

The Impact of Sleep on Creative Problem Solving: A Memory Reconsolidation-Based Explanation

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Abstract

Sleep facilitates creative problem-solving by influencing memory reorganization. Specifically, rapid eye movement (REM) sleep primarily enhances novel associations between memories, whereas non-rapid eye movement (NREM) sleep facilitates rule extraction, relational memory formation, and memory consolidation. The degree to which sleep influences creative problem-solving is modulated by variations in sleep architecture, memory manipulation during sleep, and task types. Among current theoretical explanations for sleep's impact on creative problem-solving, increased spreading activation during sleep has received less attention, while system- and cellular-level accounts have become mainstream, including hippocampal-neocortical dialogue during sleep, synaptic downscaling, and overlapping alternating memory replay. Through these mechanisms, sleep promotes memory reorganization, thereby facilitating creative problem-solving. Future research should broaden its scope by varying the types of problems requiring creative solutions and deepen mechanistic investigations based on cross-modal transfer between emotional memory and memory representations.

Full Text

The Impact of Sleep on Creative Problem-Solving: An Interpretation Based on Memory Reorganization

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Abstract: Sleep facilitates creative problem-solