Likert scale, revealed that the sleep group reported applying a significantly higher level of effort in Session 2 ($t(26) = 2.78$, $p = 0.01$) (Table 3.3). No correlations were found between behavioral measures and the level of effort applied (all $p>0.05$).

Table 3.3: *Descriptive statistic of the post-sessions questionnaire.* Descriptive statistic (mean ± standard error of the mean) of sleep and wake groups for post-sessions questionnaire and pairwise comparisons. Statistical test used: independent-samples t-test (t-test) or Mann-Whitney U test (U-test). Usefulness GPT: "The exercise from the training program helped me to solve the assigned problems: 1(not at all), 5(very useful)". Applied GPT while solving problems: "I used what I learned from the training exercise when attempting to solve the problems assigned to me: 1(not at all), 5(very useful)". Level of effort: "Please rate the level of effort you applied towards attempting to solve each problem: 1(Did not work hard at all), 10(worked as hard as I possibly could)". Questions were adapted from McCaffrey, 2012b. GPT = Generic Part Training. * $p < 0.05$.

Session	Sleep group	Wake group			
			Statistical test	Test statistic	p-value
Usefulness GPT					
Session 1	2.50±0.37	2.43±0.39	U-test	-0.19	0.87
Session 2	2.64±0.32	2.78±0.30	t-test	-0.32	0.75
Applied GPT					
Session 1	3.21±0.41	2.36±0.34	U-test	-1.60	0.11
Session 2	3.00±0.33	2.86±0.36	t-test	0.29	0.773
Level of effort					
Session 1	7.86±0.39	6.86±0.36	t-test	1.88	0.07
Session 2	8.14±0.29	6.43±0.54	t-test	2.78	**0.01***

3.6 Discussion

The present study aimed to investigate the impact of an incubation period, involving either 12 hours of sleep or wakefulness, on the ability to apply the GPT to overcome functional fixedness.

The ability of restructuring or recombining memory in a novel fashion required by insight is often challenging to achieve. On the one hand, domain expertise, and experience may facilitate problem-solving within a specific field, while on the other,

these factors might cause an inability to restructure prior knowledge to generate novel ideas (Storm et al., 2020; Weisberg, 2006). In this context, the GPT offers a potential approach by uncovering object features that can help overcome mental fixity and solve insight problems (McCaffrey, 2012a). By employing this technique and comparing participants in the sleep and wake groups, we found that the sleep group exhibited a greater improvement in solving insight problems. However, this improvement appears to be attributed to circadian influences.

The circadian rhythm, which regulates our physiological functions over a 24-hour day, has been shown to influence various aspects of human behaviour, including cognitive performance (Gerstner & Yin, 2010; May & Hasher, 2017; Volk et al., 2023). Numerous studies have reported that cognitive tasks benefit from circadian synchronization, with individuals performing better during their optimal time of day as determined by their chronotype, and experiencing impaired performance when there is asynchrony (Hasher et al., 2002; May & Hasher, 2017; Volk et al., 2023). Moreover, time of day has been found to significantly impact inhibitory function, with varying effects depending on the nature of the task. Examining the effects of time of day on problem-solving, Wieth and Zacks (2011) demonstrated that reduced attentional control during non-optimal times can enhance performance on insight problem-solving, as "outside the box" thinking becomes more dominant (Wieth & Zacks, 2011). Given that young adults tend to exhibit evening or neutral chronotypes (May et al., 1993), we could speculate that asynchronization between chronotype and time of day could have potentially boosted performance of insight. However, this speculation is limited as the study did not measure morningness and eveningness in the participants. Furthermore, a more recent study observed a beneficial effect of synchrony between circadian processes and time of day on creativity (Kühnel et al., 2022).

These findings collectively suggest the complex relationship between circadian influences and problem-solving abilities. The effects of time of day on cognitive

processes may vary depending on multiple factors, including task characteristics, individual differences in chronotype, and the interplay between circadian rhythms and other physiological and cognitive mechanisms. Further research is needed to better understand the intricate interactions between circadian rhythms, problem-solving strategies, and creative thinking abilities.

Inconclusive results are not solely limited to the consideration of time of day but are commonly observed while examining the effect of incubation on creative problems (Brodt et al., 2018; Cai et al., 2009; Hołda et al., 2020; Landmann et al., 2016; Schönauer & Pöhlchen, 2018; Sio et al., 2013; Wagner et al., 2004). For example, Schönauer and colleagues did not observe a benefit of sleep on classical insight problems and magic tricks when participants were tested after 3-h incubation period including sleep or wake (Schönauer & Pöhlchen, 2018). Similarly, Brodt and colleagues reported no effect of sleep on a different set of problems including change detection, riddles, and anagrams (Brodt et al., 2018). Other studies focused on the effect of sleep on creative problems by employing the Remote Associates Test (RAT; Mednick, 1962), or similar versions (Cai et al., 2009; Landmann et al., 2016; Sio et al., 2013). In the RAT, participants are required to find a word associated with three seemingly unrelated words (e.g. heart, sixteen, and cookie are associated with the word sweet, Cai et al., 2009). Using this task, Cai and colleagues found that REM sleep enhanced the chance of finding a solution, while Sio and colleagues found that this effect was mainly related to more difficult problems (Cai et al., 2009; Sio et al., 2013). These discrepancies emphasize the need for further exploration to better understand the underlying mechanisms and determine the specific conditions under which sleep can facilitate insight.

3.6.1 Study limitations

Despite not finding a significant effect of sleep on insight problem-solving and considering the influence of time of day on our results, it is important to acknowledge several limitations encountered in our study. One notable limitation was the loss of participants who did not correctly perform the GPT training. This issue may have arisen due to the constraints imposed by the online version of the experiment.

McCaffrey emphasized the importance of the experimenter collaboratively creating the initial parts-diagram with the participants. This collaborative process not only ensured that participants were fully engaged in understanding and constructing the diagram but also served as a means to capture their attention and reinforce their understanding of the task (McCaffrey, 2012a, 2012b). However, in our online study, we adopted a different approach by presenting participants with a pre-structured diagram that they subsequently filled in. This alteration may have diminished the level of active engagement and participation in the task, which in turn could have impacted their performance. Indeed, the online research environment comes with inherent drawbacks, including the lack of experimenter presence and control over the research setting (Finley & Penningroth, 2015). This could have contributed to participants misunderstanding instructions, skipping reading them, or failing to give them the necessary attention—all factors that could have contributed to the significant number of participants who did not correctly perform the training. To address these concerns, future studies might consider replicating the experiment within a controlled laboratory setting. This approach would ensure participants' active involvement and provide researchers with better control over the experimental conditions, for example, incorporating measurements of participants' sleep duration and sleep architecture.

Another major limitation of our study pertains to its design. Measuring perfor-

mance at various times of the day lacks control over the timing of both training and testing, rendering it vulnerable to circadian and homeostatic confounders. To address this limitation, a nap design, in which the sleep group has an interval of diurnal sleep in the afternoon while the wake group remains awake for the same duration, might be better suited to account for circadian influences and mitigate their confounding effects (Schmid et al., 2020).

3.6.2 Conclusions

This study investigated the impact of an incubation period, involving sleep or wakefulness, on overcoming functional fixedness and promoting insightful problem-solving. Our results suggest that sleep might facilitate the incorporation and integration of the GPT, ultimately resulting in enhanced performance on insight problems. Nevertheless, the interpretation of this outcome is confounded due to the influence of circadian rhythms. The influence of circadian rhythms on problem-solving remains complex and multifaceted, with divergent findings in the literature. Further investigation of the interplay between circadian influences, cognitive processes, and creative thinking, will help us to build an understanding of how circadian influences impact creativity and problem-solving, ultimately leading to the development of more effective strategies to enhance insightful thinking.

3.7 Supplementaty Material

3.7.1 Supplementary figures

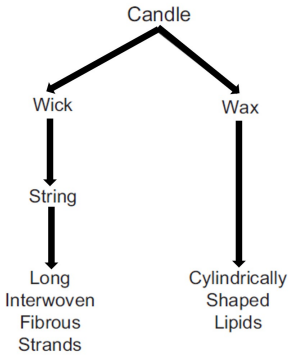


Figure 3.3: *Example of a part diagram.* Example of a part diagram obtained by following instructions of the Generic Part Technique (GPT). Descriptions at the bottom do not imply any use. Figure adapted from McCaffrey, 2012a.

3.7.2 Features example

Coffee cup features example

1. "handle" or "has a handle"

2. "Mouth is bigger than base"

3. "handle is shaped like an ear"

4. "can draw circles with it"

3.7.3 Insight problems

1. The tower problem (Isaak & Just, 1995).

   A prisoner was attempting to escape from a tower. He found in his cell a rope which was half long enough to permit him to reach the ground safely. He divided the rope in half and tied the two parts together and escaped. How could he have done this?

Solution: he cut the rope in half vertically.

2. The candle problem (Duncker, 1945).

   Sitting on a table are a candle, a box of tacks, and a book of matches. You must attach the candle to the wall so that it can burn upright and won't drip wax onto the table. How would you solve the problem?

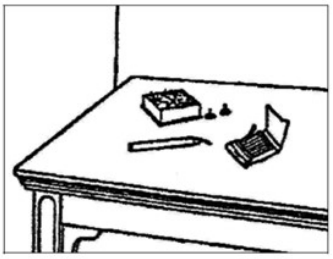


Figure 3.4: *The candle problem.*

Solution: Empty the tack-box. Tack the box to the wall. Set the candle on the platform formed by the box.

3. The circuit problem (Glucksberg et al., 1968).

   You are to complete an electrical circuit comprised of a series of short 3-inch wires that connect a series of electrical posts with screws as shown in the diagram below. The wires were screwed into the posts by a screwdriver, which you still have. When all the wires were screwed into the posts, two posts are left disconnected and so the circuit is not complete. You are missing one section of 3-inch wire. You also have a wooden ruler but have no access to anything else. How can you complete the circuit?

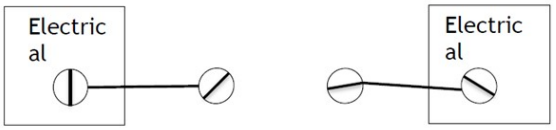


Figure 3.5: *The circuit problem.*

Solution: Use the metal part of the screwdriver to complete the circuit.

4. The two-rings problem (McCaffrey, 2018).

   You need to connect two rings together so that when you pick up one ring the other will follow. The rings weigh 3 pounds each and are made of solid gold. You do not want to damage them. You have a long, thin candle and a 2-inch cubic block of steel. How can you connect the two rings?

Figure 3.6: *The two-rings problem.*

Solution: The wick inside the candle is also a long string. Shave the wax from the candle using the steel cube, and then use the string to tie the rings together.

5. The stuck-truck problem (McCaffrey, 2018).

   A truck driver was driving his semi-trailer truck under an overpass when suddenly he came to a screeching halt. He wasn't paying enough attention and inadvertently drove under the overpass that was just barely as high as his truck. The truck was wedged so tightly that he could not go forward or backward. Without damaging either the top of the truck or the overpass, how could he, all by himself, get his semi unstuck?

Solution: the driver can deflate the tires and drive out slowly.

6. The wristwatch problem (McCaffrey, 2018).

   You own a wristwatch with a leather band. You are in an empty room and you need to open the battery case on the back of the watch. You do not want to damage the watch. Your fingernail is not strong enough to turn it. How do you do it?

   Solution: the rectangular metal piece on the watch buckle can serve as a screwdriver.

7. The hot-coals problem (McCaffrey, 2018).

   You need to transport a dozen hot coals from a campfire site to another campfire site some 100 yards away. The coals are much too hot to touch and they will quickly burn through any cloth they come in contact with. You are walking home from basketball practice in your bare feet so you are carrying a basketball and your jersey on a metal hanger. Other than that, all you have access to is a stick. How can you quickly transport all the coals at once before they cool?

   Solution: Use the hanger to poke into the air hole to deflate the ball and form it into the shape of a bowl. Use the hanger to push the coals into the basketball.

8. The desk-lamp problem (adapted from McCaffrey, 2018).

   For some bizarre reason, a desk lamp is screwed to the table by its base. You need to remove the lamp from the table without damaging either the table or the lamp. The room is empty, except for you –and your pockets are empty except for a supermarket receipt and a few coins left. You cannot

leave the room, and no one can bring you anything. How can you remove the lamp from the table?

Solution: the coin can be used to loosen the screw.

Chapter 4

Depotentiation of emotional reactivity using Targeted Memory reactivation during Rapid-Eye movement sleep

4.1 Abstract

Emotional reactivity has been shown to habituate overnight and this is thought to be mediated by memory reactivation during rapid eye movement (REM) sleep. Such reactivation can be intentionally triggered by targeted memory reactivation (TMR), a technique in which a tone previously associated with a memory during wake is re-presented during subsequent sleep. We have previously shown that TMR in REM reduces arousal responses to negative stimuli. The present study builds on this prior work by incorporating measures of heart rate deceleration (HRD) and brain activity. Participants rated the arousal of 48 affective images, paired with semantically matching sounds, on a 1-5 scale. Half of these sounds were cued during REM in the subsequent overnight sleep cycle. Following a 48-hour delay, participants rated the images again in an MRI scanner, while HRD was simultaneously recorded. An online behavioural follow-up was conducted two weeks later. TMR during REM resulted in a reduction of both HRD and responses within the insula, orbitofrontal cortex, and paracingulate gyrus. Furthermore, the impact of cueing intervention on participants' emotional responses was tied to their individual baseline arousal levels. This finding suggests that REM TMR can facilitate a decrease in physiological responses to arousal.

4.2 Introduction

Emotion exerts a powerful influence on everyday human experiences. While various findings suggest that emotional memories are preferentially consolidated during sleep (Alger et al., 2018; Cunningham et al., 2014; Groch et al., 2013; P. Hu et al., 2006; Nishida et al., 2009; Payne et al., 2008; Prehn-Kristensen et al., 2009; Wagner et al., 2001; Wagner et al., 2006), whether and how sleep also modulates the affective tone of these memories remains a topic of debate. Some researchers argue for a reduction in emotional reactivity after sleep (Bolinger et al., 2019;

Cunningham et al., 2014; Gujar et al., 2011; van der Helm et al., 2011; Zeng et al., 2021), while others suggest a preservation (Ashton et al., 2019; Baran et al., 2012; Groch et al., 2013; Jones & Spencer, 2019; Tempesta et al., 2015).

The "Sleep to forget, Sleep to Remember" (SFSR) hypothesis posits that while the content (the information) of emotional memories is strengthened over time, the emotional charge associated with their recall may be attenuated across multiple nights of sleep. It also suggests that Rapid-Eye Movement (REM) sleep is mainly involved in these processes (Helm & Walker, 2010; Walker, 2009). Indeed, the unique neurological milieu of REM sleep seems to provide optimal conditions for the processing of emotional memories (Gujar et al., 2011; Maquet et al., 1996; Menz et al., 2016; Nishida et al., 2009; Rihm & Rasch, 2015; van der Helm et al., 2011; Walker, 2009). Neuroimaging studies have revealed a higher activity in key brain regions involved in the formation and consolidation of emotional memories – such as amygdala, anterior cingulate cortex (ACC), hippocampus, and medial prefrontal cortex (mPFC) – during REM sleep (Dang-Vu et al., 2010; Maquet et al., 1996; Miyauchi et al., 2009). From a neurochemical perspective, REM sleep is characterised by significantly increased concentrations of acetylcholine (ACh), crucial for the long-term consolidation of emotional learning (McGaugh, 2004). These ACh levels are four times higher than during NREM sleep and twice that of wakefulness (Marrosu et al., 1995). Furthermore, noradrenergic and serotonergic input to the cortex, associated with high stress and anxiety disorders, are almost silenced during REM (Hasselmo, 2006; McGaugh, 2004). The specific combination of high ACh and low norepinephrine (NE) in REM sleep might account for the decreased synchronization observed between the hippocampus and the neocortex. Indeed, high ACh levels in the hippocampus could lead to feedback suppression within that region, thus attenuating the transmission of information from the hippocampus to the neocortex. A similar pattern occurs in the neocortex where the low levels of NE reduce suppression of feedback within cortical areas, thus allow-

ing for more widespread activity in the cortex without significant influence from the hippocampus. The cortex can therefore more freely re-analyze and possibly recombine or re-associate existing memories and knowledge, potentially leading to new feedforward representations (Hasselmo, 1999, 2006; Lewis et al., 2018). On the electrophysiological front, REM sleep is marked by the presence of theta oscillations (4-8 Hz), traveling waves that by synchronizing neural activity across the hippocampus, limbic, and cortical areas are proposed to modulate affective experiences in both animals and humans (Boyce et al., 2016; Lubenov & Siapas, 2009; Nishida et al., 2009; Popa et al., 2010; Pronier et al., 2023; Siapas et al., 2005). For instance, studies on rodents found that REM theta synchronization between the hippocampus, amygdala, and mPFC structures predicted the consolidation of fear memories (Popa et al., 2010); another study using optogenetics demonstrated that disrupting theta oscillations during REM sleep impairs mice in fear-conditioning tasks (Boyce et al., 2016). Human studies have found that enhanced consolidation of negative emotional memories is correlated with REM theta power (Nishida et al., 2009). Furthermore, PGO waves in rodents, that tend to be phase-locked to theta waves (Karashima et al., 2007), have been linked to emotional memory consolidation and neural plasticity (Datta et al., 2008; Ribeiro et al., 2002; Rihm & Rasch, 2015). Datta (2008) demonstrated that PGO waves mediate the increased expression of immediate-early genes and brain-derived neurotrophic factor (BDNF) in the hippocampus (Datta et al., 2008). Additionally, During REM there is a specific upregulation of the early gene Zif-268, which is involved in synaptic plasticity. It has been demonstrated that this upregulation occurs first in regions proximal to the hippocampus during initial episodes of REM sleep and later extends to more distal regions, including the cerebral cortex and the amygdala, thus providing an ideal setting for neuroplastic events to occur (Ribeiro et al., 2002).

A promising tool in investigating the sleep-dependent memory consolidation is

triggering targeted memory reactivation (TMR) during sleep. In a typical TMR experiment, a tone or an odour previously associated with a newly encoded memory during awake learning is re-presented during sleep (Rasch et al., 2007; Rudoy et al., 2009). This prompts the reactivation of the corresponding memory representation and it can be used to manipulate emotional memories (Hutchison et al., 2021; Rihm & Rasch, 2015; Sterpenich et al., 2014; Wassing et al., 2019). We previously examined the question of whether TMR reduces emotional reactivity by asking participants to rate emotional images for arousal both before and after the manipulation. This showed that TMR of emotionally arousing stimuli during REM sleep, but not during SWS, led to a significant habituation of subjective arousal (Hutchison et al., 2021). In the current study, we set out to extend this REM TMR finding by examining both physiological and neural arousal responses, in addition to subjective ratings. To this end, we used functional magnetic resonance imaging (fMRI) to examine brain activity, focusing on regions known to be involved in the processing and regulation of emotions, namely amygdala, insula, orbitofrontal cortex (OFC), and subgenual anterior cingulate cortex (sgACC). These regions have been extensively studied and are recognized as key components of the neural circuitry underlying emotional experiences and previous studies have reported activations of these regions due to sleep or emotional reactivity (Cairney et al., 2014; Gasquoine, 2014; Murty et al., 2010; Rolls, 2019, 2023; van der Helm et al., 2011; Wassing et al., 2019). Furthermore, dysfunctions within these regions have been associated with psychiatric disorders such as depression or post-traumatic stress disorders, PTSD (Benschop et al., 2022; Drevets et al., 2008; Gasquoine, 2014; Hamilton et al., 2008). In addition to brain activity, we also examined heart rate deceleration (HRD) as a physiological marker of emotional arousal. HRD, which reflects the parasympathetic response, has been shown to map onto the affective tone of a stimulus, with greater deceleration indicating higher levels of arousal (Bradley et al., 2001; Buchanan et al., 2006). Prior works discuss different effects of sleep on the parasympathetic aspects of emotional arousal, with studies showing

either a decrease (Bolinger et al., 2019; Cunningham et al., 2014) or a preservation of the HRD in response to emotional stimuli (Ashton et al., 2019; Bolinger et al., 2018; Pace-Schott et al., 2011).

Drawing on our previous findings (Hutchison et al., 2021) and supported by evidence indicating that REM sleep can provide optimal conditions for the processing of emotional memories (e.g., Helm & Walker, 2010; Hutchison & Rathore, 2015; Walker, 2009) and by studies suggesting that REM TMR may impact upon arousal responses (Wassing et al., 2019), we predicted that our manipulation would result in diminished activity in the brain's arousal system, decreased heart rate response, and reduction in subjective arousal.

4.3 Materials and Methods

4.3.1 Participants

Twenty-three right-handed, non-smoking healthy volunteers (14 females, age range: 20 – 33 years, mean ± SD: 23.61 ± 3.92) were recruited for this study, which was approved by the Ethics Committee of the School of Psychology at Cardiff University. A pre-screening questionnaire was used to ensure that participants were fluent in English, had normal or corrected to normal vision, no previous history of physical, psychological, neurological, or sleep disorders and no hearing impairments. Participants were required to be right-handed and to not regularly take any psychologically active medication or substance directly or indirectly affecting sleep quality. They agreed to abstain from alcohol 24 hours prior to each experimental session and from caffeine and other psychologically active food from 12 hours prior. Participants were also asked to refrain from engaging in intense physical activities during the period of the study. Further criteria of exclusion included a habit of daytime napping, a non-regular sleep-wake rhythm, engaging in nightshift work,

cross-continental travel in the two months before the study or having such plans during the experimental weeks. Additionally, to ensure that participants did not experience negative emotional stress over the week before starting the experiment, they were asked to complete the Depression, Anxiety and Stress Scale as inclusion criteria (DASS-42, normal scores: Depression (D) $\leq$ 9; Anxiety (A) $\leq$ 7; Stress (S) $\leq$ 14) (Lovibond & Lovibond, 1995). All participants gave written informed consent and received monetary compensation for their participation. Five participants were excluded from all analyses due to voluntary withdrawal (n = 4) or technical issues (n = 1) and three participants were unable to complete the online follow-up. Hence, the final dataset included 18 participants (11 females, age range: 20 – 30 years, mean $\pm$ SD: 23.61 $\pm$ 3.56) in Session 1 (S1) and Session 2 (S2), and n = 15 in Session 3 (S3).

4.3.2 Study design and procedure

The study consisted of three sessions (Figure 4.1), all scheduled for the same time in the evening (approximately 6 pm).

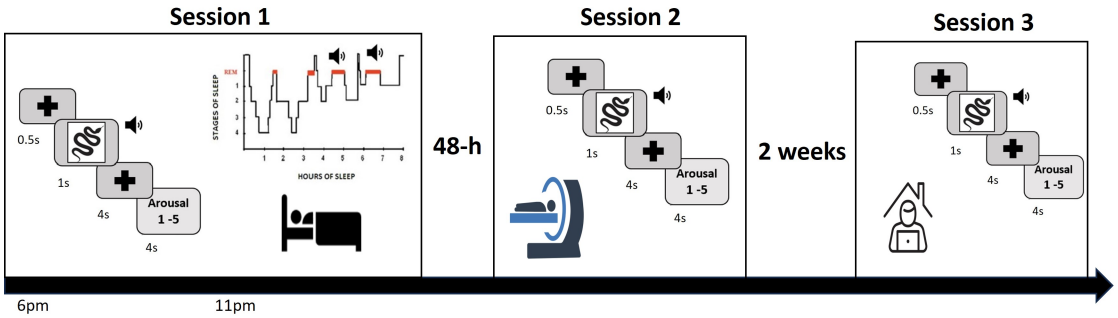


Figure 4.1: *Study design.* The study consisted of three sessions. In Session 1 (S1) two questionnaires were first filled: the Stanford Sleepiness Scale (SSS) and the Positive and Negative Affect Schedule (PANAS). They were followed by the arousal rating task, in which participants were asked to rate 48 negative IAPS pictures and the corresponding semantically related sound on a 5-point rating scale of arousal (1 = less arousing, 5 = more arousing). After filling out the PANAS a second time, participants were wired up for EEG. During the night, tones associated with half of the arousing stimuli were played in random order during REM sleep. The following morning, participants filled a sleep quality questionnaire. Session 2 (S2) and 3 (S3) had the same structure: after filling the SSS and the PANAS, participants performed the arousal rating task. The PANAS was administered again as soon as they finished the task. S2 was performed in the MRI scanner while heart rate deceleration (HRD) was recorded; it occurred 48 hours after S1. S3 was performed online (2 weeks after S1).

For all sessions, before and after performing the arousal rating task participants completed the Positive and Negative Affect Schedule (PANAS) scale (Watson et al., 1988) to evaluate their mood. The Stanford Sleepiness Scale (SSS, Hoddes et al., 1973) was instead administered at the beginning of each experimental session to determine participants' level of alertness. S1 lasted approximately 2 hours and progressed as follows: participants completed the arousal rating task, then changed into their sleepwear, were fitted for polysomnography (PSG) recording, and went to bed at around 11:30 p.m. while brown noise was delivered throughout the night to minimize noise-induced arousals. For the TMR protocol acoustic stimuli semantically related to the IAPS pictures were replayed during REM sleep to trigger reactivation of negative emotions. Participants were woken up after 7-8

hours of sleep. After removing the electrodes and before leaving the lab, they were asked to rate their sleep quality and whether they heard any sounds during the night with an adapted and translated version of a German sleep quality questionnaire (SQQ, Görtelmeyer, 1985). Participants were asked to come back to the lab 48 hours later for S2, during which the arousal rating task was performed in a 3T Siemens MRI scanner during fMRI acquisition while heart rate deceleration (HRD) was recorded. S3 (2 weeks after S1), the follow-up session, was performed online and lasted 40 minutes. In both the lab and the MR scanner, the task was presented using PsychoPy3 Experiment Runner (v2020.1.3, Peirce et al., 2019). The SSS and the PANAS questionnaires were executed using MATLAB (The MathWorks Inc., Natick, MA, 2000) and Psychophysics Toolbox Version 3 (Brainard, 1997), except for the sleep quality questionnaire, completed with pen and paper. In S3 the behavioural task was administered through the Pavlovia online platform (https://pavlovia.org/) and the SSS and PANAS questionnaires were distributed via Qualtrics software (Qualtrics, Provo, UT, USA. https://www.qualtrics.com).

4.3.3 Arousal rating task

Participants viewed 48 standardized negative images selected from the International Affective Picture System (IAPS, Lang et al., 2008, see Table 4.9 in Supplementary Material). Each image was converted to greyscale and matched in luminance and resolution (height = 600 px; width = 800 px) using the SHINE toolbox (Willenbockel et al., 2010) in MATLAB 2007a. Each image was rated using a 5-point arousal scale, corresponding to increased emotional intensity (i.e. 1 = less arousing, 5 = more arousing), and paired with a semantically related sound obtained from the International Affective Digitized Sounds database (IADS, Bradley & Lang, 1999). Participants were instructed to rate each picture-sound pair along arousal dimension. Each trial consisted of a fixation cross (500ms), picture and sound presentation (1 s), a blank screen (4 s), the arousal rating (4 s) and the

inter-trial interval (jittered: 3.5 – 4.5 – 5.5 – 6.5 s). Sounds were 400 ms long. In order to match the duration of the picture presentation on the screen (1 s) with the duration of the sounds, the 400ms sounds were repeated twice with a 200ms gap in between the two presentations: 400ms – 200ms gap – 400ms. Audacity software (www.audacityteam.org) was used to modify the length of sounds. In Session 1 only, the arousal rating task was preceded by a practice round and followed by a forced-choice task. The practice round aimed to let participants familiarize themselves with the rating scale. It consisted of four neutral IAPS pictures paired with semantically related neutral sounds taken from the IADS. The forced-choice task aimed to assess whether participants had learned the associations between images and sounds. For each trial, participants had to choose which of the four IAPS images displayed was semantically related to the sound. This task was repeated until participants reached 75% accuracy. Feedback with the correct answer was presented for 1.5 s.

4.3.4 Questionnaires

The SSS is used to provide a subjective indication of sleepiness, with participants rating their current state on a 7-point Likert scale, where 1 is most alert and 7 is least alert (Hoddes et al., 1973). The PANAS (Watson et al., 1988) is a self-report measure composed of two subscales designed to assess individuals' levels of positive and negative affect. Each subscale is composed of 10 Likert-type format items ranging from 1 (very slightly/not at all) to 5 (very much).

4.3.5 PSG data acquisition

Standard polysomnography, consisting of electroencephalography (EEG), left and right electromyography (EMG) electrodes placed on the chin, left and right electrooculography (EOG) electrodes placed below and above the eyes, was continuously recorded using passive Ag/AgCl electrodes and collected with a BrainAmp

DC Amplifier (Brain Products GmbH, Gilching, Germany). According to the international 10–20 system, six EEG electrodes were positioned on the scalp (F3, F4, C3, C4, O1, and O2) and we further attached one ground electrode to the forehead. All electrodes were referenced to the mean of the left and right mastoid electrodes applied behind the left and right ears. Impedances were maintained below 5 kΩ for each scalp electrode and below 10 kΩ for each face electrode. Electrodes were applied with Ten20 conductive paste (Weaver & Co., Aurora, USA) on sites cleaned with NuPrep exfoliating gel (Weaver & Co., Aurora, USA). Data were recorded using BrainVision Recorder software (Brain Products GmbH), sampled at 500 Hz, and saved without further filtering.

4.3.6 TMR during REM sleep

Acoustic stimuli, which had been paired with pictures during wake, were replayed to the participants during stable REM sleep, as assessed with standard AASM criteria (Iber et al., 2007). The TMR protocol was executed using MATLAB 2016b and Cogent 2000, and it consisted of the presentation of 24 cued sounds (400ms duration) repeatedly presented 20 times each (20 loops), with an inter-trial interval jittered between 2 - 2.5 – 3 - 3.5 - 4 s. Volume was adjusted for each participant to ensure that the sounds did not wake them up and to prevent arousal. Cueing was paused immediately when any sign of arousal was shown or when participants left the relevant sleep stage and resumed only when stable REM sleep was observed.

4.3.7 MRI data acquisition

Magnetic resonance imaging (MRI) data were obtained at Cardiff University Brain Imaging Centre (CUBRIC) using a Siemens Magnetom Prisma 3T scanner with a 32-channel head coil. Functional images were acquired with a T2*-weighted echo-planar imaging (EPI) sequence (repetition time (TR) = 2000 ms; echo time (TE)

= 30 ms; FA = 75°; bandwidth = 2442 Hz/Pixel, field of view (FoV) = 224 mm2; voxel-size = 3.5 mm3; slice thickness = 3.5 mm; 37 slices with a 25° axial-to-coronal tilt from the anterior–posterior commissure (AC-PC) line and interleaved slice acquisition; parallel acquisition technique (PAT) with in-plane acceleration factor 2 (GRAPPA), anterior-to-posterior phase-encoding direction). To correct for distortions in the fMRI data caused by magnetic field inhomogeneities, B0-fieldmap was acquired (TR = 1000 ms; TE1 = 4.92 ms; TE2 = 7.38 ms; FA = 75°; bandwidth 290 Hz/Pixel; FoV = 224 mm^2; voxel-size = 3.5 mm^3; slice thickness = 3.5 mm; interleaved slice acquisition; anterior-to-posterior phase-encoding direction). T1- weighted structural images were obtained using a 3D magnetization-prepared rapid-acquisition gradient echoes (MPRAGE) sequence (TR = 2300 ms; TE = 3.06 ms; FA = 9°; bandwidth 230 Hz/Pixel, FoV = 256 mm^2, voxel-size = 1 mm^3, slice thickness = 1 mm, parallel acquisition technique (PAT) with in-plane acceleration factor 2 (GRAPPA), anterior-to-posterior phase-encoding direction).

4.4 Data analysis

4.4.1 Behavioural data analysis

Differences in arousal ratings between cued and uncued items were assessed using linear mixed effects models implemented in the *lme4* package (Bates et al., 2015). To identify the contribution of Cueing on arousal ratings across time, we first fitted a model that included Cueing (two levels: Cued and Uncued), Session (two levels: S2 and S3) and their interaction as fixed effects, and participants and items as random effects.

Model 1 formula:

$$rating \sim \ cueing * session + 1|participants, \sim \ 1|items.$$

Next, we introduced the baseline variable into the model, representing the ratings provided by participants in S1, before any experimental manipulation.

Model 2 formula:

$$rating \sim \ cueing * session + baseline + 1|participants, \sim \ 1|items.$$

We employed a group mean centering (GMC) for the baseline values by subtracting each individual baseline rating from their overall score. By adopting this approach, we ensured a more accurate evaluation of the changes occurring within participants and mitigated the influence of divergent initial rating levels between individuals (Enders & Tofighi, 2007). Finally, we added an interaction term between cueing and group mean-centered baseline to examine whether the effect of cueing on arousal ratings varied depending on the participant's baseline level.

Model 3 formula:

$$rating \sim \ cueing * session + cueing * baseline + 1|participants, \sim \ 1|items.$$

To determine statistical significance, we conducted a likelihood ratio test (LRT) in which we compared all three models. The LRT yielded a substantial improvement in the model fit ($\chi^2(1) = 6.60$, p = 0.01), thus we will report our analysis based on this third model. For a model comparison analysis see Table 4.4 in Supplementary Material.

We used R (Rstudio Team (2022), www.R-project.org) and the R-packages *lme4* and *emmeans* for all our statistical analyses (Bates et al., 2015; Lenth, 2023). We used *sjPlot* (Lüdecke, 2023) for generating the regression table. This table involves σ^2 that denotes the residual variance and represents the extent of vari-

ability within the response variable (Ratings) that remains unaccounted for by the predictors included in the model. The terms τ_{00}items and τ_{00}participant represent the estimated variance component for the random effects associated with items and participants, respectively. We are therefore allowing each item (48 picture-sounds pairs) and participant to have their own influence on the *Ratings* variable, irrespective of the predictors, and we are estimating the variability across all 48 pairs and 18 participants. The Intraclass Correlation Coefficient (ICC) quantifies the proportion of the total variability in *Ratings* that can be attributed to differences between participants and items. Marginal R^2 reflects the proportion of variance explained solely by the fixed effects, whereas Conditional R^2 considers both fixed and random effects; both indicate how effectively the model explains the variability in *Ratings* (Nakagawa et al., 2017). Figures were created using *ggplot2* package (Wickham, 2009).

4.4.2 EEG data analysis

PSG recordings were manually scored in 30s epochs by two trained independent sleep scorers, according to the standard American Academy of Sleep Medicine (AASM) manual (Iber et al., 2007). Each EEG recording was scored using a publicly available interface (https://github.com/mnavarretem/psgScore). From the scored sleep stages, the following sleep macrostructure parameters were calculated: (1) total sleep time (TST, min) as the total time in any sleep stages other than wake; (2) time spent in each sleep stage; (3) percentage of time spent in each sleep stage, calculated as the time in the respective sleep stage over TST. Data from N = 2 participants was excluded due to recording issues. Sleep parameters are reported in Supplementary material.

4.4.3 MRI data analysis

Image data preparation, preprocessing, and statistical analysis were performed using fMRIPrep 20.2.7 (Esteban et al., 2019, RRID:SCR_016216), which is based on Nipype 1.7.0 (Gorgolewski et al., 2011, RRID:SCR_002502). Functional data were preprocessed in the following way: (1) a B0 nonuniformity map correction (or fieldmap); (2) co-registration to the participants' T1-weighted anatomical scan using rigid-body model; (3) motion correction (transformation matrices, and six corresponding rotation and translation parameters); (4) slice-time correction to the middle of each TR; (5) spatial normalization to Montreal Neurological Institute brain (MNI152NLin2009cAsym); (6) smoothing using a Gaussian kernel with a full-width half maximum (FHWM) of 6 x 6 x 6 mm.

4.4.3.1 First and second level analysis

Subject-level analysis was performed in Nilearn (https://nilearn.github.io/stable/index.html) using a general linear model constructed separately for each participant. The design matrix included two regressors: cued and uncued picture-sound pairs. Each regressor was convolved with the canonical haemodynamic response function (HRF) using the default Glover HRF in Nilearn. Additionally, six affine motion correction regressors estimated during realignment (translations in x, y, and z directions and rotations around x, y, and z axes) were included as non-convolved regressors of no interest in the matrix. To mitigate the effects of excessive motion during the fMRI scan, we employed scrubbing as a denoising approach (Jenkinson et al., 2002; Jones et al., 2022; Power et al., 2012). Scrubbing involved identifying volumes in the fMRI data that exhibit high motion and excluding them from statistical analysis. Frame displacement (FD), a measure of head motion between consecutive frames in fMRI, was used to define excessive motion (Power et al., 2012). Volumes exceeding a specified threshold (0.5, as suggested by Power et al., 2012), were considered to have excessive motion and were excluded or "scrubbed"

from further analysis.

The effect of cueing in REM sleep was estimated using a two-tailed t-test for Cued - Uncued. Individual contrast images resulting from the first-level analysis were carried forward to the second-level one-way t-tests performed in the Analysis of Functional NeuroImages (AFNI) software suite (Cox, 1996). A-priori defined regions of interest (ROI) consisted of the insula, sgACC, OFC, and amygdala. These regions were selected based on previous findings that reported activations (or de-activations) in these regions due to sleep or emotional reactivity (Phan et al., 2002; Rolls et al., 2020; van der Helm et al., 2011; Walker, 2009) and their involvement in psychiatric disorders (Drevets et al., 2008; Kunimatsu et al., 2020). ROIs were created using the integrated Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) in the Wake Forest University Pick Atlas toolbox (http://fmri.wfubmc.edu/software/PickAtlas) and the automated anatomical labelling atlas 3 template (AAL3, Rolls et al., 2020) was used to define the sgACC. In addition, we included a whole brain gray matter (GM) mask thresholded at 0.1.

To control for multiple comparisons, we performed cluster-level corrections. This was accomplished using the 3dttest++ function in the AFNI software suite (Cox, 1996), employing the ClustSim option for Monte Carlo simulations. By estimating the probability of false positive clusters in the data, this method provided a more stringent control for multiple comparisons. A cluster-defining threshold (CDT) of $p < 0.001$ was set to identify potential clusters showing a significant effect. The ClustSim option generated a distribution of cluster sizes under the null hypothesis, allowing us to determine a cluster-size threshold corresponding to a family-wise error (FWE) corrected p-value of less than 0.05.

4.4.4 Heart rate data analysis

In Session 2 (when the task was performed in the MR scanner), heart rate was acquired with a pulse oximetry sensor provided by the Siemens Physiological Monitoring Unit and attached to the ring finger of the non-dominant hand. R components of the QRS complexes were marked using custom-made script in Matlab 2019a (The MathWorks Inc., Natick, Massachusetts, United States) and subsequently interpolated at 1000 Hz. HRD was computed as the maximum R-R interval deceleration in the 5 s interval following each picture onset, subtracted from the mean R-R interval during the 1.5 s baseline period before each picture onset. Due to technical difficulties (high presence of motion artifacts n = 3 and poor sensor placement n = 1), data from only N = 14 participants were analysed. To compare HRD between cued and uncued stimuli, we used paired-samples t-test (Gaussian distribution). Correlations between HRD, behavioural measures, parameter estimates for our ROIs in each subject, and EEG results were assessed with Pearson's correlation or Spearman's Rho (depending on the Shapiro-Wilk test result) using *cor.test*() function in the R environment (Rstudio Team 2022, www.R-project.org). False discovery rate (FDR) correction was used to correct for multiple correlations $q < 0.05$ (Benjamini & Hochberg, 1995).

4.5 Results

4.5.1 Functional imaging arousal rating task

To determine whether our REM TMR manipulation led to a decrease in the brain's arousal response, we examined BOLD responses to both cued and uncued picture-sound pairs in our a-priori ROIs: insula, sgACC, OFC and amygdala. This revealed significant reductions in neural activity for the cued stimuli compared to the uncued ones within two key regions: the insula (peak MNI coordinates: x = -33, y = 16, z = 16) and the OFC (peak MNI coordinates: x = -37, y = 60, z = -9)

48 hours post TMR. Results were FWE corrected within each region of interest at $p<0.05$ (Figure 4.2, Table 4.1).

In addition to the ROIs, we performed a whole-brain corrected analysis of grey matter. This revealed a significant decreased activation for Cued compared to Uncued stimuli in the paracingulate gyrus contrast (FWE corrected within each region of interest at $p<0.05$, peak MNI coordinates: x = 5.5, y = 55.5, z = 13.5; Figure 4.2, Table 4.1).

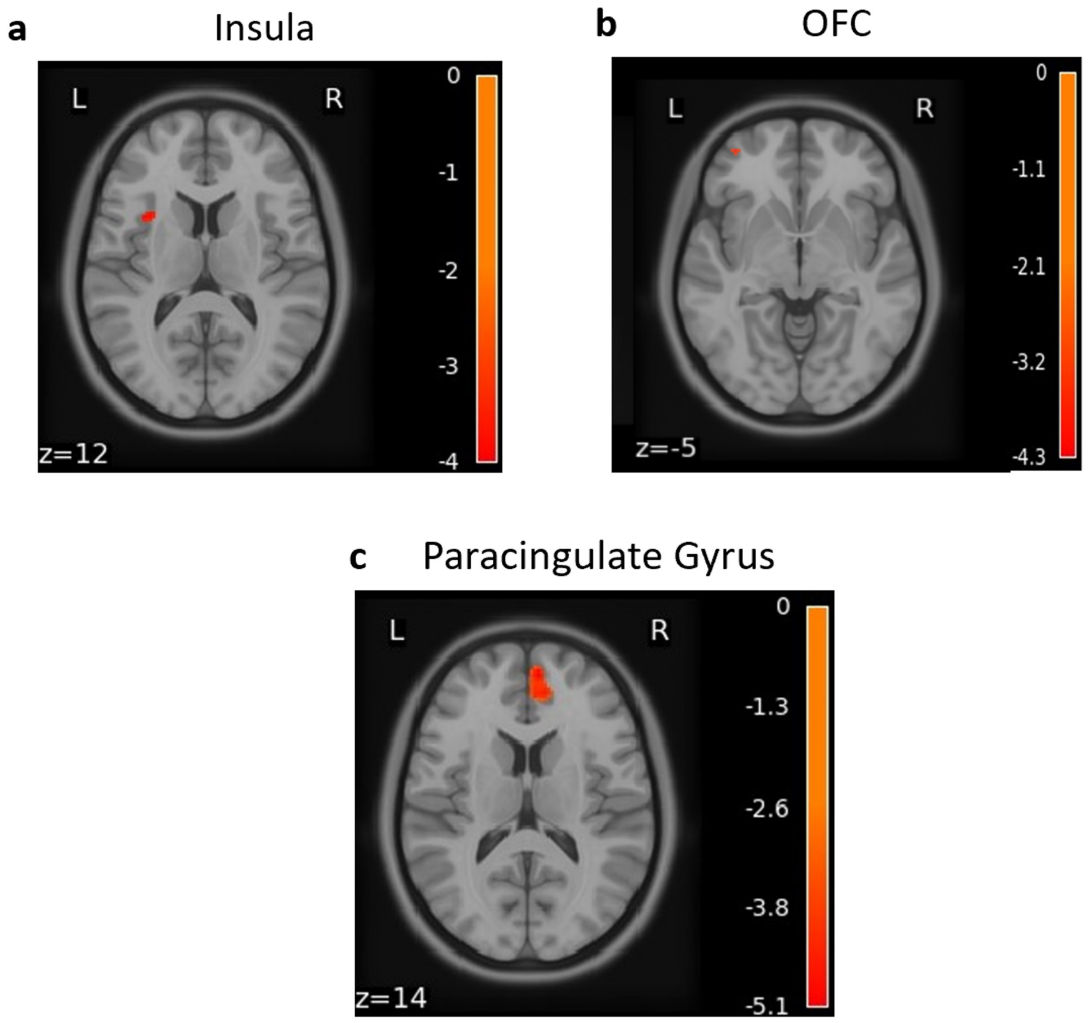


Figure 4.2: *Functional activity in response to negative picture-sound pairs.* Decrease in left insula **(a)**, left OFC **(b)** and right paracingulate gyrus **(c)** 48 hours post-stimulation in response to cued negative picture-sounds pairs. For all images, in red-orange are reported colour-coded Z-values thresholded at a significance level of pFWE < 0.05, cluster-level corrected. Results are overlaid on an MNI ICBM152 T1 template. OFC = orbitofrontal cortex.

Table 4.1: *Functional results.* Peak Z-values and corresponding MNI coordinates for regions showing activation in the contrast Cued > Uncued. Regions listed were significant with a corrected pFWE < 0.05. Number of voxels, peak Z-values, and MNI coordinates are reported.

Brain region	No. Voxels	Peak Z-value	MNI x, y, z (mm)
Insula	18	-4.01	-33, 16, 16
OFC	19	-4.29	-37, 60, -9
Paracingulate Gyrus	240	-5.13	5, 50, 14

We also observed a weaker reduction in activity within the amygdala (peak MNI coordinates: x = -26, y = 1, z = 16) and the sgACC (peak MNI coordinates: x = -6, y = 29, z = 8) at $p < 0.001$ uncorrected. However, given the limited number of voxels surviving at these thresholds (only 1 and 2 voxels, respectively) we also examined the overall mean activity for these two ROIs and performed a paired t-test of the mean values for cued and uncued conditions. This revealed a mean deactivation in the sgACC ($t(17) = -2.77$, $p = 0.01$, Figure 4.3a), but no significant result in the amygdala ($t(17) = -0.88$, $p = 0.39$, Figure 4.3b).

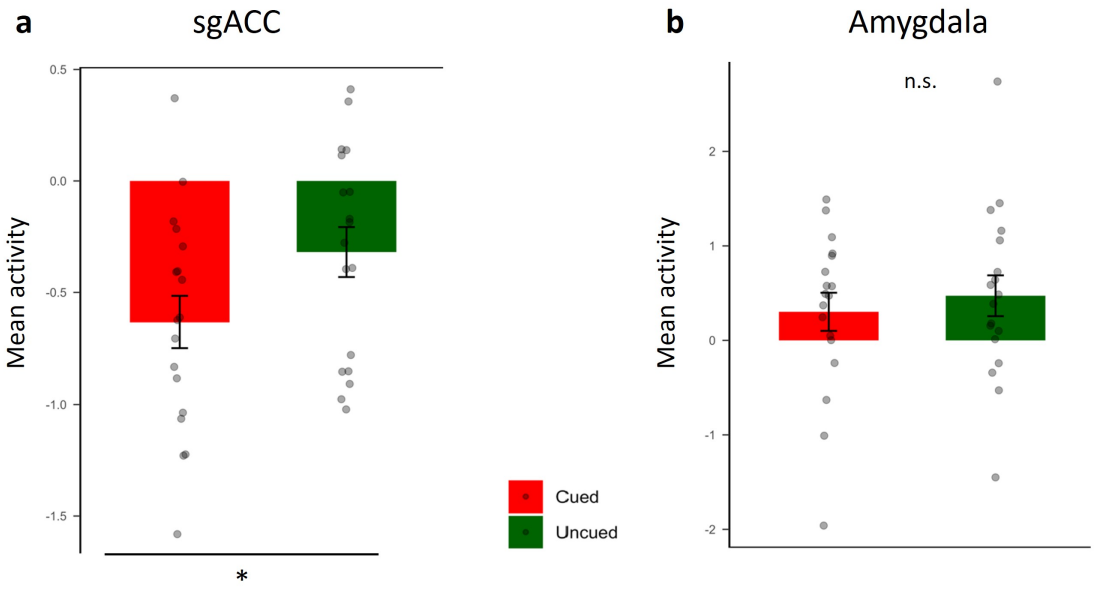
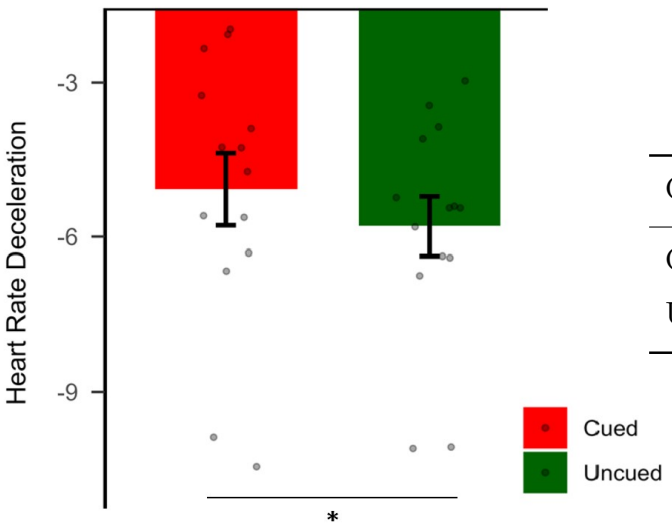


Figure 4.3: *Mean functional activity: sgACC and amygdala.* Mean functional activity in the sgACC **(a)** and amgdala **(b)** in response to cued and uncued stimuli. Grey dots represent individual data points. sgACC = subgenual anterior cingulate cortex. n.s. = non significant.

No correlations emerged between the mean parameter estimates, HRD, and behavioural results (all $p_{adj} > 0.05$, see Table 4.6 in Supplementary Material).

4.5.2 Heart rate deceleration

A paired-samples t-test revealed that heart rate differed between cued and uncued stimuli during stimulus presentation in Session 2 (48-h post-manipulation). Specifically, heart rate deceleration was greater for Uncued stimuli (M ± SE cued = -4.53 ± 0.68; M ± SE uncued = -5.24 ± 0.98; t13 = 2.51; p = 0.02), indicating a stronger emotional reactivity for Uncued images (Figure 4.4). No significant correlations were found between HRD and sleep or behaviour (all $p_{adj} > 0.05$, see Table 4.7 in Supplementary Material).



Cueing	Mean	Median	SE
Cued	-5.08	-4.54	0.70
Uncued	-5.79	-5.42	0.57

Figure 4.4: *Heart rate deceleration.* On the left, HR responses for the negative Cued (red) and Uncued (green) image-sound pairs at S2, 48 hours after S1. *P = <0.05. Data are shown as means (±SEM). Grey dots represent individual participants. On the right, descriptive statistics of the HRD.

4.5.3 Arousal Rating Task

To investigate the effects of REM TMR on subjective arousal ratings over time, we employed a linear mixed model (LMM) with Cueing (cued and uncued), group mean centered baseline (ratings at S1), and Session (S2 and S3) as fixed effects (formula: $rating \sim cueing * session + cueing * baseline$), and participants and items as random effects (formula: $1|participants, \sim 1|items$).

This revealed no main effect of cueing (β = 0.04, 95% CI = [-0.07, 0.15], t(1556) = 0.74, p = 0.457; Figure 4.5, Table 4.2) but a significant interaction between cueing and baseline (β = 0.10, 95% CI = [0.02, 0.17], t(1556) = 2.57, p = 0.010). A post-hoc analysis of this interaction (see Table 4.5 in Supplementary Material.) revealed that cueing tended to decrease arousal ratings for items that were rated as higher than average arousal at baseline, while simultaneously increasing arousal ratings for items rated as having lower than average arousal at baseline (Figure 4.5). There was also a significant negative effect of session on subjective arousal

ratings (β = -0.24, 95% CI = [-0.36, -0.13], t(1556) = -4.06, p < .001), indicating a decrease in arousal rating over time (Figure 4.5, Table 4.2). Descriptive statistic of the task is reported in Table 4.3 in Supplementary Material.

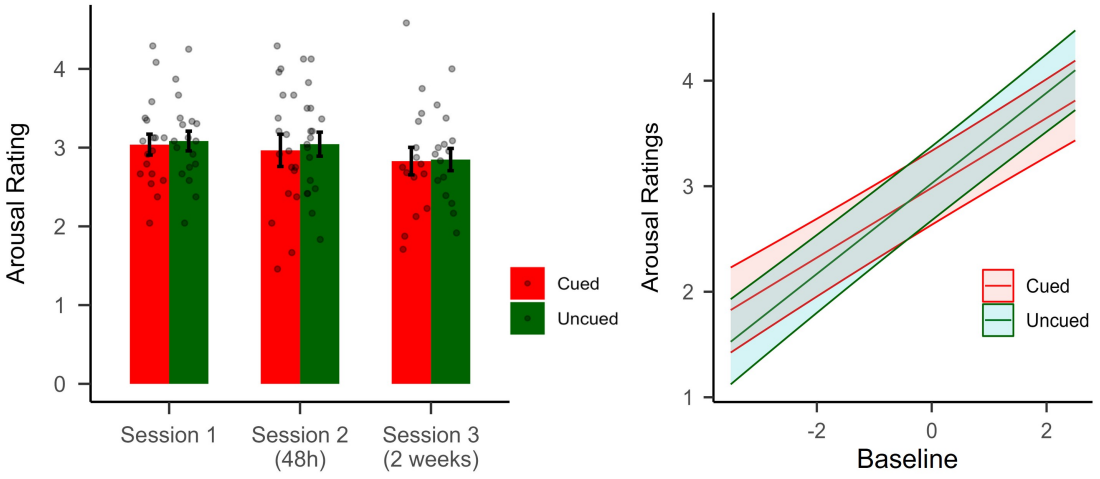


Figure 4.5: *Arousal ratings.* On the left, Arousal ratings for cued (red) and uncued (green) negative image-sound pairs across time. Ratings range from 1 (less arousing) to 5 (more arousing). Error bars depict standard error of the mean (SEM). N = 18 for Session 1 and Session 2; n = 15 for Session 3. On the right, the model predicted interaction between Cueing and mean-centered Baseline, depicting arousal ratings in Session 1. Shadowed areas represent 95% Confidence Intervals.

Table 4.2: *LME results.* Results of the mixed effect model examining the effect of Cueing (Cued/Uncued), Sessions (Session2/Session3) and Baseline (arousal ratings in Session 1) on subjective ratings.

Predictors	*Estimates*	*CI*	*p*
(Intercept)	2.98	2.63 – 3.33	**<0.001**
cueing [Uncued]	0.04	-0.07 – 0.15	0.457
Baseline	0.33	0.27 – 0.39	**<0.001**
Session [3]	-0.24	-0.36 – -0.13	**<0.001**
Cueing [Uncued] × Baseline	0.10	0.02 – 0.17	**0.010**
Cueing [Uncued] × Session [3]	-0.05	-0.21 – 0.12	0.564
Random Effects			
σ	0.67		
τ00 item	0.14		
τ00 participant	0.49		
ICC	0.49		
N participant	18		
N item	48		
Observations	1565		
Marginal R / Conditional R	0.134 / 0.555		

Note: σ^2 = residual variance. τ_{00}items and τ_{00}participant = estimated variance component for the random effects associated with items and participants. ICC = Intraclass Correlation Coefficient.

4.6 Discussion

The current study examines the effects of targeted memory reactivation during REM sleep on neural, physiological, and subjective emotional responses. Our findings demonstrate that REM TMR modulates activation of the brain's arousal system as well as autonomic activity and subjective emotional responses. These results offer further support to the *Sleep to Forget, Sleep to Remember* (SFSR) hypothesis, which proposes that the dissipation of the emotional charge can occur

through memory reactivation in REM sleep (Helm & Walker, 2010; Walker, 2009).

Relatively few studies have examined the impact of TMR during REM sleep on emotional reactivity. However, recent research conducted with patients has shown promising evidence that memory reactivation during REM sleep may have the potential to decrease the affective tone associated with negative experiences. For instance, Wassing and colleagues induced self-conscious emotions of shame in volunteers suffering from insomnia to explore the impact of disrupted REM sleep on emotional distress. Their findings indicate that discontinuities in REM can prevent the brain from processing and reducing emotional distress as reflected by continuous amygdala reactivity (Wassing et al., 2019). Another recent study showed that TMR during REM for two consecutive weeks reduced the frequency of nightmares while promoting more positive dream emotions (Schwartz et al., 2022). Our new findings combine with this prior work to underscore the therapeutic potential of REM TMR.

Turning first to our MR data, we showed that the insula, the OFC, and the sgACC were markedly less responsive to negative sound-image stimuli after REM TMR. The insula is believed to be critical for feelings, especially when examined in light of the James Lange theory of emotion, which posits a fundamental connection between physiological arousal and the emergence of emotional experiences (James, 1884). Notably, this brain region has been extensively involved in the processing and integration of interoceptive information that comprises bodily signals such as heart rate and visceral responses, intricately connected with emotional and cognitive processing (Craig, 2009; Gasquoine, 2014; Kark & Kensinger, 2019; Seeley et al., 2007; Strigo & Craig, 2016). Damasio (2003) further argued that because of the insula's capacity to encode interoceptive signals, it serves as the neural locus where subjective feelings of emotion are generated (Damasio, 2003). Neuroimaging studies have supported this assertion and revealed concurrent activation of the

insula and anterior cingulate cortex (ACC) when individuals experience emotional feelings. Seeley and colleagues (2007) shed further light on this by examining resting-state functional connectivity and uncovered two critical networks: an executive control network and an emotional salience one. Of particular note is the latter which involves the insula in conjunction with the anterior cingulate cortex, amygdala, and hypothalamus. This reinforces the notion that the insula is not solely associated with the processing of subjective feelings originating from the body. Instead, it appears to play a central role in orchestrating a diverse spectrum of subjective emotional experiences across different emotional categories (Seeley et al., 2007). Furthermore, there is evidence from neuroimaging studies that link abnormal grey matter volumes and hyper or hypo-activity levels within the insula with conditions like anxiety and mood disorders (see Gasquoine, 2014, for a review).

The orbitofrontal cortex plays a critical role in representing the reward value associated with a range of stimuli and outcomes. It encodes the emotional and affective significance of different inputs, thus contributing to the modulation of emotional responses (Rolls, 2019). The significance of the OFC in shaping emotional experiences and behavioural responses becomes even more apparent when we consider its network of outputs that involve regions such as the anterior cingulate cortex and the insula. This network allows the reward value representations generated by the OFC to have a broad influence on various facets of emotional processing, ultimately contributing to the complexity of our emotional experiences and arising behaviours (Rolls, 2019; Rolls et al., 2020).

The sgACC (area 25) is also central to emotion regulation and arousal. Numerous studies identified that degeneration in this area correlates with depression, anhedonia, and loss of positive emotions (Alexander et al., 2020; Mayberg et al., 1999; Pizzagalli, 2011; Rudebeck et al., 2014; Stevens, 2011, e.g.). Animal studies

have further underscored its importance by demonstrating that overactivation of this area is linked to a reduction in parasympathetic tone: reduced heart rate variability, diminished vagal tone and alterations in cortisol levels, effectively mirroring the physiological changes observed in stress-related disorders (Alexander et al., 2020). Moreover, the sgACC is known for its anatomical and functional connectivity with the amygdala (Alexander et al., 2020; Drevets et al., 2008; Fullana et al., 2016; Hakamata et al., 2022; Stevens, 2011).

Unexpectedly, and contrary to previous studies that proposed that the role of REM sleep in emotional adaptive processes involves changes in neuronal circuits including the amygdala (van der Helm et al., 2011; Wassing et al., 2019), we didn't find a significant result in this region. A potential explanation for this finding may lie in the temporal dynamics of memory reorganization (Landmann et al., 2015; Lewis et al., 2018; Pereira & Lewis, 2020; Seibt & Frank, 2019). REM sleep has been proposed to facilitate memory reorganization that – in the context of emotions - involves the detachment of the emotional intensity from its context over time (Landmann et al., 2015). The reorganization process predominantly involves cortical regions. Given that REM TMR is thought to play a role in the modulation of emotional reactivity by triggering memory reactivation during sleep, it's plausible that the amygdala might show pronounced reactivity immediately post-manipulation, as evidenced by previous studies (van der Helm et al., 2011; Wassing et al., 2019). However, as days pass, the engagement of subcortical regions might diminish in favour of cortical regions where the reorganization processes are supposed to play out. This could potentially explain why in our study we found significant results in cortical regions but not in the amygdala. It's important to note that this interpretation remains speculative, especially given the absence of correlations between our neural findings and other arousal or sleep measurements.

Finally, whole-brain gray matter analysis revealed a significant reduction of re-

sponse in the right paracingulate gyrus, a region closely linked with the anterior cingulate cortex, after cueing. Although this was not one of our a-priori regions of interest, the fact that the response survived whole-brain correction, and is quite extensive (240 voxels), demonstrates that this area is modulated by our cueing manipulation. Indeed, this region is strongly associated with emotional processing. A meta-analysis conducted by Marwood and colleagues (2018) reported a substantial decrease in activation within this brain region subsequent to psychological interventions targeting depression and anxiety disorders (Marwood et al., 2018). The paracingulate gyrus is deeply involved in both emotional processing and regulation, and dysfunction within this region has been associated with compromised cognitive control over emotional responses, contributing to challenges in managing emotional reactions. Additionally, individuals facing this dysfunction often exhibit a diminished capacity to redirect their attention away from negative emotional states, which can exacerbate emotional distress (Pizzagalli, 2011).

In terms of autonomic responses, our results reveal a depotentiation in visceral reactivity to stimuli that were cued overnight. The majority of studies that indicated a sleep-dependent preservation of physiological arousal in response to negative stimuli have investigated the effect of either a nap or a single night of sleep (Ashton et al., 2019; Bolinger et al., 2018; Pace-Schott et al., 2011). One study observed a sleep-related preservation of affective reactivity in the short term (following a night of sleep or wake), whereas reduced HRD was found after a week, suggesting that time might play an important role in the modulation of emotional strength (Bolinger et al., 2019). In the current study, we measured HRD 48h after the first exposure to the task, so we speculate that the combined effect of TMR and time might further help decrease affective reactivity.

Partially in line with our previous study (Hutchison et al., 2021), cueing had an effect on arousal ratings however, the impact of cueing intervention on partici-

pants' emotional responses was tied to their individual baseline arousal levels. We speculate that this could be due to a generalization effect of TMR, where the manipulation influences a reduced emotional intensity of stimuli characterized by higher initial arousing levels, while simultaneously increasing the intensity of stimuli characterized by lower initial arousal levels. This pattern is consistent with the work of Pereira et al. (2022), who observed that SWS TMR on emotional material reduced responses in the orbitofrontal cortex for negative items, while simultaneously increasing them for neutral items (Pereira et al., 2022). Although our study did not include a neutral category, it is possible that the brain could have treated items that were rated as less arousing at baseline as if they were essentially neutral. This would make sense from an evolutionary perspective, as it would be much more important to disarm truly upsetting memories than those that are minimally arousing. Taken together, our results suggest that REM TMR has an impact on arousal which is apparent from brain activity, autonomic measures, and subjective measurements. Overall, these findings support the possibility that targeted reactivation of emotionally arousing memories in REM could potentially offer a way to make these memories less upsetting. As such, our method could lead to clinically important opportunities for the early treatment of psychiatric disorders such as depression and post-traumatic stress disorder PTSD.

4.7 Supplementary Material

Table 4.3: *Descriptive statistic of the Arousal Rating Task.*

Sessions	Cueing	Mean	Meadian	SD	SE
Session 1	Cued	3.04	3.00	1.24	0.06
	Uncued	3.08	3.00	1.22	0.06
Session 2	Cued	2.97	3.00	1.29	0.06

	Uncued	3.04	3.00	1.22	0.06
Session 3	Cued	2.83	3.00	1.26	0.06
	Uncued	2.85	3.00	1.17	0.06

Note: SD = standard deviation; SE = standard error of the mean.

Table 4.4: *Model comparison.*

	AIC	BIC	Chisq	Df	Pr(>Chisq)
Model1	4260.83	4298.32			
Model2	4001.07	4043.92	261.75	1	0.00
Model3	3996.48	4044.68	6.60	1	0.01

Note: AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) are both measures of the relative quality of statistical models. Chisq = Chi-squared, test statistic for the LRT.

Table 4.5: *Post-hoc analysis.* Post-hoc analysis of the interaction between Cueing and Baseline.

Contrast	*Estimate*	*SE*	*df*	*t.ratio*	*p.value*
Baseline = -2:					
Cued - Uncued	0.18	0.09	1518	2.02	**0.04**

Baseline = -1:					
Cued - Uncued	0.08	0.06	1519	1.38	**0.17**
Baseline = 0:					
Cued - Uncued	-0.02	0.04	1515	-0.42	0.67
Baseline = 1:					
Cued - Uncued	-0.11	0.06	1511	-2.04	**0.04**
Baseline = 2:					
Cued - Uncued	-0.21	0.09	1511	-2.46	**0.01**

Table 4.6: *Correlations between mean parameter estimates, behavioral results, and HRD.* Results of Pearson's correlations between the mean parameter estimates for each subject in our ROIs, behavioral results in S2, and heart rate deceleration (HRD). Both the uncorrected and FDR-corrected p-values are reported.

		Cued			Uncued		
		Pearson's correlation	p-value	p-value (FDR corr)	Pearson's correlation	p-value	p-value (FDR corr)
Ratings S2	Insula	0.23	0.36	0.54	0.06	0.80	0.80
	OFC	0.18	0.49	0.56	0.15	0.56	0.56
	sgACC	-0.01	0.97	0.97	-0.20	0.44	0.66
	Amygdala	0.10	0.70	0.70	0.38	0.12	0.36
HRD	Insula	-0.09	0.75	0.75	0.33	0.25	0.33
	OFC	-0.25	0.38	0.38	0.36	0.20	0.27
	sgACC	-0.63	0.02	0.08	0.15	0.62	0.62
	Amygdala	0.14	0.63	0.63	0.39	0.17	0.23

Table 4.7: *Correlations between HRD, sleep, and behavioural measurements.* Results of Pearson's correlations between HRD for cued and uncued image-sound pairs and the percentage of time spent in each sleep stage, total sleep time, and behavioural results in S2. Both the uncorrected and FDR-corrected p=values are reported.

		Cued			Uncued		
		Pearson's correlation	p-value	p-value (FDR corr)	Pearson's correlation	p-value	p-value (FDR corr)
HRD	TST (min)	0.01	0.95	0.97	-0.09	0.76	0.94
	N2 (%)	0.21	0.44	0.97	0.06	0.85	0.94
	N3(%)	-0.09	0.75	0.97	-0.06	0.84	0.94
	REM (%)	0.24	0.37	0.97	0.19	0.52	0.94
HRD	Ratings S2	0.07	0.81	0.82	0.13	0.65	0.73

Table 4.8: *Sleep parameters.* Time spent in each sleep stages is reported in minutes and as percentage of total sleep time. No correlations were found between sleep parameters and any other measurements. TST = total sleep time; W = wake; N1 = NREM Stage 1; N2 = NREM Stage 2; N3 = NREM Stage 3; REM = Rapid Eye Movement Sleep. N = 16.

Sleep data	Mean	SD
TST (min)	528.91	37.38
W (%)	8.09	7.13
N1 (%)	5.03	2.86
N2 (%)	42.16	7.11
N3 (%)	24.34	8.32
REM (%)	17.94	5.02
W (min)	43.47	39.05
N1 (min)	26.31	14.20
N2 (min)	222.84	39.85

N3 (min)	128.34	44.23
REM (min)	95.09	27.42

Table 4.9: *IAPS images.* 48 standardized images taken from the IAPS database. Overall valence = Mean ± SD, 2.57 ± 0.75; overall arousal = Mean ± SD, 5.81 ± 0.68.

Slide No.	**Description**	**Valence (M±SD)**	**Arousal (M±SD)**
1112	Snake	4.71(1.70)	4.60(2.44)
1300	PitBull	3.55(1.78)	6.79(1.84)
1930	Shark	3.79(1.92)	6.42(2.07)
2095	Toddler	1.79(1.18)	5.25(2.34)
2717	DrugAddict	2.58(1.32)	5.70(2.16)
2799	Funeral	2.42(1.41)	5.02(1.99)
2800	CryingBoy	2.45(1.42)	5.09(2.15)
3016	Mutilation	1.90(1.31)	5.82(2.44)
3051	Mutilation	2.30(1.86)	5.62(2.45)
3068	Mutilation	1.80(1.56)	6.77(2.49)
3170	BabyTumor	1.46(1.01)	7.21(1.99)
3210	Surgery	4.49(1.91)	5.39(1.91)
3215	BurnVictim	2.51(1.32)	5.44(2.16)
3225	Mutilation	1.82(1.22)	5.95(2.46)
3230	Dyingman	2.02(1.30)	5.41(2.21)
3261	Tumor	1.82(1.34)	5.75(2.64)
3301	InjuredChild	1.80(1.28)	5.21(2.26)
6000	Prison	4.04(1.74)	4.91(2.17)

6021	Assault	2.21(1.51)	6.06(2.38)
6242	Gang	2.69(1.59)	5.43(2.36)
6315	BeatenFem	2.31(1.69)	6.38(2.39)
6550	Attack	2.73(2.38)	7.09(1.98)
6560	Attack	2.16(1.41)	6.53(2.42)
6834	Police	2.91(1.73)	6.28(1.90)
8485	Fire	2.73(1.62)	6.46(2.10)
9000	Cemetery	2.55(1.55)	4.06(2.25)
9041	ScaredChild	2.98(1.58)	4.64(2.26)
9050	PlaneCrash	2.42(1.61)	6.36(1.97)
9230	OilFire	3.89(1.58)	5.77(2.36)
9252	DeadBody	1.98(1.59)	6.64(2.33)
9253	Mutilation	2.00(1.19)	5.53(2.40)
9254	Assault	2.03(1.35)	6.04(2.35)
9301	Toilet	2.26(1.56)	5.28(2.46)
9320	Vomit	2.65(1.92)	4.93(2.70)
9405	SlicedHead	1.83(1.17)	6.08(2.40)
9410	Soldier	1.51(1.15)	7.07(2.06)
9420	Soldier	2.32(1.59)	5.69(2.28)
9423	Assault	2.61(1.51)	5.66(2.15)
9424	Bomb	2.87(1.62)	5.78(2.12)
9425	Assault	2.67(1.44)	5.92(2.13)
9429	Assault	2.68(1.26)	5.63(2.04)
9571	Cat	2.46(1.61)	5.41(2.27)
9582	DentalExam	4.18(2.28)	5.29(2.21)
9622	Jet	3.10(1.90)	6.26(1.98)
9630	Bomb	2.96(1.72)	6.06(2.22)
9800	Skinhead	2.04(1.57)	6.05(2.71)

9900	CarAccident	2.46(1.39)	5.58(2.13)
9921	Fire	2.04(1.47)	6.52(1.94)

Chapter 5

General Discussion

5.1 Overview

The primary objective of this thesis was to investigate various methods of manipulating sleep to enhance cognitive processes.

Over the past years, sleep has been recognized as a cognitive enhancer, influencing a broad spectrum of functions, from attention and reasoning to memory and learning. Within the domain of learning and memory, there's compelling evidence supporting sleep's pivotal role in memory consolidation, subsequent learning, and memory reorganization. However, these benefits are not applicable across all circumstances and not for all types of memories equally. Furthermore, there are still questions about whether and how the different stages of sleep are involved in these processes. By employing a combination of behavioural memory tests, polysomnography (PSG), functional magnetic resonance imaging (fMRI), heart rate (HR) measurements, and cued memory reactivation, our work has raised important questions for future research and extended the existent understanding of the interplay between sleep and cognition.

The below discussion unfolds in three distinct sections: an initial summary of the key findings that have emerged from the three chapters, a deeper dive into their implications, and finally, reflections on encountered limitations and potential avenues for future research.

5.2 Summary of findings

In Chapter 2, given the early onset of dawn during summer – sometimes as early as 5 a.m. – we explored the potential cognitive benefits of using an eye mask to block out early natural light. This non-invasive intervention was primarily investigated for its effects on the encoding of declarative material, sustained attention, and procedural memory, all known to be sensitive to sleep (Lim & Dinges, 2008;

Loganathan, 2014; Van Der Werf et al., 2011; Walker et al., 2002; Yoo et al., 2007) and light (Alkozei et al., 2017; Chellappa et al., 2011; Fowler et al., 2021; Vandewalle et al., 2007). Across two experiments and compared to a control mask condition, we found that wearing an eye mask during sleep significantly improved the encoding of new information - a benefit that positively correlated with time spent in SWS – and increased alertness the following day. The memory encoding findings were discussed alongside existing literature suggesting that the encoding of declarative material is enhanced when slow-wave activity (SWA) is increased (Antonenko et al., 2013; Ong et al., 2018) and impaired when SWA is reduced or suppressed (Van Der Werf et al., 2009; Van Der Werf et al., 2011). Even though we could only speculate that wearing an eye mask might have increased SWA, given the minimal nature of the sleep-tracking device used in the study, we recognize the importance of this finding: the essential role of memory encoding in both academic and professional tasks. Moreover, the observed increase in alertness emphasizes the potential utility of the mask for tasks that require sustained attention, such as driving. While no evidence was found to suggest that the eye mask enhanced procedural memory, its positive impact on other cognitive areas indicates its overall potential as a beneficial intervention.

Chapter 3 set out to explore the role of sleep in promoting insightful problem-solving and overcoming functional fixedness, a barrier to creative thinking and innovation (Duncker, 1945). Participants underwent a cognitive training – the Generic Part Technique (McCaffrey, 2012b) - before solving a set of insight problems. After a period of nocturnal sleep or daytime wakefulness, other insight problems were presented followed by a listing feature task. Although we hypothesised that sleep would serve as a mechanism to consolidate the effects of the training leading to enhanced creative insight, the results were confounded by a time-of-day effect, with participants performing better in the morning than in the evening. This outcome underscores the importance of further exploring the

intricate relationship between sleep, creativity, and time of day.

In the final experimental chapter, Chapter 4, we aimed to investigate the effects of Targeted Memory Reactivation (TMR) during REM sleep on arousal processing. The objective was to determine whether REM TMR could lead to habituation of emotional reactivity employing objective and subjective measurements of arousal. Using functional magnetic resonance imaging (fMRI), the research probed the activity of key brain regions involved in emotion regulation, such as the insula, orbitofrontal cortex (OFC), subgenual anterior cingulate cortex (sgACC), and amygdala. A significant decrease in activation in the insula, OFC, and sgACC was observed when participants were exposed to cued arousing stimuli as opposed to uncued stimuli, thus suggesting a diminished arousal response 48 hours post-manipulation. Furthermore, the study monitored heart rate deceleration (HRD) as a marker of emotional arousal, revealing a depotentiation in visceral reactivity to stimuli that were cued overnight. Finally, we observed that the effect of cueing on subjective arousal ratings varied based on participants' initial baseline ratings, suggesting that the manipulation might have led to a reduction in emotional intensity for highly arousing stimuli. Collectively, these findings advocate for the potential of REM TMR in mitigating emotional reactivity, as evidenced by neural activity, autonomic markers, and subjective reports.

5.3 Implications and integration of the findings

5.3.1 Affordable sleep solution in a fast-paced world

Chapter 2 delved into the effect of blocking natural light at night, using an eye mask, on cognitive functions. Light exposure has been shown to modulate almost every aspect of human physiology and behaviours, including circadian rhythms and sleep (Blume et al., 2019; Borbely, 1982; Boubekri et al., 2014; Wams et

al., 2017), mood and emotional wellbeing (Lewy et al., 2009; W. H. Walker et al., 2020), alertness and cognitive performance (Alkozei et al., 2017; Chellappa et al., 2011; Lockley et al., 2006; Sleegers et al., 2013; Vandewalle et al., 2007), metabolism and hormonal regulation (Mason et al., 2022; Ouyang et al., 2018). These influences are collectively known as non-image-forming responses (NIF). While most light-related research has been confined to controlled laboratory settings, utilizing specific light-dark environments and scheduled use of artificial light, our experiments were conducted in a naturalistic context, specifically during summertime. We found that sleeping with an eye mask prior to learning enhanced declarative performance and this improvement was positively correlated with time spent in SWS. This result can be contextualized within the Synaptic Homeostasis Hypothesis (Tononi & Cirelli, 2003, 2006, see General Introduction, section 1.3.2), which postulates a global down-scaling and desaturation of synapses that were potentiated during preceding periods of wakefulness. This "resetting" ensures that the brain is ready to efficiently encode new information during the next period of being awake and SWA is believed to be instrumental in this process, preparing synapses for new learning (Tononi & Cirelli, 2006, 2014). Even if we can only speculate that the encountered benefit on subsequent declarative encoding might be related to SWA, this interpretation is in line with studies that demonstrated that SWA is related to subsequent learning (Antonenko et al., 2013; Ong et al., 2018; Van Der Werf et al., 2009) and with research that indicated that nighttime light exposure can be detrimental for SWA (Cho et al., 2013). To provide a more definite understanding, further investigation using EEG is essential.

Consistent with studies that highlighted the importance of limiting light exposure during nighttime sleep to maintain alertness (Bedrosian & Nelson, 2017; Daurat et al., 1996), our findings demonstrated that participants exhibited improved alertness levels when wearing the eye mask. Overall, the implications of our findings hold significance for two main reasons. Firstly, in recent years, there has

been a surge in the market for high-cost systems and products claiming to provide revolutionary hacks for enhancing sleep and overall well-being. In contrast to these expensive propositions, our research introduces an alternative that stands out in its simplicity and affordability and that can be seamlessly integrated into individuals' daily lives at home, making it a practical choice for many. Secondly, we emphasize the tangible benefits that can be derived from this straightforward intervention. Enhanced memory encoding allows for a more efficient retention of information, benefitting students and professionals alike. Enhanced alertness, on the other hand, ensures that individuals remain attentive and responsive to their environment. In today's fast-paced world, where multitasking is often a norm, both these cognitive enhancements are crucial. They can mean the difference in academic and professional success or in staying safe while driving, reducing the risk of accidents. When individuals remember better and stay alert, they can complete tasks more efficiently, make fewer errors, and potentially achieve more in less time. In essence, our research offers a practical strategy that can positively impact the daily lives of many.

5.3.2 Chronotype influence on creativity and insight

In the introduction, I reviewed a substantial body of research that indicates that the repetitive reactivation of hippocampo-cortical networks during sleep leads to a stabilization, integration, and reorganization of memory representations, central tenet of the Active Systems account (see sections 1.3.2 and 1.4). However, there is ongoing debate regarding whether this process also includes a qualitative reorganization of memories and the specific circumstances under which such reorganization might occur. Arguing in favour of this idea are studies that demonstrated a sleep-dependent improvement on creative problem solving (Beijamini et al., 2014; Cai et al., 2009; Monaghan et al., 2015; Sio et al., 2013; Wagner et al., 2004). However, there is also contradictory evidence that has shown no effect of sleep on

creative reorganization (Brodt et al., 2018; Hołda et al., 2020; Landmann et al., 2016; Schönauer & Pöhlchen, 2018), and others have argued that sleep-mediated benefits on creative problem solving are not robust (Cordi & Rasch, 2021).

Our experiment in Chapter 3 cannot conclusively link sleep to memory restructuring due to the confounding effect of the time of day. However, this sheds light on the impact that time of day has on creative abilities and insight.

According to the two-process model of sleep regulation, the homeostatic *process S* and the circadian *process C* are two mechanisms that jointly contribute to the observed fluctuations in cognitive performance over the course of the day (Borbely, 1982; Borbély et al., 2016). Process S embodies the concept of sleep debt, which steadily accumulates during wakefulness together with a concomitant rise in feelings of sleepiness and a decline in cognitive performance and alertness; Process C represents a (nearly) 24-hour spontaneous oscillatory variation in the propensity for sleep. Chronotype reflects individual variations in the peak period of cognitive functioning. Naturally, some people are 'owl' types, displaying higher activity levels later in the day, whilst others are early 'lark' types, mainly active during the early morning hours. Interestingly, chronotype evolves across the lifespan, moving towards eveningness in the early 20s (Fromm et al., 2011).

While there is an extensive corpus of research on creativity, there's limited evidence on how chronotype might influence it. Kuehnel and colleagues (2022) proposed that creativity is facilitated when an individual's chronotype aligns with the time of day and this relationship might be moderated by factors like positive mood and creative self-efficacy (Kühnel et al., 2022). Across three experiments, they tested participants on the Alternative Uses Task (AUT), a task designed to measure creativity by prompting participants to generate alternative uses for common objects (Guilford, 1967). Their findings revealed participants' creative performance was indeed enhanced when their chronotype matched the time of day. Interestingly, this alignment effect appeared most consistently among individuals classified as

late chronotypes. However, the mediating role of positive mood and creative self-efficacy varied across the three studies. Positive mood was identified as a key mediator in two experiments, while creative self-efficacy was a significant factor in just one. Thus, these findings underscore the complex relationship among these variables (Kühnel et al., 2022).

Given that our participants were recruited from the University and fell within the age range of 18-35, it is likely that most exhibited an evening chronotype (May et al., 1993). Consequently, our findings would diverge from the outcomes of the study conducted by Kühnel and colleagues while aligning more closely with Wieth and Zacks, who found that non-optimal time of day enhanced participants' performance in insight problems (Wieth & Zacks, 2011). Interestingly, when reviewing the tasks employed in the above-mentioned studies, a major distinction emerges between divergent and convergent thinking tasks (Guilford, 1967). Divergent thinking is characterized by the generation of numerous diverse ideas, as exemplified by the AUT used by Kühnel and colleagues (Kühnel et al., 2022). On the other hand, convergent thinking refers to the formulation of a single correct solution. This was the case for the insight problems used by Wieth and Zacks (Wieth & Zacks, 2011), as well as the ones we employed, which were designed by McCaffrey to have a single correct solution (McCaffrey, 2012a).

Given this context, our speculation that participants performed better in the morning due to a misalignment with their circadian rhythm appears to be more plausible. However, we also have to acknowledge that our experiment was conducted during COVID-19 pandemic, a period marked by notable disruptions in circadian rhythms due to the increased time spent indoors, less daylight exposure, and lifestyle changes (Morin et al., 2020). All these factors might have influenced participants' chronotype and our research findings.

Our work underscores the crucial role of chronotype when exploring creativity and insight. It's possible that the beneficial impact of sleep on creativity might be more pronounced when post-sleep assessments do not align with participants'

chronotypes.

5.3.3 Sleep and emotions

5.3.3.1 Does time play a role in this relationship?

Sleep appears to diminish the affective tone of emotional memories, a process believed to rely on the spontaneous reactivation of these memories during sleep (Walker, 2009). In line with this, Chapter 4 employed TMR during REM to investigate its effect on the habituation of arousal responses. The current findings, spanning neural, physiological, and behavioural domains, suggest an attenuation in arousal responses.

The core idea behind the Sleep to forget, Sleep to remember (SFSR) hypothesis is that REM sleep strengthens the content of memories while attenuating the visceral charge associated with their recall over time (Helm & Walker, 2010; Walker, 2009). An often overlooked but important variable in this dynamic is the passage of time.

While some studies failed to find a sleep depotentiation effect on the emotional tone of memories (Ashton et al., 2019; Baran et al., 2012; Jones & Spencer, 2019; Lehmann et al., 2016; Sterpenich et al., 2014), those that examined this effect over multiple nights of sleep, did find significant changes in subjective or physiological reactivity (Bolinger et al., 2018; Rihm & Rasch, 2015; Schwartz et al., 2022; Werner et al., 2021; Zeng et al., 2021). For instance, Zeng and colleagues examined the effect of sleep and sleep deprivation on subjective ratings to negative images at two distinct time points: after a delay of 12h, either post-sleep or post-deprivation, and after a delay of 60h. In the sleep group, affective ratings to negative images were preserved after 12h but attenuated 60h post-encoding test, suggesting a long-term depotentiation effect (Zeng et al., 2021). A similar pattern was found by Bolinger and colleagues using a between-subject design with a Sleep

and a Wake group. They assessed subjective responses after 10 hours (spent either asleep or awake) and after 7 days. The sleep-induced emotional dampening became apparent only after a week, a finding further supported by physiological data indicating that while heart rate deceleration remained stable after one night, it declined after a week (Bolinger et al., 2018). In another study, TMR during REM was used in combination with imagery rehearsal therapy (IRT) for patients with nightmare disorder (ND, Schwartz et al., 2022). The group that underwent both REM TMR and IRT for two weeks displayed a clinical reduction of nightmare frequency and more positive dream emotions than their counterparts who underwent only IRT. Notably, the nightmares' frequency decrease was sustained after 3 months (Schwartz et al., 2022).

In our own investigation, while we didn't explicitly test for the effect of time, we observed a significant depotentiation effect two days post-intervention. We argue that the single-night design, often used to study the relationship between sleep and emotion regulation, may not adequately capture the modulating role of REM sleep in emotional processing. It seems plausible that multiple nights of sleep are necessary for affective charges to gradually dissipate. Nevertheless, future studies are warranted to examine these temporal dynamics in more detail.

5.3.3.2 NREM, REM or both?

The SFSR hypothesis (Helm & Walker, 2010; Walker, 2009) is challenged not only by studies that showed that emotional reactivity is preserved across REM sleep (Baran et al., 2012) but also by a growing body of research suggesting that emotional memory consolidation is facilitated by SWS rather than REM (Cairney et al., 2014; Lehmann et al., 2016; Wagner et al., 2007). Such findings raise the question of whether the effects of sleep on arousal are sleep-stage dependent or both. Supporting the latter point, a complementary role for both SWS and REM in the processing of emotional memories has been proposed (Cairney et al., 2015;

Hutchison & Rathore, 2015; Kim & Payne, 2020; Wassing et al., 2019).
Notably, not all memories are consolidated equally (Stickgold & Walker, 2013) and sleep might favour the consolidation of memories "tagged" as emotionally salient during wakeful encoding (Seibt & Frank, 2019). During SWS, electrophysiological events (neocortical slow oscillations, hippocampal sharp wave ripples, and spindles), combined with low levels of acetylcholine, enable the gradual transformation of memory traces from the hippocampus into long-term representations within the neocortex (Rasch & Born, 2013). On the other hand, REM sleep's theta oscillations are believed to prioritize the consolidation of emotionally salient memories (Hutchison & Rathore, 2015; Nishida et al., 2009; Popa et al., 2010). In rodents, theta activity was found to be synchronized across the amygdala, hippocampus, and medial PFC – key brain structures for the formation and maintenance of emotional memories (LaBar & Cabeza, 2006; Popa et al., 2010). Additionally, animal studies revealed that theta synchronization between the amygdala and the hippocampus is boosted in association with ponto-geniculo-occipital (PGO) waves, which density predicts the expression of plasticity-related genes in these regions (Datta et al., 2008). REM-related plasticity changes (e.g., spine formation and pruning) can therefore reflect the selective processing of emotional memory traces, either strengthening or weakening the newly acquired memory (Seibt & Frank, 2019).

Why can the interleaving of SWS and REM sleep therefore be necessary for the processing of emotional memories?

1. *Selective tagging and consolidation:* REM sleep can drive the selectivity process by tagging specific memories for subsequent consolidation during NREM. As explained by the sleep-stress interaction model (Kim & Payne, 2020), when an arousal/stress response is activated in close proximity to the learning phase, it triggers a cascade of neuromodulators that modulates plas-

ticity in the amygdala and the hippocampus and enhances the connectivity within the amygdala-hippocampus-mPFC network. This primes the system for preferential encoding of emotional memories, which in turn interacts with subsequent SWS-REM cycles to promote their selective consolidation (Kim & Payne, 2020). Biologically, there is compelling evidence suggesting that gene expression and protein synthesis are involved in long-term memory consolidation and updating (see Almeida-Filho et al., 2018, for a review). According to Seibt and Frank, 2019, tagged neuronal ensembles during wakefulness are reactivated during subsequent NREM sleep where they capture Plasticity-Related-Products (PRPs). In subsequent REM sleep stages, PRPs are translated into proteins. Thus, while memory reactivation during SWS serves as the first step to memory consolidation, REM sleep is where gene expressions and protein synthesis predominantly occur, facilitating the consolidation of "tagged" memories (Seibt & Frank, 2019). For emotional memories, these biological processes are more pronounced in the amygdala-hippocampus-mPFC network, whose activity is also increased during REM sleep (Kim & Payne, 2020).

2. *Decoupling of the emotional tone from information:* During REM, the decoupling of the declarative information from its emotional resonance can be facilitated by the inhibited communication between the neocortex and limbic/paralimbic structures, which is driven by elevated concentrations of acetylcholine and low levels of both noradrenaline and serotonin states, which has additional implication for the decoupling (Hasselmo, 2006; Hutchison & Rathore, 2015; Walker, 2009).

This framework can be integrated into the context of synaptic and systems consolidation (Frankland & Bontempi, 2005), thus bringing us back to the importance of time mentioned in the above section. In fact, while synaptic consolidation un-

folds over minutes to hours after learning, systems consolidation, which involves corticalization and reorganization, occurs over long periods of time. Notably, both these phenomena have been ascribed to REM sleep (Pereira & Lewis, 2020) and the detachment of the emotional intensity from its context is a crucial aspect of memory reorganization (Landmann et al., 2015). In light of the above, it becomes evident that the time span of studying the relationship between sleep and arousal cannot be constrained to a single night or immediate post-sleep evaluations.

5.4 Limitations

Before diving into future research, it's important to acknowledge the limitations of this thesis.

In Chapter 2, the primary limitation was related to the use of the Dream headband (DH, Arnal et al., 2020). Its minimal recording capability didn't allow us to measure sleep microarchitecture. Consequently, we could only hypothesize that wearing an eye mask might have led to an increase in SWA. However, this device enabled us to conduct a study in participants' own environment.

The limitations of the experiment in Chapter 3 have already been discussed, but they deserve reiteration. Most notably, out of the fifty-three healthy volunteers who participated in the study, twenty-five did not correctly perform the Generic Part Training (GPT, McCaffrey, 2012a, 2012b), leading to their exclusion from the analysis. This limitation might have emerged due to the constraints posed by the online format of the experiment, which deviated from the original protocol outlined by McCaffrey (McCaffrey, 2012a, 2012b). Specifically, McCaffrey emphasized the importance of a collaborative process between the experimenter and participants when creating the initial parts-diagram for the GPT. This collaboration ensured that participants were fully engaged, understood the task, and actively constructed

the diagram. It also served to capture participants' attention and reinforce their understanding of the task. In our online study, we provided participants with written instructions and a pre-structured diagram that they subsequently completed. This change may have diminished participants' active engagement and involvement in the task, possibly affecting their performance. Another limitation is our inability to fully disentangle the effects of circadian rhythms from the specific impacts of sleep and wakefulness on the task. The presence of a circadian confound raises questions about how these factors might have influenced the effects of sleep and wakefulness on insight problem-solving. A nap study, as outlined in the next section, could address this limitation.

A shared limitation in all Chapters is the issue of statistical power, which is essential for deriving reliable and valid conclusions from research findings. Statistical power is the ability of a study to detect a genuine effect, if one exists, and to reject the null hypothesis (Dorey, 2011). Insufficient statistical power increases the risk of a Type II error, diminishing the likelihood of detecting a true effect and increasing the chance of observing a non-existent one (Brysbaert, 2019). Many studies in the sleep field are underpowered, possibly due to the demanding nature of the experiments, as researchers often must remain awake from evening to late the following morning. When additional measurements are incorporated into polysomnography research, the complexity and difficulty of the study increase. The underpowered nature of many of these studies implies that their findings might not be consistently replicated in future research, contributing to the reproducibility crisis, a persistent issue in the scientific community (Vankov et al., 2014). A potential solution could be a collaborative approach. By pooling resources and expertise, multiple labs worldwide could work in tandem and finally examine research questions in a sufficiently powered sample and using the same methodologies.

5.5 Future research

The findings presented in this thesis pave the way for further research and exploration.

In Chapter 2 we offer valuable insights into the benefits of wearing an eye mask to block early light during sleep for enhancing cognitive function. A critical subsequent step is delving deeper into the mechanisms underlying the observed benefits on memory and vigilance. Polysomnography is essential for measuring the impact on SWA in this context. Moreover, assessing ambient light levels can refine our understanding of the eye mask's efficacy in mitigating external light. While the adverse effects of sleeping in non-dark settings are well-documented (Bradley & Lang, 1999; Park & Bischof, 2013), some light sources might subtly affect cognition and remain overlooked. It would also be beneficial to investigate whether the observed benefits persist or diminish over extended periods. Importantly, we exclusively recruited participants who had never used an eye mask. Examining habitual eye mask users could determine whether the benefits for new users arise from the novelty of the experience or the genuine advantages of blocking early light.

Turning to creativity, it remains crucial for future research to understand the role of sleep in fostering creative processes. Creativity has always been a vital component of human progress and now, more than ever, as we navigate a new era dominated by artificial intelligence and digital technologies, understanding this link is of paramount importance. Furthermore, the world is still reeling from the effects of a global pandemic - which brought with it not only health concerns but also profound impacts on mental well-being – and facing climate challenges that are gradually disrupting ecosystems, economies, and communities. If sleep indeed plays a pivotal role in enhancing creativity, understanding this relationship can be

a game-changer.

To address the limitations highlighted in Chapter 3, future experiments should: (1) incorporate a daytime nap to differentiate the effects of sleep from circadian influences; (2) include measures of participants' circadian rhythms, such as the Morningness-Eveningness Questionnaire (Horne & Östberg, 1976), to understand how individuals' peak times relate to their performance, thus offering deeper insights into the relationship between circadian rhythms and problem-solving abilities; and (3) aim to replicate McCaffrey's original protocol as closely as possible (McCaffrey, 2012b).

Chapter 4 introduces a compelling research challenge: understanding how sleep influences emotional memories and their emotional tone over extended durations. There's already evidence suggesting that multiple nights of sleep might gradually mitigate affective charges (Bolinger et al., 2019; Schwartz et al., 2022; Werner et al., 2021; Zeng et al., 2021). Therefore, future studies should explore the temporal dynamics of this phenomenon, specifically determining the number of nights of sleep required for this effect to emerge and the progression of affective charges over time. This exploration should be coupled with an evaluation of both subjective and autonomic habituation. However, researchers should be mindful of the natural habitation effect triggered by repeated exposure to emotionally charged images. Codispoti and colleagues observed that after viewing the same affective images 60 times, participants judged unpleasant images as less pleasant and less arousing, with the drop in arousal ratings being more pronounced during the habituation phase. This indicates that repetitive exposure primarily alters the intensity rather than the hedonic value of such images, a finding further supported by observed changes in autonomic responses, such as skin conductance and heart rate (Codispoti et al., 2006). Moreover, it's crucial that research starts placing more emphasis on the interplay between different sleep stages and emotions. Given that a full sleep cycle encompasses both REM and SWS stages, understanding their

complementary roles in emotional processing is paramount.

5.6 Conclusion

This thesis explored methods of sleep manipulation to enhance cognitive functions. Across all experimental chapters, there was evidence that sleep holds the potential to enhance cognitive abilities. Specifically, Chapter 2 presented compelling evidence for this relationship through a straightforward yet effective intervention. Using an eye mask to block light during sleep not only improved the encoding of new information but also heightened alertness the following day.

Chapter 3, while exploring the relationship between sleep and creativity, introduced a layer of complexity with the time-of-day effect. However, the very fact that such an effect was observed emphasizes the intricate interplay between sleep, cognitive performance, and circadian rhythms.

Chapter 4 observed the benefits of Targeted Memory Reactivation during REM sleep to modulate emotional reactivity. The observed neural, visceral, and subjective changes post-manipulation not only highlight the profound impact of sleep on emotional processing but also extend the understanding of sleep's role in cognitive-emotional interplay.

This thesis provides novel insights into how a simple intervention during sleep can benefit memory and alertness, the intricate relationship between sleep, creativity, and circadian rhythms, and underscores the potential effects of sleep on arousal habituation.

References

Abbott, L. F., & Nelson, S. B. (2000). Synaptic plasticity: Taming the beast. *Nature Neuroscience*, *3*, 1178–1183.

Alexander, L., Wood, C. M., Gaskin, P. L. R., Sawiak, S. J., Fryer, T. D., Hong, Y. T., McIver, L., Clarke, H. F., & Roberts, A. C. (2020). Over-activation of primate subgenual cingulate cortex enhances the cardiovascular, behavioral and neural responses to threat. *Nature Communications*, *11*(1), 5386. https://doi.org/10.1038/s41467-020-19167-0

Alger, S. E., Kensinger, E. A., & Payne, J. D. (2018). Preferential consolidation of emotionally salient information during a nap is preserved in middle age [Publisher: Elsevier Inc]. *Neurobiology of Aging*, *68*, 34–47. https://doi.org/10.1016/j.neurobiolaging.2018.03.030

Alkozei, A., Smith, R., Dailey, N. S., Bajaj, S., & Killgore, W. D. S. (2017). Acute exposure to blue wavelength light during memory consolidation improves verbal memory performance (E. Ito, Ed.). *PLOS ONE*, *12*(9), e0184884. https://doi.org/10.1371/journal.pone.0184884

Allen, M., Poggiali, D., Whitaker, K., Marshall, T. R., & Kievit, R. A. (2019). Raincloud plots: A multi-platform tool for robust data visualization [version 1; peer review: 2 approved]. *Wellcome Open Research*, *4*, 1–46. https://doi.org/10.12688/wellcomeopenres.15191.1

Almeida-Filho, D. G., Queiroz, C. M., & Ribeiro, S. (2018). Memory corticalization triggered by REM sleep: Mechanisms of cellular and systems consolidation. *Cellular and Molecular Life Sciences*, *75*(20), 3715–3740. https://doi.org/10.1007/s00018-018-2886-9

Ambrosini & Giuditta, A. (2001). Learning and sleep: The sequential hypothesis. *Sleep Medicine Reviews*, *5*(6), 477–490. https://doi.org/10.1053/smrv.2001.0180

Ambrosini, Langella, M., Gironicarnevale, U., & Giuditta, A. (1992). The sequential hypothesis of sleep function. III. the structure of postacquisition sleep in learning and nonlearning rats. *Physiology & Behavior*, *51*(2), 217–226. https://doi.org/10.1016/0031-9384(92)90134-N

Ambrosini, Mariucci, G., Bruschelli, G., Colarieti, L., & Giuditta, A. (1995). Sequential hypothesis of sleep function. v. lengthening of post-trial SS episodes in reminiscent rats. *Physiology & Behavior*, *58*(5), 1043–1049. https://doi.org/10.1016/0031-9384(95)00143-7

Anderson, A. K., Christoff, K., Panitz, D., De Rosa, E., & Gabrieli, J. D. E. (2003). Neural correlates of the automatic processing of threat facial signals. *The Journal of Neuroscience*, *23*(13), 5627–5633. https://doi.org/10.1523/JNEUROSCI.23-13-05627.2003

Andrillon, T., Nir, Y., Staba, R. J., Ferrarelli, F., Cirelli, C., Tononi, G., & Fried, I. (2011). Sleep spindles in humans: Insights from intracranial EEG and unit recordings. *Journal of Neuroscience*, *31*(49), 17821–17834. https://doi.org/10.1523/JNEUROSCI.2604-11.2011

Antonenko, D., Diekelmann, S., Olsen, C., Born, J., & Mölle, M. (2013). Napping to renew learning capacity: Enhanced encoding after stimulation of sleep slow oscillations. *European Journal of Neuroscience*, *37*(7), 1142–1151. https://doi.org/10.1111/ejn.12118

Antony, J. W., Gobel, E. W., O'Hare, J. K., Reber, P. J., & Paller, K. A. (2013). Cued memory reactivation during sleep influences skill learning. *Nature Neuroscience*, *15*(8), 1114–111661. https://doi.org/10.1038/nn.3152

Arnal, P. J., Thorey, V., Debellemaniere, E., Ballard, M. E., Hernandez, A. B., Guillot, A., Jourde, H., Harris, M., Guillard, M., van Beers, P., Chennaoui, M., & Sauvet, F. (2020). The dreem headband compared to polysomnography for electroencephalographic signal acquisition and sleep staging. *Sleep*, *43*(11), 1–13. https://doi.org/10.1093/sleep/zsaa097

Aserinsky, E., & Kleitman, N. (1953). Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science*, *118*, 273–274.

Ashton, J. E., Harrington, M. O., Guttesen, A. Á., Smith, A. K., & Cairney, S. A. (2019). Sleep preserves physiological arousal in emotional memory. *Scientific Reports*, *9*(1), 1–10. https://doi.org/10.1038/s41598-019-42478-2

Ashton, J. E., Harrington, M. O., Langthorne, D., Ngo, H.-V. V., & Cairney, S. A. (2020). Sleep deprivation induces fragmented memory loss. *Learning & Memory*, *27*(4), 130–135. https://doi.org/10.1101/lm.050757.119

Astori, S., Wimmer, R. D., & Lüthi, A. (2013). Manipulating sleep spindles - expanding views on sleep, memory, and disease. *Trends in Neurosciences*, *36*(12), 738–748. https://doi.org/10.1016/j.tins.2013.10.001

Badia, P., Myers, B., Boecker, M., Culpepper, J., & Harsh, J. R. (1991). Bright light effects on body temperature, alertness, EEG and behavior. *Physiology and Behavior*, *50*(3), 583–588. https://doi.org/10.1016/0031-9384(91)90549-4

Bani Younis, M., Hayajneh, FA, & Alduraidi, H. (2019). Effectiveness of using eye mask and earplugs on sleep length and quality among intensive care patients: A quasi-experimental study. *International Journal of Nursing Practice*, *25*(3). https://doi.org/10.1111/ijn.12740

Baran, B., Pace-Schott, E. F., Ericson, C., & Spencer, R. M. (2012). Processing of emotional reactivity and emotional memory over sleep. *Journal of Neu-*

roscience, *32*(3), 1035–1042. https://doi.org/10.1523/JNEUROSCI.2532-11.2012

Basner, M., & Dinges, D. F. (2011). Maximizing sensitivity of the psychomotor vigilance test (PVT) to sleep loss. *Sleep*, *34*(5), 581–591. https://doi.org/10.1093/sleep/34.5.581

Bass, J., & Takahashi, J. S. (2010). Circadian integration of metabolism and energetics. *Science*, *330*(6009), 1349–1354. https://doi.org/10.1126/science.1195027

Bates, D. M., Machler, M., Bolker, B., & Walker, S. (2015). *Fitting linear mixed-effects models 548 using {lme4}*. https://doi.org/10.18637/jss.v067.i01

Bedrosian, T. A., & Nelson, R. J. (2017). Timing of light exposure affects mood and brain circuits. *Translational Psychiatry*, *7*(1), e1017–e1017. https://doi.org/10.1038/tp.2016.262

Beijamini, F., Pereira, S. I. R., Cini, F. A., & Louzada, F. M. (2014). After being challenged by a video game problem, sleep increases the chance to solve it (G. F. Gilestro, Ed.). *PLoS ONE*, *9*(1), e84342. https://doi.org/10.1371/journal.pone.0084342

Benchenane, K., Peyrache, A., Khamassi, M., Tierney, P. L., Gioanni, Y., Battaglia, F. P., & Wiener, S. I. (2010). Coherent theta oscillations and reorganization of spike timing in the hippocampal- prefrontal network upon learning. *Neuron*, *66*(6), 921–936. https://doi.org/10.1016/j.neuron.2010.05.013

Bendor, D., & Wilson, M. A. (2012). Biasing the content of hippocampal replay during sleep. *Nature Neuroscience*, *15*(10), 1439–1444. https://doi.org/10.1038/nn.3203

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *57*(1), 289–300.

Benschop, L., Vanhollebeke, G., Li, J., Leahy, R. M., Vanderhasselt, M.-A., & Baeken, C. (2022). Reduced subgenual cingulate–dorsolateral prefrontal

connectivity as an electrophysiological marker for depression. *Scientific Reports*, *12*(1), 16903. https://doi.org/10.1038/s41598-022-20274-9

Bergmann, T. O., Mölle, M., Diedrichs, J., Born, J., & Siebner, H. R. (2012). Sleep spindle-related reactivation of category-specific cortical regions after learning face-scene associations. *NeuroImage*, *59*(3), 2733–2742. https://doi.org/10.1016/j.neuroimage.2011.10.036

Bergmann, T. O., Mölle, M., Marshall, L., Kaya-Yildiz, L., Born, J., & Roman Siebner, H. (2008). A local signature of LTP- and LTD-like plasticity in human NREM sleep: Signature of plasticity in NREM sleep. *European Journal of Neuroscience*, *27*(9), 2241–2249. https://doi.org/10.1111/j.1460-9568.2008.06178.x

Bjorvatn, B., & Pallesen, S. (2009). A practical approach to circadian rhythm sleep disorders. *Sleep Medicine Reviews*, *13*(1), 47–60. https://doi.org/10.1016/j.smrv.2008.04.009

Blanca, M., Alarcón, R., Arnau, J., Bono, R., & Bendayan, R. (2017). Non-normal data: Is ANOVA still a valid option? *Psicothema*, *29*(4), 552–557.

Blume, C., Garbazza, C., & Spitschan, M. (2019). Effects of light on human circadian rhythms, sleep and mood. *Somnologie*, *23*(3), 147–156. https://doi.org/10.1007/s11818-019-00215-x

Bolinger, E., Born, J., & Zinke, K. (2018). Sleep divergently affects cognitive and automatic emotional response in children [Publisher: Elsevier Ltd]. *Neuropsychologia*, *117*, 84–91. https://doi.org/10.1016/j.neuropsychologia.2018.05.015

Bolinger, E., Cunningham, T. J., Payne, J. D., Bowman, M. A., Bulca, E., Born, J., & Zinke, K. (2019). Sleep's benefits to emotional processing emerge in the long term [Publisher: Elsevier Ltd]. *Cortex*, *120*, 457–470. https://doi.org/10.1016/j.cortex.2019.07.008

Borbely, A. A. (1982). A two process model of sleep regulation. *Human Neurobiology*, *1*(3), 195–204.

Borbély, A. A., Daan, S., Wirz-Justice, A., & Deboer, T. (2016). The two-process model of sleep regulation: A reappraisal. *Journal of Sleep Research*, *25*(2), 131–143. https://doi.org/10.1111/jsr.12371

Born, J., Rasch, B., & Gais, S. (2006). Sleep to remember. *The Neuroscientist*, *12*(5), 410–424. https://doi.org/10.1177/1073858406292647

Boubekri, M., Cheung, I. N., Reid, K. J., Wang, C.-H., & Zee, P. C. (2014). Impact of windows and daylight exposure on overall health and sleep quality of office workers: A case-control pilot study. *Journal of Clinical Sleep Medicine*, *10*(6), 603–611. https://doi.org/10.5664/jcsm.3780

Boyce, R., Glasgow, S. D., Williams, S., & Adamantidis, A. (2016). Causal evidence for the role of REM sleep theta rhythm in contextual memory consolidation. *Science*, *352*(6287), 812–816. https://doi.org/10.1126/science.aad5252

Bradley, Codispoti, M., Cuthbert, B. N., & Lang, P. J. (2001). Emotion and motivation i: Defensive and appetitive reactions in picture processing. *Emotion*, *1*(3), 276–298. https://doi.org/10.1037/1528-3542.1.3.276

Bradley & Lang, P. (1999). *International affective digitized sounds (IADS): Stimuli, instruction manual and affective ratings. technical report b-2.* [ISSN: 02149915].

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433–436. https://doi.org/10.1163/156856897X00357

Brodt, S., Pöhlchen, D., Täumer, E., Gais, S., & Schönauer, M. (2018). Incubation, not sleep, AIDS problem-solving. *Sleep*, *41*(10), 1–11. https://doi.org/10.1093/sleep/zsy155

Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? a tutorial of power analysis with reference tables. *Journal of Cognition*, *2*(1), 16. https://doi.org/10.5334/joc.72

Buchanan, T. W., Etzel, J. A., Adolphs, R., & Tranel, D. (2006). The influence of autonomic arousal and semantic relatedness on memory for emotional

words. *International Journal of Psychophysiology*, *61*(1), 26–33. https://doi.org/10.1016/j.ijpsycho.2005.10.022

Buzsáki, G. (1986). Hippocampal sharp waves: Their origin and significance. *Brain Research*, *398*(2), 242–253.

Cai, D. J., Mednick, S. A., Harrison, E. M., Kanady, J. C., & Mednick, S. C. (2009). REM, not incubation, improves creativity by priming associative networks. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(25), 10130–10134. https://doi.org/10.1073/pnas.0900271106

Cairney, S. A., Durrant, S. J., Power, R., & Lewis, P. A. (2015). Complementary roles of slow-wave sleep and rapid eye movement sleep in emotional memory consolidation. *Cerebral Cortex*, *25*(6), 1565–1575. https://doi.org/10.1093/cercor/bht349

Cairney, S. A., Durrant, S. J., Hulleman, J., & Lewis, P. A. (2014). Targeted memory reactivation during slow wave sleep facilitates emotional memory consolidation. *Sleep*, *37*(4), 701–707. https://doi.org/10.5665/sleep.3572

Cairney, S. A., Guttesen, A. á., El Marj, N., & Staresina, B. P. (2018). Memory consolidation is linked to spindle-mediated information processing during sleep. *Current Biology*, *28*(6), 948–954.e4. https://doi.org/10.1016/j.cub.2018.01.087

Cairney, S. A., Sobczak, J. M., Lindsay, S., & Gaskell, M. G. (2017). Mechanisms of memory retrieval in slow-wave sleep. *Sleep*, *40*(9). https://doi.org/10.1093/sleep/zsx114

Chang, A.-M., Aeschbach, D., Duffy, J. F., & Czeisler, C. A. (2015). Evening use of light-emitting eReaders negatively affects sleep, circadian timing, and next-morning alertness. *Proceedings of the National Academy of Sciences*, *112*(4), 1232–1237. https://doi.org/10.1073/pnas.1418490112

Chellappa, S. L., Steiner, R., Blattner, P., Oelhafen, P., Götz, T., & Cajochen, C. (2011). Non-visual effects of light on melatonin, alertness and cognitive

performance: Can blue-enriched light keep us alert? (M. H. Herzog, Ed.). *PLoS ONE*, *6*(1), e16429. https://doi.org/10.1371/journal.pone.0016429

Cho, J. R., Joo, E. Y., Koo, D. L., & Hong, S. B. (2013). Let there be no light: The effect of bedside light on sleep quality and background electroencephalographic rhythms. *Sleep Medicine*, *14*(12), 1422–1425. https://doi.org/10.1016/j.sleep.2013.09.007

Codispoti, M., Ferrari, V., & Bradley, M. M. (2006). Repetitive picture processing: Autonomic and cortical correlates. *Brain Research*, *1068*(1), 213–220. https://doi.org/10.1016/j.brainres.2005.11.009

Colrain, I. M. (2005). The k-complex : A 7-decade history. *Sleep*, *28*(2), 255–273.

Comtet, H., Geoffroy, P. A., Kobayashi Frisk, M., Hubbard, J., Robin-Choteau, L., Calvel, L., Hugueny, L., Viola, A. U., & Bourgin, P. (2019). Light therapy with boxes or glasses to counteract effects of acute sleep deprivation [Publisher: Springer US]. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-019-54311-x

Cordi, M. J., & Rasch, B. (2021). How robust are sleep-mediated memory benefits? [Publisher: Elsevier Ltd]. *Current Opinion in Neurobiology*, *67*, 1–7. https://doi.org/10.1016/j.conb.2020.06.002

Cousins, J. N., El-Deredy, W., Parkes, L. M., Hennies, N., & Lewis, P. A. (2014). Cued memory reactivation during slow-wave sleep promotes explicit knowledge of a motor sequence. *Journal of Neuroscience*, *34*(48), 15870–15876. https://doi.org/10.1523/JNEUROSCI.1011-14.2014

Cousins, J. N., El-Deredy, W., Parkes, L. M., Hennies, N., & Lewis, P. A. (2016). Cued reactivation of motor learning during sleep leads to overnight changes in functional brain activity and connectivity (F. P. Battaglia, Ed.). *PLOS Biology*, *14*(5), e1002451. https://doi.org/10.1371/journal.pbio.1002451

Cox, R. W. (1996). AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research*, *29*(3), 162–173. https://doi.org/10.1006/cbmr.1996.0014

Craig, D. (2009). How do you feel — now? the anterior insula and human awareness. *Nature Reviews Neuroscience*, *10*(1), 59–70.

Cunningham, T. J., Crowell, C. R., Alger, S. E., Kensinger, E. A., Villano, M. A., Mattingly, S. M., & Payne, J. D. (2014). Psychophysiological arousal at encoding leads to reduced reactivity but enhanced emotional memory following sleep [Publisher: Elsevier Inc.]. *Neurobiology of Learning and Memory*, *114*, 155–164. https://doi.org/10.1016/j.nlm.2014.06.002

Damasio, A. (2003). Feelings of emotion and the self. *Annals of the New York Academy of Sciences*, *1001*(1), 253–261. https://doi.org/10.1196/annals.1279.014

Dang-Vu, T. T., Schabus, M., Desseilles, M., Sterpenich, V., Bonjean, M., & Maquet, P. (2010). Functional neuroimaging insights into the physiology of human sleep. *Sleep*, *33*(12), 1589–1603. https://doi.org/10.1093/sleep/33.12.1589

Datta, S., Li, G., & Auerbach, S. (2008). Activation of phasic pontine-wave generator in the rat: A mechanism for expression of plasticity-related genes and proteins in the dorsal hippocampus and amygdala. *European Journal of Neuroscience*, *27*(7), 1876–1892. https://doi.org/10.1111/j.1460-9568.2008.06166.x

Daurat, A., Foret, J., Touitou, Y., & Benoit, O. (1996). Detrimental influence of bright light exposure on alertness, performance, and mood in the early morning. *Neurophysiologie Clinique/Clinical Neurophysiology*, *26*(1), 8–14. https://doi.org/10.1016/0987-7053(96)81529-2

De Gennaro, L., & Ferrara, M. (2003). Sleep spindles: An overview. *Sleep Medicine Reviews*, *7*(5), 423–440. https://doi.org/10.1053/smrv.2002.0252

Deuker, L., Olligs, J., Fell, J., Kranz, T. A., Mormann, F., Montag, C., Reuter, M., Elger, C. E., & Axmacher, N. (2013). Memory consolidation by replay of stimulus-specific neural activity. *Journal of Neuroscience*, *33*(49), 19373–19383. https://doi.org/10.1523/JNEUROSCI.0414-13.2013

Diano, M., Celeghin, A., Bagnis, A., & Tamietto, M. (2017). Amygdala response to emotional stimuli without awareness: Facts and interpretations. *Frontiers in Psychology*, *7*. https://doi.org/10.3389/fpsyg.2016.02029

Diekelmann, S., Biggel, S., Rasch, B., & Born, J. (2012). Offline consolidation of memory varies with time in slow wave sleep and can be accelerated by cuing memory reactivations. *Neurobiology of Learning and Memory*, *98*(2), 103–111. https://doi.org/10.1016/j.nlm.2012.07.002

Diekelmann, S., & Born, J. (2010). The memory function of sleep [Publisher: Nature Publishing Group]. *Nature Reviews Neuroscience*, *11*(2), 114–126. https://doi.org/10.1038/nrn2762

Diekelmann, S., Büchel, C., Born, J., & Rasch, B. (2011). Labile or stable: Opposing consequences for memory when reactivated during waking and sleep. *Nature Neuroscience*, *14*(3), 381–386. https://doi.org/10.1038/nn.2744

Dijk, D. J., Beersma, D. G., Daan, S., & Lewy, A. J. (1989). Bright morning light advances the human circadian system without affecting NREM sleep homeostasis. *American Journal of Physiology - Regulatory Integrative and Comparative Physiology*, *256*(1). https://doi.org/10.1152/ajpregu.1989.256.1.r106

Dijk, D. J., Visscher, C. A., Bloem, G. M., Beersma, D. G., & Daan, S. (1987). Reduction of human sleep duration after bright light exposure in the morning. *Neuroscience Letters*, *73*(2), 181–186. https://doi.org/10.1016/0304-3940(87)90014-0

Dolan, R. J. (2002). Emotion, cognition, and behavior. *Science*, *298*, 1191–1195. https://doi.org/10.1126/science.1076358

Dorey, F. J. (2011). In brief: Statistics in brief: Statistical power: What is it and when should it be used? *Clinical Orthopaedics & Related Research*, *469*(2), 619–620. https://doi.org/10.1007/s11999-010-1435-0

Dorrian, J., Rogers, N. L., & Dinges, D. F. (2004). Psychomotor vigilance performance: Neurocognitive assay sensitive to sleep loss. *Sleep Deprivation*, 39–70. https://doi.org/10.3109/9780203998007-4

Drevets, W. C., Savitz, J., & Trimble, M. (2008). The subgenual anterior cingulate cortex in mood disorders. *CNS Spectrums*, *13*(8), 663–681. https://doi.org/10.1017/S1092852900013754

Duncker, K. (1945). On problem-solving. (L. S. Lees, Trans.). *Psychological Monographs*, *58*(5), i–113. https://doi.org/10.1037/h0093599

Durrant, S. J., Taylor, C., Cairney, S., & Lewis, P. A. (2011). Sleep-dependent consolidation of statistical learning [Publisher: Elsevier Ltd]. *Neuropsychologia*, *49*(5), 1322–1331. https://doi.org/10.1016/j.neuropsychologia.2011.02.015

Eckert, M. J., McNaughton, B. L., & Tatsuno, M. (2020). Neural ensemble reactivation in rapid eye movement and slow-wave sleep coordinate with muscle activity to promote rapid motor skill learning. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1799), 20190655. https://doi.org/10.1098/rstb.2019.0655

Ellenbogen, J. M., Hu, P. T., Payne, J. D., Titone, D., & Walker, M. P. (2007). Human relational memory requires time and sleep. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(18), 7723–7728. https://doi.org/10.1073/pnas.0700094104

Ellenbogen, J. M., Payne, J. D., & Stickgold, R. (2006). The role of sleep in declarative memory consolidation: Passive, permissive, active or none? *Current Opinion in Neurobiology*, *16*(6), 716–722. https://doi.org/10.1016/j.conb.2006.10.006

Enders, C. K., & Tofighi, D. (2007). Centering predictor variables in cross-sectional multilevel models: A new look at an old issue. *Psychological Methods*, *12*(2), 121–138. https://doi.org/10.1037/1082-989X.12.2.121

Esteban, O., Markiewicz, C. J., Blair, R. W., Moodie, C. A., Isik, A. I., Erramuzpe, A., Kent, J. D., Goncalves, M., DuPre, E., Snyder, M., Oya, H.,

Ghosh, S. S., Wright, J., Durnez, J., Poldrack, R. A., & Gorgolewski, K. J. (2019). fMRIPrep: A robust preprocessing pipeline for functional MRI. *Nature Methods*, *16*(1), 111–116. https://doi.org/10.1038/s41592-018-0235-4

Euston, D. R., Tatsuno, M., & McNaughton, B. L. (2007). Fast-forward playback of recent memory sequences in prefrontal cortex during sleep. *Science*, *318*(5853), 1147–1150. https://doi.org/10.1126/science.1148979

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using g*power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, *41*(4), 1149–1160. https://doi.org/10.3758/BRM.41.4.1149

Fernandez, L. M., & Lüthi, A. (2020). Sleep spindles: Mechanisms and functions. *Physiological Reviews*, *100*(2), 805–868. https://doi.org/10.1152/physrev.00042.2018

Ferrarelli, F., Kaskie, R., Laxminarayan, S., Ramakrishnan, S., Reifman, J., & Germain, A. (2019). An increase in sleep slow waves predicts better working memory performance in healthy individuals. *NeuroImage*, *191*, 1–9. https://doi.org/10.1016/j.neuroimage.2019.02.020

Ficca, G., Lombardo, P., Rossi, L., & Salzarulo, P. (2000). Morning recall of verbal material depends on prior sleep organization. *Behavioural Brain Research*, *112*(1), 159–163. https://doi.org/10.1016/S0166-4328(00)00177-7

Finley, A., & Penningroth, S. (2015). *Online versus in-lab: Pros and cons of an online prospective memory experiment* (In A. M.Columbus (Ed.), Advances inPsychology Research, Vol. 113). New York, NY: Nova.

Fogel, S. M., & Smith, C. T. (2011). The function of the sleep spindle: A physiological index of intelligence and a mechanism for sleep-dependent memory consolidation. *Neuroscience & Biobehavioral Reviews*, *35*(5), 1154–1165. https://doi.org/10.1016/j.neubiorev.2010.12.003

Fogel, S. M., Smith, C. T., & Cote, K. A. (2007). Dissociable learning-dependent changes in REM and non-REM sleep in declarative and procedural memory

systems. *Behavioural Brain Research*, *180*(1), 48–61. https://doi.org/10.1016/j.bbr.2007.02.037

Forget, D., Morin, C. M., & Bastien, C. H. (2011). The role of the spontaneous and evoked k-complex in good-sleeper controls and in individuals with insomnia. *Sleep*, *34*(9), 1251–1260. https://doi.org/10.5665/SLEEP.1250

Foster, D. J., & Wilson, M. A. (2006). Reverse replay of behavioural sequences in hippocampal place cells during the awake state. *Nature*, *440*(7084), 680–683. https://doi.org/10.1038/nature04587

Fowler, P. M., Knez, W., Thornton, H. R., Sargent, C., Mendham, A. E., Crowcroft, S., Miller, J., Halson, S., & Duffield, R. (2021). Sleep hygiene and light exposure can improve performance following long-haul air travel. *International Journal of Sports Physiology and Performance*, *16*(4), 517–526. https://doi.org/10.1123/ijspp.2019-0931

Fox, J. (2016). *Applied regression analysis and generalized linear models (3rd ed).* Sage Publications.

Frankland, P. W., & Bontempi, B. (2005). The organization of recent and remote memories. *Nature Reviews Neuroscience*, *6*(2), 119–130. https://doi.org/10.1038/nrn1607

Fromm, E., Horlebein, C., Meergans, A., Niesner, M., & Randler, C. (2011). Evaluation of a dawn simulator in children and adolescents. *Biological Rhythm Research*, *42*(5), 417–425. https://doi.org/10.1080/09291016.2010.525851

Fuentemilla, L., Miró, J., Ripollés, P., Vilà-Balló, A., Juncadella, M., Castañer, S., Salord, N., Monasterio, C., Falip, M., & Rodríguez-Fornells, A. (2013). Hippocampus-dependent strengthening of targeted memories via reactivation during sleep in humans. *Current Biology*, *23*(18), 1769–1775. https://doi.org/10.1016/j.cub.2013.07.006

Fullana, M. A., Harrison, B. J., Soriano-Mas, C., Vervliet, B., Cardoner, N., Àvila-Parcet, A., & Radua, J. (2016). Neural signatures of human fear condition-

ing: An updated and extended meta-analysis of fMRI studies. *Molecular Psychiatry*, *21*(4), 500–508. https://doi.org/10.1038/mp.2015.88

Gais, S., & Born, J. (2004). Declarative memory consolidation: Mechanisms acting during human sleep [ISBN: 4945150036]. *Learning and Memory*, *11*(6), 679–685. https://doi.org/10.1101/lm.80504

Gais, S., Lucas, B., & Born, J. (2006). Sleep after learning aids memory recall. *Learning & Memory*, *13*(3), 259–262. https://doi.org/10.1101/lm.132106

Gasquoine, P. G. (2014). Contributions of the insula to cognition and emotion. *Neuropsychology Review*, *24*(2), 77–87. https://doi.org/10.1007/s11065-014-9246-9

Gelman, A., & Hill, J. (2007). *Data analysis using regression and multilevel/hierarchical models, 1 ed.* Cambridge University Press.

Genzel, L., Dragoi, G., Frank, L., Ganguly, K., de la Prida, L., Pfeiffer, B., & Robertson, E. (2020). A consensus statement: Defining terms for reactivation analysis. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1799), 20200001. https://doi.org/10.1098/rstb.2020.0001

German, T. P., & Defeyter, M. A. (2000). Immunity to functional fixedness in young children. *Psychonomic Bulletin & Review*, *7*(4), 707–712. https://doi.org/10.3758/BF03213010

Gerstner, J. R., & Yin, J. C. P. (2010). Circadian rhythms and memory formation. *Nature Reviews Neuroscience*, *11*(8), 577–588. https://doi.org/10.1038/nrn2881

Gilhooly, K. J. (2016). Incubation and intuition in creative problem solving. *Frontiers in Psychology*, *7*, 1–9. https://doi.org/10.3389/fpsyg.2016.01076

Girardeau, G., & Zugaro, M. (2011). Hippocampal ripples and memory consolidation. *Current Opinion in Neurobiology*, *21*(3), 452–459. https://doi.org/10.1016/j.conb.2011.02.005

Giuditta, A., Ambrosini, M. V., Montagnese, P., Mandile, P., Cotugno, M., Zucconi, G. G., & Vescia, S. (1995). The sequential hypothesis of the function

of sleep. *Behavioural Brain Research*, *69*(1), 157–166. https://doi.org/10.1016/0166-4328(95)00012-I

Gorgolewski, K., Burns, C. D., Madison, C., Clark, D., Halchenko, Y. O., Waskom, M. L., & Ghosh, S. S. (2011). Nipype: A flexible, lightweight and extensible neuroimaging data processing framework in python. *Frontiers in Neuroinformatics*, *5*. https://doi.org/10.3389/fninf.2011.00013

Görtelmeyer, R. (1985). On the development of a standardized sleep inventory for the assessment of sleep. In S. Kubicki & W. Herrmann (Eds.), *Methods of sleep research* (pp. 93–98). Gustav Fischer.

Gott, J. A., Liley, D. T., & Hobson, J. A. (2017). Towards a functional understanding of PGO waves. *Frontiers in Human Neuroscience*, *11*, 1–12. https://doi.org/10.3389/fnhum.2017.00089

Groch, S., Wilhelm, I., Diekelmann, S., & Born, J. (2013). The role of REM sleep in the processing of emotional memories: Evidence from behavior and event-related potentials [Publisher: Elsevier Inc.]. *Neurobiology of Learning and Memory*, *99*, 1–9. https://doi.org/10.1016/j.nlm.2012.10.006

Groch, S., Zinke, K., Wilhelm, I., & Born, J. (2015). Dissociating the contributions of slow-wave sleep and rapid eye movement sleep to emotional item and source memory [Publisher: Elsevier Inc.]. *Neurobiology of Learning and Memory*, *122*, 122–130. https://doi.org/10.1016/j.nlm.2014.08.013

Guerrien, A., Dujardin, K., Mandal, O., Sockeel, P., & Leconte, P. (1989). Enhancement of memory by auditory stimulation during postlearning REM sleep in humans. *Physiology and Behavior*, *45*(5), 947–950. https://doi.org/10.1016/0031-9384(89)90219-9

Guilford, J. (1967). *The nature of human intelligence*. McGraw-Hill.

Gujar, N., McDonald, S. A., Nishida, M., & Walker, M. P. (2011). A role for rem sleep in recalibrating the sensitivity of the human brain to specific emotions. *Cerebral Cortex*, *21*(1), 115–123. https://doi.org/10.1093/cercor/bhq064

Hahn, M. A., Heib, D., Schabus, M., Hoedlmoser, K., & Helfrich, R. F. (2020). Slow oscillation-spindle coupling predicts enhanced memory formation from childhood to adolescence. *eLife*, *9*, e53730. https://doi.org/10.7554/eLife.53730

Hakamata, Y., Mizukami, S., Izawa, S., Okamura, H., Mihara, K., Marusak, H., Moriguchi, Y., Hori, H., Hanakawa, T., Inoue, Y., & Tagaya, H. (2022). Implicit and explicit emotional memory recall in anxiety and depression: Role of basolateral amygdala and cortisol-norepinephrine interaction. *Psychoneuroendocrinology*, *136*, 105598. https://doi.org/10.1016/j.psyneuen.2021.105598

Hamilton, J. P., Siemer, M., & Gotlib, I. H. (2008). Amygdala volume in major depressive disorder: A meta-analysis of magnetic resonance imaging studies. *Molecular Psychiatry*, *13*(11), 993–1000. https://doi.org/10.1038/mp.2008.57

Harrington, M. O., Johnson, J. M., Croom, H. E., Pennington, K., & Durrant, S. J. (2018). The influence of REM sleep and SWS on emotional memory consolidation in participants reporting depressive symptoms [Publisher: Elsevier Ltd]. *Cortex*, *99*, 281–295. https://doi.org/10.1016/j.cortex.2017.12.004

Hars, B., Hennevin, E., & Pasques, P. (1985). IMPROVEMENT OF LEARNING BY CUEING DURING POSTLEARN1ng PARADOXICAL. *Behavioural Brain Research*, *18*, 241–250.

Hasher, L., Chung, C., May, C. P., & Foong, N. (2002). Age, time of testing, and proactive interference. *Canadian Journal of Experimental Psychology / Revue canadienne de psychologie expérimentale*, *56*(3), 200–207. https://doi.org/10.1037/h0087397

Hasselmo. (1999). Neuromodulation: Acetylcholine and memory consolidation. *Trends in Cognitive Sciences*, *101*(9), 162–183.

Hasselmo. (2006). The role of acetylcholine in learning and memory [ISBN: 0959-4388 (Print)]. *Current Opinion in Neurobiology*, *16*(6), 710–715. https://doi.org/10.1016/j.conb.2006.09.002.The

Hauner, K. K., Howard, J. D., Zelano, C., & Gottfried, J. A. (2013). Stimulus-specific enhancement of fear extinction during slow-wave sleep. *Nature Neuroscience*, *16*(11), 1553–1555. https://doi.org/10.1038/nn.3527

Haxby, J. V., Gobbini, M. I., Furey, M. L., Ishai, A., Schouten, J. L., & Pietrini, P. (2001). Distributed and overlapping representations of faces and objects in ventral temporal cortex. *Science*, *293*(5539), 2425–2430. https://doi.org/10.1126/science.1063736

Helfrich, R. F., Lendner, J. D., Mander, B. A., Guillen, H., Paff, M., Mnatsakanyan, L., Vadera, S., Walker, M. P., Lin, J. J., & Knight, R. T. (2019). Bidirectional prefrontal-hippocampal dynamics organize information transfer during sleep in humans. *Nature Communications*, *10*(1), 3572. https://doi.org/10.1038/s41467-019-11444-x

Helm, E. V. D., & Walker, M. P. (2010). Overnight therapy? the role of sleep in emotional. *Psychological bulletin*, *135*(5), 731–748. https://doi.org/10.1037/a0016570.Overnight

Henke, K. (2010). A model for memory systems based on processing modes rather than consciousness. *Nature Reviews Neuroscience*, *11*(7), 523–532. https://doi.org/10.1038/nrn2850

Hennevin, E., & Hars, B. (1987). Is increase in post-learning paradoxical sleep modified by cueing? *Behavioural Brain Research*, *24*(3), 243–249. https://doi.org/10.1016/0166-4328(87)90062-3

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R., & Dement, W. (1973). Quantification of sleepiness: A new approach. [ISBN: 978-1-4419-9892-7]. *Psychophysiology*, *10*(4), 431–436.

Hoffman, K. L., & McNaughton, B. L. (2002). Coordinated reactivation of distributed memory traces in primate neocortex. *Science*, *297*(5589), 2070–2073. https://doi.org/10.1126/science.1073538

Hołda, M., Głodek, A., Dankiewicz-Berger, M., Skrzypińska, D., & Szmigielska, B. (2020). Ill-defined problem solving does not benefit from daytime napping. *Frontiers in Psychology*, *11*, 559. https://doi.org/10.3389/fpsyg.2020.00559

Hu, Cheng, L. Y., Chiu, M. H., & Paller, K. (2020). Promoting memory consolidation during sleep: A meta-analysis of targeted memory reactivation [ISBN: 0471140864]. *Phychological bullettin*, *146*(3), 218–244. https://doi.org/10.1037/bul0000223

Hu, P., Stylos-Allan, M., & Walker, M. P. (2006). Sleep facilitates consolidation of emotional declarative memory. *Psychological Science*, *17*(10), 891–898. https://doi.org/10.1111/j.1467-9280.2006.01799.x

Huber, R., Ghilardi, M. F., Massimini, M., Ferrarelli, F., Riedner, B. A., Peterson, M. J., & Tononi, G. (2006). Arm immobilization causes cortical plastic changes and locally decreases sleep slow wave activity. *Nature Neuroscience*, *9*(9), 1169–1176. https://doi.org/10.1038/nn1758

Hutchison, I. C., Pezzoli, S., Tsimpanouli, M. E., Abdellahi, M. E., & Lewis, P. A. (2021). Targeted memory reactivation in REM but not SWS selectively reduces arousal responses [Publisher: Springer US ISBN: 4200302101]. *Communications Biology*, *4*(1), 1–6. https://doi.org/10.1038/s42003-021-01854-3

Hutchison, I. C., & Rathore, S. (2015). The role of REM sleep theta activity in emotional memory. *Frontiers in Psychology*, *6*, 1–15. https://doi.org/10.3389/fpsyg.2015.01439

Iber, C., Ancoli- Israel, S., Chesson, J., & Quan, S. (2007). *The AASM manual for the scoring of sleep and associated events: Rules terminology and technical speci cations 1st ed.* American Acaemy of Sleep Medicine.

Ioannides, A. A., Liu, L., & Kostopoulos, G. K. (2019). The emergence of spindles and k-complexes and the role of the dorsal caudal part of the anterior cingulate as the generator of k-complexes. *Frontiers in Neuroscience*, *13*, 1–21. https://doi.org/10.3389/fnins.2019.00814

Isaak, M., & Just, M. (1995). *Constraints on thinking in insight and invention.* (In R. J. Sternberg & J. E. Davidson (Eds.), The nature of insight). Cambridge, MA: MIT Press.

Jahnke, K., von Wegner, F., Morzelewski, A., Borisov, S., Maischein, M., Steinmetz, H., & Laufs, H. (2012). To wake or not to wake? the two-sided nature of the human k-complex [Publisher: Elsevier Inc.]. *NeuroImage*, *59*(2), 1631–1638. https://doi.org/10.1016/j.neuroimage.2011.09.013

James, W. (1884). II.—WHAT IS AN EMOTION ? *Mind*, *os-IX*(34), 188–205. https://doi.org/10.1093/mind/os-IX.34.188

Jenkinson, M., Bannister, P., Brady, M., & Smith, S. (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images. *NeuroImage*, *17*(2), 825–841. https://doi.org/10.1006/nimg.2002.1132

Ji, D., & Wilson, M. A. (2007). Coordinated memory replay in the visual cortex and hippocampus during sleep. *Nature Neuroscience*, *10*(1), 100–107. https://doi.org/10.1038/nn1825

Jiang, X., Gonzalez-Martinez, J., & Halgren, E. (2019). Posterior hippocampal spindle ripples co-occur with neocortical theta bursts and downstates-upstates, and phase-lock with parietal spindles during NREM sleep in humans. *The Journal of Neuroscience*, *39*(45), 8949–8968. https://doi.org/10.1523/JNEUROSCI.2858-18.2019

Johnson, L. A., Euston, D. R., Tatsuno, M., & McNaughton, B. L. (2010). Stored-trace reactivation in rat prefrontal cortex is correlated with down-to-up state fluctuation density. *Journal of Neuroscience*, *30*(7), 2650–2661. https://doi.org/10.1523/JNEUROSCI.1617-09.2010

Jones & Spencer, R. M. (2019). Sleep preserves subjective and sympathetic emotional response of memories. *Neurobiology of Learning and Memory*, *166*, 107096. https://doi.org/10.1016/j.nlm.2019.107096

Jones, Zhu, Z., Bajracharya, A., Luor, A., & Peelle, J. E. (2022). A multi-dataset evaluation of frame censoring for motion correction in task-based fMRI. *Aperture Neuro*, 1–25. https://doi.org/10.52294/ApertureNeuro.2022.2.NXOR2026

Kandel, R. (2001). The molecular biology of memory storage : A dialogue between genes and synapses. *Science*, *294*, 1030–1039.

Karashima, A., Katayama, N., & Nakao, M. (2007). Phase-locking of spontaneous and tone-elicited pontine waves to hippocampal theta waves during REM sleep in rats. *Brain Research*, *1182*, 73–81. https://doi.org/10.1016/j.brainres.2007.08.060

Kark, S. M., & Kensinger, E. A. (2019). Physiological arousal and visuocortical connectivity predict subsequent vividness of negative memories. *NeuroReport*, *30*(12), 800–804. https://doi.org/10.1097/WNR.0000000000001274

Killgore, W. D. (2010). *Effects of sleep deprivation on cognition* (Vol. 185) [Publication Title: Progress in Brain Research Issue: C ISSN: 00796123]. Elsevier B.V. https://doi.org/10.1016/B978-0-444-53702-7.00007-5

Kim, S. Y., & Payne, J. D. (2020). Neural correlates of sleep, stress, and selective memory consolidation. *Current Opinion in Behavioral Sciences*, *33*, 57–64. https://doi.org/10.1016/j.cobeha.2019.12.009

Knufinke, M., Fittkau-Koch, L., Møst, E. I. S., Kompier, M. A. J., & Nieuwenhuys, A. (2019). Restricting short-wavelength light in the evening to improve sleep in recreational athletes – a pilot study. *European Journal of Sport Science*, *19*(6), 728–735. https://doi.org/10.1080/17461391.2018.1544278

Kounios, J., & Beeman, M. (2014). The cognitive neuroscience of insight. *Annual Review of Psychology*, *65*, 71–93. https://doi.org/10.1146/annurev-psych-010213-115154

Kühnel, J., Bledow, R., & Kiefer, M. (2022). There is a time to be creative: The alignment between chronotype and time of day. *Academy of Management Journal*, *65*(1), 218–247. https://doi.org/10.5465/amj.2019.0020

Kunimatsu, A., Yasaka, K., Akai, H., Kunimatsu, N., & Abe, O. (2020). MRI findings in posttraumatic stress disorder. *Journal of Magnetic Resonance Imaging*, *52*(2), 380–396. https://doi.org/10.1002/jmri.26929

LaBar, K. S., & Cabeza, R. (2006). Cognitive neuroscience of emotional memory. *Nature Reviews Neuroscience*, *7*(1), 54–64. https://doi.org/10.1038/nrn1825

Landmann, N., Kuhn, M., Maier, J.-G., Feige, B., Spiegelhalder, K., Riemann, D., & Nissen, C. (2016). Sleep strengthens but does not reorganize memory traces in a verbal creativity task. *Sleep*, *39*(3), 705–713. https://doi.org/10.5665/sleep.5556

Landmann, N., Kuhn, M., Maier, J.-G., Spiegelhalder, K., Baglioni, C., Frase, L., Riemann, D., Sterr, A., & Nissen, C. (2015). REM sleep and memory reorganization: Potential relevance for psychiatry and psychotherapy. *Neurobiology of Learning and Memory*, *122*, 28–40. https://doi.org/10.1016/j.nlm.2015.01.004

Lang, P., Bradley, M. M., & Cuthbert, B. (2008). *International affective picture system (IAPS): Affective ratings of pictures and instruction manual. technical report a-8.* Gainesville, FL: University of Florida.

Lange, T., Dimitrov, S., & Born, J. (2010). Effects of sleep and circadian rhythm on the human immune system: Annals of the new york academy of sciences [ISBN: 9781573317696]. *Annals of the New York Academy of Sciences*, *1193*, 48–59. https://doi.org/10.1111/j.1749-6632.2009.05300.x

Latchoumane, C.-F. V., Ngo, H.-V. V., Born, J., & Shin, H.-S. (2017). Thalamic spindles promote memory formation during sleep through triple phase-locking of cortical, thalamic, and hippocampal rhythms. *Neuron*, *95*(2), 424–435.e6. https://doi.org/10.1016/j.neuron.2017.06.025

Laventure, S., Fogel, S., Lungu, O., Albouy, G., Sévigny-Dupont, P., Vien, C., Sayour, C., Carrier, J., Benali, H., & Doyon, J. (2016). NREM2 and sleep spindles are instrumental to the consolidation of motor sequence memories (F. P. Battaglia, Ed.). *PLOS Biology*, *14*(3), e1002429. https://doi.org/10.1371/journal.pbio.1002429

Laventure, S., Pinsard, B., Lungu, O., Carrier, J., Fogel, S., Benali, H., Lina, J.-M., Boutin, A., & Doyon, J. (2018). Beyond spindles: Interactions between sleep spindles and boundary frequencies during cued reactivation of motor memory representations. *Sleep*, *41*(9). https://doi.org/10.1093/sleep/zsy142

Lee, A. K., & Wilson, M. A. (2002). Memory of sequential experience in the hippocampus during slow wave sleep. *Neuron*, *36*(6), 1183–1194. https://doi.org/10.1016/S0896-6273(02)01096-6

Léger, D., Debellemaniere, E., Rabat, A., Bayon, V., Benchenane, K., & Chennaoui, M. (2018). Slow-wave sleep: From the cell to the clinic. *Sleep Medicine Reviews*, *41*, 113–132. https://doi.org/10.1016/j.smrv.2018.01.008

Lehmann, M., Schreiner, T., Seifritz, E., & Rasch, B. (2016). Emotional arousal modulates oscillatory correlates of targeted memory reactivation during NREM, but not REM sleep [Publisher: Nature Publishing Group]. *Scientific Reports*, *6*(1), 1–13. https://doi.org/10.1038/srep39229

Lenth, R. (2023). *Emmeans: Estimated marginal means, aka least-squares means.* https://CRAN.R-project.org/package=emmeans

Lewis, P. A., & Durrant, S. J. (2011). Overlapping memory replay during sleep builds cognitive schemata. *Trends in Cognitive Sciences*, *15*(8), 343–351. https://doi.org/10.1016/j.tics.2011.06.004

Lewis, P. A., Knoblich, G., & Poe, G. (2018). How memory replay in sleep boosts creative problem-solving [Publisher: Elsevier Ltd]. *Trends in Cognitive Sciences*, *22*(6), 491–503. https://doi.org/10.1016/j.tics.2018.03.009

Lewy, A. J., Emens, J. S., Songer, J. B., Sims, N., Laurie, A. L., Fiala, S. C., & Buti, A. (2009). Winter depression: Integrating mood, circadian rhythms, and the sleep/wake and light/dark cycles into a bio-psycho-social-environmental model. *Sleep Medicine Clinics*, *4*(2), 285–299. https://doi.org/10.1016/j.jsmc.2009.02.003

Lim, J., & Dinges, D. F. (2008). Sleep deprivation and vigilant attention. *Annals of the New York Academy of Sciences*, *1129*, 305–322. https://doi.org/10.1196/annals.1417.002

Lipinska, G., Stuart, B., Thomas, K. G. F., Baldwin, D. S., & Bolinger, E. (2019). Preferential consolidation of emotional memory during sleep: A meta-analysis. *Frontiers in Psychology*, *10*, 1014. https://doi.org/10.3389/fpsyg.2019.01014

Liu, Y., Dolan, R. J., Kurth-Nelson, Z., & Behrens, T. E. (2019). Human replay spontaneously reorganizes experience. *Cell*, *178*(3), 640–652.e14. https://doi.org/10.1016/j.cell.2019.06.012

Locihová, H., Axmann, K., Padyšáková, H., & Fejfar, J. (2018). Effect of the use of earplugs and eye mask on the quality of sleep in intensive care patients: A systematic review. *Journal of Sleep Research*, *27*(3), 1–12. https://doi.org/10.1111/jsr.12607

Lockley, S., Evans, E., Scheer, F., Brainard, G., Czeisler, C., & Aeschbach, D. (2006). Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. *Sleep*, *29*(2), 161–168. https://doi.org/10.1093/sleep/29.2.161

Loganathan, R. (2014). The role of sleep in motor learning. *Postdoc journal*. https://doi.org/10.14304/surya.jpr.v2n4.2

Louie, K., & Wilson, M. A. (2001). Temporally structured replay of awake hippocampal ensemble activity during rapid eye movement sleep. *Neuron*, *29*(1), 145–156. https://doi.org/10.1016/S0896-6273(01)00186-6

Lovibond, S., & Lovibond, P. (1995). *Manual for the depression anxiety stress scales.* (Psychology Foundation, Ed.).

Lubenov, E. V., & Siapas, A. G. (2009). Hippocampal theta oscillations are travelling waves. *Nature*, *459*(7246), 534–539. https://doi.org/10.1038/nature08010

Lüdecke, D. (2023). *sjPlot: Data visualization for statistics in social science.* https://CRAN.R-project.org/package=sjPlot

Maho, C., & Hennevin, E. (2002). Appetitive conditioning-induced plasticity is expressed during paradoxical sleep in the medial geniculate, but not in the lateral amygdala. *Behavioral Neuroscience*, *116*(5), 807–823. https://doi.org/10.1037/0735-7044.116.5.807

Maingret, N., Girardeau, G., Todorova, R., Goutierre, M., & Zugaro, M. (2016). Hippocampo-cortical coupling mediates memory consolidation during sleep. *Nature Neuroscience*, *19*(7), 959–964. https://doi.org/10.1038/nn.4304

Mair, P., & Wilcox, R. (2020). Robust statistical methods in r using the WRS2 package. *Behavior Research Methods*, *52*(2), 464–488. https://doi.org/10.3758/s13428-019-01246-w

Mangiafico, S. S. (2020). Rcompanion: Functions to support extension education program evaluation [r statistical package].

Maquet, P., Peters, J. M., Aerts, J., Delfiore, G., Degueldre, C., Luxen, A., & Franck, G. (1996). Functional neuroanatomy of human rapid-eye-movement sleep and dreaming. *Nature*, *383*(6596), 163–166. https://doi.org/10.1038/383163a0

Maquet, P., Laureys, S., Peigneux, P., Fuchs, S., Petiau, C., Phillips, C., Aerts, J., Del Fiore, G., Degueldre, C., Meulemans, T., Luxen, A., Franck, G., Van Der Linden, M., Smith, C., & Cleeremans, A. (2000). Experience-dependent changes in cerebral activation during human REM sleep. *Nature Neuroscience*, *3*(8), 831–836. https://doi.org/10.1038/77744

Marr, D. (1971). Simple memory: A theory for archicortex. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *262*(841), 23–81. https://doi.org/10.1098/rstb.1971.0078

Marrosu, F., Portas, C., Mascia, M. S., Casu, M. A., Fà, M., Giagheddu, M., Imperato, A., & Gessa, G. L. (1995). Microdialysis measurement of cortical and hippocampal acetylcholine release during sleep-wake cycle in freely moving cats. *Brain Research*, *671*(2), 329–332. https://doi.org/10.1016/0006-8993(94)01399-3

Marwood, L., Wise, T., Perkins, A. M., & Cleare, A. J. (2018). Meta-analyses of the neural mechanisms and predictors of response to psychotherapy in depression and anxiety. *Neuroscience & Biobehavioral Reviews*, *95*, 61–72. https://doi.org/10.1016/j.neubiorev.2018.09.022

Mason, I. C., Grimaldi, D., Reid, K. J., Warlick, C. D., Malkani, R. G., Abbott, S. M., & Zee, P. C. (2022). Light exposure during sleep impairs cardiometabolic function. *Proceedings of the National Academy of Sciences*, *119*(12), e2113290119. https://doi.org/10.1073/pnas.2113290119

Massimini, M., Huber, R., Ferrarelli, F., Hill, S., & Tononi, G. (2004). The sleep slow oscillation as a traveling wave. *Journal of Neuroscience*, *24*(31), 6862–6870. https://doi.org/10.1523/JNEUROSCI.1318-04.2004

May, C. P., & Hasher, L. (2017). Synchrony affects performance for older but not younger neutral-type adults. *Timing & Time Perception*, *5*(2), 129–148. https://doi.org/10.1163/22134468-00002087

Mayberg, H. S., Liotti, M., Brannan, S. K., McGinnis, S., Mahurin, R. K., Jerabek, P. A., Silva, J. A., Tekell, J. L., Martin, C. C., Lancaster, J. L., & Fox, P. T. (1999). Reciprocal limbic-cortical function and negative mood: Converging PET findings in depression and normal sadness. *American Journal of Psychiatry*, *156*(5), 675–682. https://doi.org/10.1176/ajp.156.5.675

McCaffrey, T. (2012a). *The obscure features hypothesis for innovation: One key to improving performance in insight problems* (Doctoral dissertation). Massachusetts Amherst.

McCaffrey, T. (2012b). Innovation relies on the obscure: A key to overcoming the classic problem of functional fixedness. *Psychological Science*, *23*(3), 215–218. https://doi.org/10.1177/0956797611429580

McCaffrey, T. (2018). *Overcome any obstacle to creativity.* Rowman & Littlefield Publishers.

McCaffrey, T., & Krishnamurty, S. (2015). The obscure features hypothesis in design innovation. *International Journal of Design Creativity and Innovation*, *3*(1), 1–28. https://doi.org/10.1080/21650349.2014.893840

McGaugh. (2000). Memory - a century of consolidation. *Science*, *287*(5451), 248–251. https://doi.org/10.1126/science.287.5451.248

McGaugh. (2004). The amygdala modulates the consolidation of memories of emotionally arousing experiences. *Annual Review of Neuroscience*, *27*, 1–28. https://doi.org/10.1146/annurev.neuro.27.070203.144157

McGaugh & Roozendaal, B. (2002). Role of adrenal stress hormones in forming lasting memories in the brain james l McGaugh and benno roozendaal. *Current opinion in neurobiology*, *12*, 205–210.

Mednick, S., Nakayama, K., & Stickgold, R. (2003). Sleep-dependent learning: A nap is as good as a night. *Nature Neuroscience*, *6*(7), 697–698. https://doi.org/10.1038/nn1078

Mednick, S. (1962). The associative basis of the creative process. *Psychological Review*, *69*(3), 220–232. https://doi.org/10.1037/h0048850

Menz, Rihm, J., Salari, N., Born, J., Kalisch, R., Pape, H. C., Marshall, L., & Büchel, C. (2013). The role of sleep and sleep deprivation in consolidating fear memories. *NeuroImage*, *75*, 87–96. https://doi.org/10.1016/j.neuroimage.2013.03.001

Menz, Rihm, J. S., & Bcüche, C. (2016). Rem sleep is causal to successful consolidation of dangerous and safety stimuli and reduces return of fear after extinction. *Journal of Neuroscience*, *36*(7), 2148–2160. https://doi.org/10.1523/JNEUROSCI.3083-15.2016

Mignot, E. (2008). Why we sleep: The temporal organization of recovery. *PLoS Biology*, *6*(4), 661–669. https://doi.org/10.1371/journal.pbio.0060106

Miyauchi, S., Misaki, M., Kan, S., Fukunaga, T., & Koike, T. (2009). Human brain activity time-locked to rapid eye movements during REM sleep. *Experimental Brain Research*, *192*(4), 657–667. https://doi.org/10.1007/s00221-008-1579-2

Mölle, M., Bergmann, T. O., Marshall, L., & Born, J. (2011). Fast and slow spindles during the sleep slow oscillation: Disparate coalescence and engagement in memory processing. *Sleep*, *34*(10), 1411–1421. https://doi.org/10.5665/SLEEP.1290

Monaghan, P., Sio, U. N., Lau, S. W., Woo, H. K., Linkenauger, S. A., & Ormerod, T. C. (2015). Sleep promotes analogical transfer in problem solving [Publisher: Elsevier B.V.]. *Cognition*, *143*, 25–30. https://doi.org/10.1016/j.cognition.2015.06.005

Morin, Carrier, J., Bastien, C., Godbout, R., & On behalf of the Canadian Sleep and Circadian Network. (2020). Sleep and circadian rhythm in response to the COVID-19 pandemic. *Canadian Journal of Public Health*, *111*(5), 654–657. https://doi.org/10.17269/s41997-020-00382-7

Morin, Doyon, J., Dostie, V., Barakat, M., Tahar, A. H., Korman, M., Benali, H., Karni, A., Ungerleider, L. G., & Carrier, J. (2008). Motor sequence learning increases sleep spindles and fast frequencies in post-training sleep. *Sleep*, *31*(8), 1149–1156. https://doi.org/10.5665/sleep/31.8.1149

Moser, D., Anderer, P., Gruber, G., Parapatics, S., Loretz, E., Boeck, M., Kloesch, G., Heller, E., Schmidt, A., Danker-Hopfe, H., Saletu, B., Zeitlhofer, J., & Dorffner, G. (2009). Sleep classification according to AASM and rechtschaf-

fen and kales: Effects on sleep scoring parameters. *Sleep*, *32*(2), 139–149. https://doi.org/10.1111/j.1365-2869.2009.00785.x

Muehlroth, B. E., Sander, M. C., Fandakova, Y., Grandy, T. H., Rasch, B., Shing, Y. L., & Werkle-Bergner, M. (2019). Precise slow oscillation–spindle coupling promotes memory consolidation in younger and older adults. *Scientific Reports*, *9*(1), 1940. https://doi.org/10.1038/s41598-018-36557-z

Münch, M., Nowozin, C., Regente, J., Bes, F., De Zeeuw, J., Hädel, S., Wahnschaffe, A., & Kunz, D. (2017). Blue-enriched morning light as a countermeasure to light at the wrong time: Effects on cognition, sleepiness, sleep, and circadian phase. *Neuropsychobiology*, *74*(4), 207–218. https://doi.org/10.1159/000477093

Munoz-Rubke, F., Olson, D., Will, R., & James, K. H. (2018). Functional fixedness in tool use: Learning modality, limitations and individual differences. *Acta Psychologica*, *190*, 11–26. https://doi.org/10.1016/j.actpsy.2018.06.006

Murty, V. P., Ritchey, M., Adcock, R. A., & LaBar, K. S. (2010). FMRI studies of successful emotional memory encoding: A quantitative meta-analysis [Publisher: Elsevier Ltd]. *Neuropsychologia*, *48*(12), 3459–3469. https://doi.org/10.1016/j.neuropsychologia.2010.07.030

Nakagawa, S., Johnson, P. C. D., & Schielzeth, H. (2017). The coefficient of determination r2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of The Royal Society Interface, 14*. https://doi.org/https://doi.org/10.1098/rsif.2017.0213

Navarro, D. J. (2015). Learning statistics with r: A tutorial for psychology students and other beginners (version 0.6), danielle navarro university of new south wales [ISBN: 9781326189723], 1–564. http://learningstatisticswithr.comhttp//ua.edu.au/ccs/teaching/lsrhttp://www.lulu.com/content/13570633http://twitter.com/lsrbook

Nir, Y., Staba, R. J., Andrillon, T., Vyazovskiy, V. V., Cirelli, C., Fried, I., & Tononi, G. (2011). Regional slow waves and spindles in human sleep. *Neuron*, *70*(1), 153–169. https://doi.org/10.1016/j.neuron.2011.02.043

Nishida, M., Pearsall, J., Buckner, R. L., & Walker, M. P. (2009). REM sleep, prefrontal theta, and the consolidation of human emotional memory. *Cerebral Cortex*, *19*(5), 1158–1166. https://doi.org/10.1093/cercor/bhn155

O'Keefe, J., & Dostrovsky, J. (1971). The hippocampus as a spatial map. preliminary evidence from unit activity in the freely-moving rat. *Brain Research*, *34*(1), 171–175. https://doi.org/10.1016/0006-8993(71)90358-1

Ong, J. L., Patanaik, A., Poh, J.-H., & Chee, M. W. L. (2018). Auditory stimulation of sleep slow oscillations modulates subsequent memory encoding through altered hippocampal function. *42*(2). https://doi.org/doi:10.1093/sleep/zsy240

Osborne, J., & Waters, E. (2002). Four assumptions of multiple regression that researchers should always test. *Practical Assessment, Research & Evaluation*, *8*.

Oudiette, D., Antony, J. W., & Paller, K. A. (2014). Fear not: Manipulating sleep might help you forget. *Trends in Cognitive Sciences*, *18*(1), 3–4. https://doi.org/10.1016/j.tics.2013.10.003

Oudiette, D., & Paller, K. A. (2013). Upgrading the sleeping brain with targeted memory reactivation [Publisher: Elsevier Ltd]. *Trends in Cognitive Sciences*, *17*(3), 142–149. https://doi.org/10.1016/j.tics.2013.01.006

Ouyang, J. Q., Davies, S., & Dominoni, D. (2018). Hormonally mediated effects of artificial light at night on behavior and fitness: Linking endocrine mechanisms with function. *Journal of Experimental Biology*, *221*(6), jeb156893. https://doi.org/10.1242/jeb.156893

Pace-Schott, E. F., Shepherd, E., Spencer, R. M., Marcello, M., Tucker, M., Propper, R. E., & Stickgold, R. (2011). Napping promotes inter-session habitu-

ation to emotional stimuli. *Neurobiology of Learning and Memory*, *95*(1), 24–36. https://doi.org/10.1016/j.nlm.2010.10.006

Park & Bischof, G. N. (2013). The aging mind: Neuroplasticity in response to cognitive training. *Dialogues in Clinical Neuroscience*, *15*(1), 109–119. Retrieved March 16, 2023, from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3622463/

Park, White, A. J., Jackson, C. L., Weinberg, C. R., & Sandler, D. P. (2019). Association of exposure to artificial light at night while sleeping with risk of obesity in women. *JAMA Internal Medicine*, *179*(8), 1061. https://doi.org/10.1001/jamainternmed.2019.0571

Pavlides, C., & Winson, J. (1989). Influences of hippocampal place cell firing in the awake state on the activity of these cells during subsequent sleep episodes. *9*(8), 2907–2918.

Payne, J. D., Chambers, A. M., & Kensinger, E. A. (2012). Sleep promotes lasting changes in selective memory for emotional scenes. *Frontiers in Integrative Neuroscience*, *6*, 1–51. https://doi.org/10.3389/fnint.2012.00108

Payne, J. D., Schacter, D. L., Propper, R. E., Huang, L. W., Wamsley, E. J., Tucker, M. A., Walker, M. P., & Stickgold, R. (2009). The role of sleep in false memory formation [Publisher: Elsevier Inc.]. *Neurobiology of Learning and Memory*, *92*(3), 327–334. https://doi.org/10.1016/j.nlm.2009.03.007

Payne, J. D., Stickgold, R., Swanberg, K., & Kensinger, E. A. (2008). Sleep preferentially enhances memory for emotional components of scenes. *Psychological Science*, *19*(8), 781–788. https://doi.org/10.1111/j.1467-9280.2008.02157.x

Peever, J., & Fuller, P. M. (2017). The biology of REM sleep [Publisher: Elsevier Ltd]. *Current Biology*, *27*(22), R1237–R1248. https://doi.org/10.1016/j.cub.2017.10.026

Peigneux, P. (2015). Neuroimaging studies of sleep and memory in humans [ISBN: 9783642209246]. *Curr. Top. Behav. Neurosci.*, *25*, 239–268. https://doi.org/10.1007/7854

Peigneux, P., Laureys, S., Fuchs, S., Collette, F., Perrin, F., Reggers, J., Phillips, C., Degueldre, C., Del Fiore, G., Aerts, J., Luxen, A., & Maquet, P. (2004). Are spatial memories strengthened in the human hippocampus during slow wave sleep? *Neuron*, *44*(3), 535–545. https://doi.org/10.1016/j.neuron.2004.10.007

Peigneux, P., Laureys, S., Fuchs, S., Destrebecqz, A., Collette, F., Delbeuck, X., Phillips, C., Aerts, J., Del Fiore, G., Degueldre, C., Luxen, A., Cleeremans, A., & Maquet, P. (2003). Learned material content and acquisition level modulate cerebral reactivation during posttraining rapid-eye-movements sleep. *NeuroImage*, *20*(1), 125–134. https://doi.org/10.1016/S1053-8119(03)00278-7

Peirce, J., Gray, J. R., Simpson, S., Macaskill, M., Höchenberger, R., Sogo, H., Kastman, E., Lindeløv, J. K., & Peirce, J. (2019). PsychoPy2 : Experiments in behavior made easy [Publisher: Behavior Research Methods], *3*, 195–203.

Pereira, S. I. R., & Lewis, P. A. (2020). The differing roles of NREM and REM sleep in the slow enhancement of skills and schemas [Publisher: Elsevier Ltd]. *Current Opinion in Physiology*, *15*, 82–88. https://doi.org/10.1016/j.cophys.2019.12.005

Pereira, S. I. R., Tsimpanouli, M. E., Hutchison, I., Schneider, J., Anderson, I. M., McFarquhar, M., Elliott, R., & Lewis, P. A. (2022). Cueing emotional memories during slow wave sleep modulates next-day activity in the orbitofrontal cortex and the amygdala [Publisher: Elsevier Inc.]. *NeuroImage*, *253*, 119120. https://doi.org/10.1016/j.neuroimage.2022.119120

Peyrache, A., Khamassi, M., Benchenane, K., Wiener, S. I., & Battaglia, F. P. (2009). Replay of rule-learning related neural patterns in the prefrontal

cortex during sleep. *Nature Neuroscience*, *12*(7), 919–926. https://doi.org/10.1038/nn.2337

Phan, K., Wager, T., Taylor, S. F., & Liberzon, I. (2002). Functional neuroanatomy of emotion: A meta-analysis of emotion activation studies in PET and fMRI. *NeuroImage*, *16*(2), 331–348. https://doi.org/10.1006/nimg.2002.1087

Phelps, E. A. (2004). Human emotion and memory: Interactions of the amygdala and hippocampal complex. *Current Opinion in Neurobiology*, *14*(2), 198–202. https://doi.org/10.1016/j.conb.2004.03.015

Phipps-Nelson, J., Redman, J. R., Dijk, D. J., & Rajaratnam, S. M. (2003). Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. *Sleep*, *26*(6), 695–700. https://doi.org/10.1093/sleep/26.6.695

Pizzagalli, D. A. (2011). Frontocingulate dysfunction in depression: Toward biomarkers of treatment response. *Neuropsychopharmacology*, *36*(1), 183–206. https://doi.org/10.1038/npp.2010.166

Poe, G. R., Nitz, D. A., McNaughton, B. L., & Barnes, C. A. (2000). Experience-dependent phase-reversal of hippocampal neuron firing during REM sleep. *Brain Research*, *855*(1), 176–180. https://doi.org/10.1016/S0006-8993(99)02310-0

Popa, D., Duvarci, S., Popescu, A. T., Léna, C., & Paré, D. (2010). Coherent amygdalocortical theta promotes fear memory consolidation during paradoxical sleep. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(14), 6516–6519. https://doi.org/10.1073/pnas.0913016107

Power, J. D., Barnes, K. A., Snyder, A. Z., Schlaggar, B. L., & Petersen, S. E. (2012). Spurious but systematic correlations in functional connectivity MRI networks arise from subject motion. *NeuroImage*, *59*(3), 2142–2154. https://doi.org/10.1016/j.neuroimage.2011.10.018

Prehn-Kristensen, A., Göder, R., Chirobeja, S., Breßmann, I., Ferstl, R., & Baving, L. (2009). Sleep in children enhances preferentially emotional declarative

but not procedural memories [Publisher: Elsevier Inc.]. *Journal of Experimental Child Psychology*, *104*(1), 132–139. https://doi.org/10.1016/j.jecp.2009.01.005

Pronier, É., Morici, J. F., & Girardeau, G. (2023). The role of the hippocampus in the consolidation of emotional memories during sleep. *Trends in Neurosciences*, S0166223623001911. https://doi.org/10.1016/j.tins.2023.08.003

Qin, Y.-L., Mcnaughton, B. L., Skaggs, W. E., & Barnes, C. A. (1997). Memory reprocessing in corticocortical and hippocampocortical neuronal ensembles. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *352*(1360), 1525–1533. https://doi.org/10.1098/rstb.1997.0139

Rasch, B., & Born, J. (2013). About sleep's role in memory. *Physiological Reviews*, *93*(2), 681–766. https://doi.org/10.1152/physrev.00032.2012

Rasch, B., Büchel, C., Gais, S., & Born, J. (2007). Odor cues during slow-wave sleep prompt declarative memory consolidation. *Science*, *315*(5817), 1426–1429. https://doi.org/10.1126/science.1138581

Rauchs, G., Bertran, F., Guillery-Girard, B., Desgranges, B., Kerrouche, N., Denise, P., Foret, J., & Eustache, F. (2004). Consolidation of strictly episodic memories mainly requires rapid eye movement sleep. *Sleep*, *27*(3), 395–401. https://doi.org/10.1093/sleep/27.3.395

Ribeiro, S., Mello, C. V., Velho, T., Gardner, T. J., Jarvis, E. D., & Pavlides, C. (2002). Induction of hippocampal long-term potentiation during waking leads to increased extrahippocampal *zif-268* expression during ensuing rapid-eye-movement sleep. *The Journal of Neuroscience*, *22*(24), 10914–10923. https://doi.org/10.1523/JNEUROSCI.22-24-10914.2002

Rihm, J. S., & Rasch, B. (2015). Replay of conditioned stimuli during late REM and stage n2 sleep influences affective tone rather than emotional memory strength [Publisher: Elsevier Inc.]. *Neurobiology of Learning and Memory*, *122*, 142–151. https://doi.org/10.1016/j.nlm.2015.04.008

Rolls, E. T. (2019). The orbitofrontal cortex and emotion in health and disease, including depression [Publisher: Elsevier Ltd]. *Neuropsychologia*, *128*, 14–43. https://doi.org/10.1016/j.neuropsychologia.2017.09.021

Rolls, E. T. (2023). Emotion, motivation, decision-making, the orbitofrontal cortex, anterior cingulate cortex, and the amygdala. *Brain Structure and Function*, *228*(5), 1201–1257. https://doi.org/10.1007/s00429-023-02644-9

Rolls, E. T., Huang, C.-C., Lin, C.-P., Feng, J., & Joliot, M. (2020). Automated anatomical labelling atlas 3. *NeuroImage*, *206*, 116189. https://doi.org/10.1016/j.neuroimage.2019.116189

Rudebeck, P. H., Putnam, P. T., Daniels, T. E., Yang, T., Mitz, A. R., Rhodes, S. E. V., & Murray, E. A. (2014). A role for primate subgenual cingulate cortex in sustaining autonomic arousal. *Proceedings of the National Academy of Sciences*, *111*(14), 5391–5396. https://doi.org/10.1073/pnas.1317695111

Rudoy, J., Voss, J., Westerberg, C., & Paller, K. (2009). Strengthening individual memories by reactivating them during sleep [ISBN: 6176321972]. *Science*, *23*(1), 1–7. https://doi.org/10.1126/science.1179013

Runco, M. A., & Jaeger, G. J. (2012). The standard definition of creativity. *Creativity Research Journal*, *24*(1), 92–96. https://doi.org/10.1080/10400419.2012.650092

Sanders, K. E., Osburn, S., Paller, K. A., & Beeman, M. (2019). Targeted memory reactivation during sleep improves next-day problem solving. *Psychological Science*, *30*(11), 1616–1624. https://doi.org/10.1177/0956797619873344

Schabus, M., Dang-Vu, T. T., Albouy, G., Balteau, E., Boly, M., Carrier, J., Darsaud, A., Degueldre, C., Desseilles, M., Gais, S., Phillips, C., Rauchs, G., Schnakers, C., Sterpenich, V., Vandewalle, G., Luxen, A., & Maquet, P. (2007). Hemodynamic cerebral correlates of sleep spindles during human non-rapid eye movement sleep. *Proceedings of the National Academy of Sciences*, *104*(32), 13164–13169. https://doi.org/10.1073/pnas.0703084104

Schabus, M., Gruber, G., Parapatics, S., Sauter, C., Klösch, G., Anderer, P., Klimesch, W., Saletu, B., & Zeitlhofer, J. (2004). Sleep spindles and their significance for declarative memory consolidation. *Sleep*, *27*(8), 1479–1485. https://doi.org/10.1093/sleep/27.7.1479

Schmid, D., Erlacher, D., Klostermann, A., Kredel, R., & Hossner, E.-J. (2020). Sleep-dependent motor memory consolidation in healthy adults: A meta-analysis. *Neuroscience & Biobehavioral Reviews*, *118*, 270–281. https://doi.org/10.1016/j.neubiorev.2020.07.028

Schönauer, M., Alizadeh, S., Jamalabadi, H., Abraham, A., Pawlizki, A., & Gais, S. (2017). Decoding material-specific memory reprocessing during sleep in humans. *Nature Communications*, *8*. https://doi.org/10.1038/ncomms15404

Schönauer, M., Geisler, T., & Gais, S. (2013). Strengthening procedural memories by reactivation in sleep. *Journal of Cognitive Neuroscience*, 143–153. https://doi.org/10.1162/jocn

Schönauer, M., & Pöhlchen, D. (2018). Sleep spindles [Publisher: Elsevier]. *Current Biology*, *28*(19), R1129–R1130. https://doi.org/10.1016/j.cub.2018.07.035

Schreiner, T., Petzka, M., Staudigl, T., & Staresina, B. P. (2021). Endogenous memory reactivation during sleep in humans is clocked by slow oscillation-spindle complexes. *Nature Communications*, *12*(1), 3112. https://doi.org/10.1038/s41467-021-23520-2

Schreiner, T., & Rasch, B. (2015). Boosting vocabulary learning by verbal cueing during sleep. *Cerebral Cortex*, *25*(11), 4169–4179. https://doi.org/10.1093/cercor/bhu139

Schreiner, T., & Staudigl, T. (2020). Electrophysiological signatures of memory reactivation in humans. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1799). https://doi.org/10.1098/rstb.2019.0293

Schwartz, S., Clerget, A., & Perogamvros, L. (2022). Enhancing imagery rehearsal therapy for nightmares with targeted memory reactivation. *Current Biology*, *32*(22), 4808–4816.e4. https://doi.org/10.1016/j.cub.2022.09.032

Seeley, W. W., Menon, V., Schatzberg, A. F., Keller, J., Glover, G. H., Kenna, H., Reiss, A. L., & Greicius, M. D. (2007). Dissociable intrinsic connectivity networks for salience processing and executive control. *The Journal of Neuroscience*, *27*(9), 2349–2356. https://doi.org/10.1523/JNEUROSCI.5587-06.2007

Seibt, J., & Frank, M. G. (2019). Primed to sleep: The dynamics of synaptic plasticity across brain states. *Frontiers in Systems Neuroscience*, *13*, 2. https://doi.org/10.3389/fnsys.2019.00002

Shimizu, R. E., Connolly, P. M., Cellini, N., Armstrong, D. M., Hernandez, L. T., Estrada, R., Aguilar, M., Weisend, M. P., Mednick, S. C., & Simons, S. B. (2018). Closed-loop targeted memory reactivation during sleep improves spatial navigation. *Frontiers in Human Neuroscience*, *12*, 28. https://doi.org/10.3389/fnhum.2018.00028

Siapas, A. G., Lubenov, E. V., & Wilson, M. A. (2005). Prefrontal phase locking to hippocampal theta oscillations. *Neuron*, *46*(1), 141–151. https://doi.org/10.1016/j.neuron.2005.02.028

Siegel, J. M. (2008). Do all animals sleep? *Trends in Neurosciences*, *31*(4), 208–213. https://doi.org/10.1016/j.tins.2008.02.001

Silber, M. H., Ancoli-Israel, S., Bonnet, M. H., Chokroverty, S., Grigg-Damberger, M. M., Hirshkowitz, M., Kapen, S., Keenan, S. A., Kryger, M. H., Penzel, T., Pressman, M. R., & Iber, C. (2007). The visual scoring of sleep in adults. *Journal of Clinical Sleep Medicine*, *3*(2), 121–131. https://doi.org/10.5664/jcsm.26814

Simor, P., van der Wijk, G., Nobili, L., & Peigneux, P. (2020). The microstructure of REM sleep: Why phasic and tonic? [Publisher: Elsevier Ltd]. *Sleep Medicine Reviews*, *52*, 101305. https://doi.org/10.1016/j.smrv.2020.101305

Sio, U. N., Monaghan, P., & Ormerod, T. (2013). Sleep on it, but only if it is difficult: Effects of sleep on problem solving. *Memory and Cognition*, *41*(2), 159–166. https://doi.org/10.3758/s13421-012-0256-7

Sio, U. N., & Ormerod, T. C. (2009). Does incubation enhance problem solving? a meta-analytic review. *Psychological Bulletin*, *135*(1), 94–120. https://doi.org/10.1037/a0014212

Siraji, M. A., Spitschan, M., Kalavally, V., & Haque, S. (2023). Light exposure behaviors predict mood, memory and sleep quality. *Scientific Reports*, *13*(1), 12425. https://doi.org/10.1038/s41598-023-39636-y

Skaggs, W. E., & McNaughton, B. L. (1996). Replay of neuronal firing sequences in rat hippocampus during sleep following spatial experience. *Science*, *271*(5257), 1870–1873. https://doi.org/10.1126/science.271.5257.1870

Sleegers, P., Moolenaar, N., Galetzka, M., Pruyn, A., Sarroukh, B., & Van Der Zande, B. (2013). Lighting affects students' concentration positively: Findings from three dutch studies. *Lighting Research & Technology*, *45*(2), 159–175. https://doi.org/10.1177/1477153512446099

Smith, C. (2001). Sleep states and memory processes in humans: Procedural versus declarative memory systems. *Sleep Medicine Reviews*, *5*(6), 491–506. https://doi.org/10.1053/smrv.2001.0164

Smith, C., & Weeden, K. (1990). Post training REMs coincident auditory stimulation enhances memory in humans. *Psychiatric Journal of the University of Ottawa*, *15*(2), 85–90.

Squire, L. R., & Alvarez, P. (1995). Retrograde amnesia and memory consolidation: A neurobiological perspective. *Current Opinion in Neurobiology*, *5*(2), 169–177. https://doi.org/10.1016/0959-4388(95)80023-9

Squire, L. R., & Dede, A. J. (2015). Conscious and unconscious memory systems [ISBN: 9781119132363]. *Cold Spring Harb Perspect Biol.*, *7*(3). https://doi.org/10.1002/9781119132363.ch40

Squire, L. R., & Zola, S. M. (1996). Structure and function of declarative and nondeclarative memory systems. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(24), 13515–13522. https://doi.org/10.1073/pnas.93.24.13515

Steriade, M., Amzica, F., & Contreras, D. (1996). Synchronization of fast (30-40 hz) spontaneous cortical rhythms during brain activation. *The Journal of Neuroscience*, *16*(1), 392–417. https://doi.org/10.1523/JNEUROSCI.16-01-00392.1996

Sterpenich, V., Schmidt, C., Albouy, G., Matarazzo, L., Vanhaudenhuyse, A., Boveroux, P., Degueldre, C., Leclercq, Y., Balteau, E., Collette, F., Luxen, A., Phillips, C., & Maquet, P. (2014). Memory reactivation during rapid eye movement sleep promotes its generalization and integration in cortical stores. *Sleep*, *37*(6), 1061–1075. https://doi.org/10.5665/sleep.3762

Stevens, F. L. (2011). Anterior cingulate cortex: Unique role in cognition and emotion. *J Neuropsychiatry Clin Neurosci*, 6.

Stickgold, R., & Walker, M. P. (2013). Sleep-dependent memory triage: Evolving generalization through selective processing HHS public access author manuscript. *Nature Neuroscience Neurosci*, *16*(2), 139–145. https://doi.org/10.1038/nn.3303.Sleep-dependent

Stickgold, R., Whidbee, D., Schirmer, B., Patel, V., & Hobson, J. A. (2000). Visual discrimination task improvement: A multi-step process occurring during sleep. *Journal of Cognitive Neuroscience*, *12*(2), 246–254. https://doi.org/10.1162/089892900562075

Storm, B. C., Ditta, A. S., & George, T. (2020). Memory. In *Encyclopedia of creativity* (pp. 116–120). Elsevier. https://doi.org/10.1016/B978-0-12-809324-5.06232-5

Strigo, I. A., & Craig, D. (2016). Interoception, homeostatic emotions and sympathovagal balance. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*, 9. https://doi.org/http://dx.doi.org/10.1098/rstb.2016.0010

Tamminen, J., Payne, J. D., Stickgold, R., Wamsley, E. J., & Gaskell, M. G. (2010). Sleep spindle activity is associated with the integration of new

memories and existing knowledge. *Journal of Neuroscience*, *30*(43), 14356–14360. https://doi.org/10.1523/JNEUROSCI.3028-10.2010

Tasali, E., Leproult, R., Ehrmann, D. A., & Cauter, E. V. (2008). *Sciences of the USA 1044-1049 PNAS* [Volume: 105 Issue: 3].

Tempesta, D., De Gennaro, L., Natale, V., & Ferrara, M. (2015). Emotional memory processing is influenced by sleep quality [Publisher: Elsevier B.V.]. *Sleep Medicine*, *16*(7), 862–870. https://doi.org/10.1016/j.sleep.2015.01.024

Tononi, G., & Cirelli, C. (2003). Sleep and synaptic homeostasis: A hypothesis [ISBN: 1608263606]. *Brain Research Bulletin*, *62*(2), 143–150. https://doi.org/10.1016/j.brainresbull.2003.09.004

Tononi, G., & Cirelli, C. (2006). Sleep function and synaptic homeostasis. *Sleep Medicine Reviews*, *10*(1), 49–62. https://doi.org/10.1016/j.smrv.2005.05.002

Tononi, G., & Cirelli, C. (2014). Sleep and the price of plasticity: From synaptic and cellular homeostasis to memory consolidation and integration [Publisher: Elsevier Inc.]. *Neuron*, *81*(1), 12–34. https://doi.org/10.1016/j.neuron.2013.12.025

Tse, D., Langston, R. F., Kakeyama, M., Bethus, I., Spooner, P. A., Wood, E. R., Witter, M. P., & Morris, R. G. (2007). Schemas and memory consolidation. *Science*, *316*(5821), 76–82. https://doi.org/10.1126/science.1135935

Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., & Joliot, M. (2002). Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. *NeuroImage*, *15*(1), 273–289. https://doi.org/10.1006/nimg.2001.0978

Ulrich, D. (2016). Sleep spindles as facilitators of memory formation and learning [Publisher: Hindawi Publishing Corporation]. *Neural Plasticity*, *2016*. https://doi.org/10.1155/2016/1796715

Van Cauter, E., Spiegel, K., Tasali, E., & Leproult, R. (2008). Metabolic consequences of sleep and sleep loss. *Sleep Medicine*, *9*, 23–28. https://doi.org/10.1016/S1389-9457(08)70013-3

Van Der Werf, Y. D., Altena, E., Schoonheim, M. M., Sanz-Arigita, E. J., Vis, J. C., De Rijke, W., & Van Someren, E. J. (2009). Sleep benefits subsequent hippocampal functioning. *Nature Neuroscience*, *12*(2), 122–123. https://doi.org/10.1038/nn.2253

Van Der Werf, Y. D., Altena, E., Vis, J. C., Koene, T., & Van Someren, E. J. (2011). Reduction of nocturnal slow-wave activity affects daytime vigilance lapses and memory encoding but not reaction time or implicit learning [ISBN: 9780444538390]. *Progress in Brain Research*, *193*, 245–255. https://doi.org/10.1016/B978-0-444-53839-0.00016-8

van der Heijden, A., van den Heuvel, O., van der Werf, Y., Talamini, L., & van Marle, H. (2022). Sleep as a window to target traumatic memories. *Neuroscience & Biobehavioral Reviews*, *140*, 104765. https://doi.org/10.1016/j.neubiorev.2022.104765

van der Helm, E., Yao, J., Dutt, S., Rao, V., Saletin, J. M., & Walker, M. P. (2011). REM sleep depotentiates amygdala activity to previous emotional experiences. *Current Biology*, *21*(23), 2029–2032. https://doi.org/10.1016/j.cub.2011.10.052

Van Kesteren, M. T., Fernández, G., Norris, D. G., & Hermans, E. J. (2010). Persistent schema-dependent hippocampal-neocortical connectivity during memory encoding and postencoding rest in humans. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(16), 7550–7555. https://doi.org/10.1073/pnas.0914892107

Van Kesteren, M. T., Rijpkema, M., Ruiter, D. J., & Fernández, G. (2010). Retrieval of associative information congruent with prior knowledge is related to increased medial prefrontal activity and connectivity. *Journal of Neuro-*

science, *30*(47), 15888–15894. https://doi.org/10.1523/JNEUROSCI.2674-10.2010

Vandewalle, G., Gais, S., Schabus, M., Balteau, E., Carrier, J., Darsaud, A., Sterpenich, V., Albouy, G., Dijk, D. J., & Maquet, P. (2007). Wavelength-dependent modulation of brain responses to a working memory task by daytime light exposure. *Cerebral Cortex*, *17*(12), 2788–2795. https://doi.org/10.1093/cercor/bhm007

Vankov, I., Bowers, J., & Munafò, M. R. (2014). Article commentary: On the persistence of low power in psychological science. *Quarterly Journal of Experimental Psychology*, *67*(5), 1037–1040. https://doi.org/10.1080/17470218.2014.885986

Volk, S., Lowe, K. B., & Barnes, C. M. (2023). Circadian leadership: A review and integration of chronobiology and leadership. *Journal of Organizational Behavior*, *44*(2), 180–201. https://doi.org/10.1002/job.2659

Vuilleumier, P., Armony, J. L., Driver, J., & Dolan, R. J. (2001). Effects of attention and emotion on face processing in the human brain: An event-related fMRI study. *Neuron*, *30*, 829–841.

Wagner, U., Gais, S., & Born, J. (2001). Emotional memory formation is enhanced across sleep intervals with high amounts of rapid eye movement sleep [ISBN: 4945150036]. *Learning and Memory*, *8*(2), 112–119. https://doi.org/10.1101/lm.36801

Wagner, U., Gais, S., Haider, H., Verleger, R., & Born, J. (2004). Sleep inspires insight. *Nature*, *427*(6972), 352–355. https://doi.org/10.1038/nature02223

Wagner, U., Hallschmid, M., Rasch, B., & Born, J. (2006). Brief sleep after learning keeps emotional memories alive for years. *Biological Psychiatry*, *60*(7), 788–790. https://doi.org/10.1016/j.biopsych.2006.03.061

Wagner, U., Kashyap, N., Diekelmann, S., & Born, J. (2007). The impact of post-learning sleep vs. wakefulness on recognition memory for faces with different

facial expressions. *Neurobiology of Learning and Memory*, *87*(4), 679–687. https://doi.org/10.1016/j.nlm.2007.01.004

Walker. (2009). The role of sleep in cognition and emotion [ISBN: 9781573317528]. *Annals of the New York Academy of Sciences*, *1156*, 168–197. https://doi.org/10.1111/j.1749-6632.2009.04416.x

Walker, Brakefield, T., Morgan, A., Hobson, J. A., & Stickgold, R. (2002). Practice with sleep makes perfect: Sleep-dependent motor skill learning. *Neuron*, *35*(1), 205–211. https://doi.org/10.1016/S0896-6273(02)00746-8

Walker, W. H., Walton, J. C., DeVries, A. C., & Nelson, R. J. (2020). Circadian rhythm disruption and mental health. *Translational Psychiatry*, *10*(1), 28. https://doi.org/10.1038/s41398-020-0694-0

Wams, E. J., Woelders, T., Marring, I., Van Rosmalen, L., Beersma, D. G., Gordijn, M. C., & Hut, R. A. (2017). Linking light exposure and subsequent sleep: A field polysomnography study in humans. *Sleep*, *40*(12). https://doi.org/10.1093/sleep/zsx165

Warton, D. I., Lyons, M., Stoklosa, J., & Ives, A. R. (2016). Three points to consider when choosing a LM or GLM test for count data (H. Schielzeth, Ed.). *Methods in Ecology and Evolution*, *7*(8), 882–890. https://doi.org/10.1111/2041-210X.12552

Wassing, R., Lakbila-Kamal, O., Ramautar, J. R., Stoffers, D., Schalkwijk, F., & Van Someren, E. J. (2019). Restless REM sleep impedes overnight amygdala adaptation. *Current Biology*, *29*(14), 2351–2358.e4. https://doi.org/10.1016/j.cub.2019.06.034

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: The PANAS scales. *Journal of Personality and Social Psychology*, *54*(6), 1063–1070. https://doi.org/10.1037/0022-3514.54.6.1063

Weisberg, R. W. (2006). *Creativity: Understanding innovation in problem solving, science, invention, and the arts*. John Wiley & Sons, Inc., Hoboken, New Jersey.

Werner, G. G., Schabus, M., Blechert, J., & Wilhelm, F. H. (2021). Differential effects of REM sleep on emotional processing: Initial evidence for increased short-term emotional responses and reduced long-term intrusive memories. *Behavioral Sleep Medicine*, *19*(1), 83–98. https://doi.org/10.1080/15402002.2020.1713134

Whalen, P. J., Rauch, S. L., Etcoff, N. L., McInerney, S. C., Lee, M. B., & Jenike, M. A. (1998). Masked presentations of emotional facial expressions modulate amygdala activity without explicit knowledge. *The Journal of Neuroscience*, *18*(1), 411–418. https://doi.org/10.1523/JNEUROSCI.18-01-00411.1998

Whitmore, N. W., Harris, J. C., Kovach, T., & Paller, K. A. (2022). Improving memory via automated targeted memory reactivation during sleep. *Journal of Sleep Research*, *31*(6). https://doi.org/10.1111/jsr.13731

Wickham, H. (2009). Ggplot2 elegant graphics for data analysis [ISBN: 9780387981406]. *Media*, *35*, 211. http://had.co.nz/ggplot2/book

Wieth, M. B., & Zacks, R. T. (2011). Time of day effects on problem solving: When the non-optimal is optimal. *Thinking & Reasoning*, *17*(4), 387–401. https://doi.org/10.1080/13546783.2011.625663

Wilhelm, I., Kurth, S., Ringli, M., Mouthon, A.-L., Buchmann, A., Geiger, A., Jenni, O. G., & Huber, R. (2014). Sleep slow-wave activity reveals developmental changes in experience-dependent plasticity. *The Journal of Neuroscience*, *34*(37), 12568–12575. https://doi.org/10.1523/JNEUROSCI.0962-14.2014

Willenbockel, V., Sadr, J., Fiset, D., Horne, G. O., Gosselin, F., & Tanaka, J. W. (2010). Controlling low-level image properties: The SHINE toolbox. *Behav-*

ior research methods, *42*(3), 671–84. https://doi.org/10.3758/BRM.42.3.671

Williams, S. E., Ford, J. H., & Kensinger, E. A. (2022). The power of negative and positive episodic memories. *Cognitive, Affective, & Behavioral Neuroscience*, *22*(5), 869–903. https://doi.org/10.3758/s13415-022-01013-z

Wilson, M., & McNaughton, B. (1994). Reactivation of hippocampal ensemble memories during sleep. *Science*, *265*(5172), 676–679.

Yang, S.-R., Sun, H., Huang, Z.-L., Yao, M.-H., & Qu, W.-M. (2012). Repeated sleep restriction in adolescent rats altered sleep patterns and impaired spatial learning/memory ability. *Sleep*, *35*(6), 849–859. https://doi.org/10.5665/sleep.1888

Yoo, S. S., Hu, P. T., Gujar, N., Jolesz, F. A., & Walker, M. P. (2007). A deficit in the ability to form new human memories without sleep. *Nature Neuroscience*, *10*(3), 385–392. https://doi.org/10.1038/nn1851

Yotsumoto, Y., Sasaki, Y., Chan, P., Vasios, C. E., Bonmassar, G., Ito, N., Náñez, J. E., Shimojo, S., & Watanabe, T. (2009). Location-specific cortical activation changes during sleep after training for perceptual learning. *Current Biology*, *19*(15), 1278–1282. https://doi.org/10.1016/j.cub.2009.06.011

Zeng, S., Lin, X., Wang, J., & Hu, X. (2021). Sleep's short-term memory preservation and long-term affect depotentiation effect in emotional memory consolidation: Behavioral and EEG evidence. *Sleep*, *44*(11), 1–14. https://doi.org/10.1093/sleep/zsab155

Zhang, H., Fell, J., & Axmacher, N. (2018). Electrophysiological mechanisms of human memory consolidation. *Nature Communications*, *9*(1), 4103. https://doi.org/10.1038/s41467-018-06553-y

Zhou, Y., Lai, C. S. W., Bai, Y., Li, W., Zhao, R., Yang, G., Frank, M. G., & Gan, W. B. (2020). REM sleep promotes experience-dependent dendritic spine elimination in the mouse cortex [Publisher: Springer US]. *Nature Communications*, *11*(1), 1–12. https://doi.org/10.1038/s41467-020-18592-5

Zielinski, M. R., McKenna, J. T., & McCarley, R. W. (2016). Functions and mechanisms of sleep. *AIMS Neuroscience*, *3*(1), 67–104. https://doi.org/10.3934/Neuroscience.2016.1.67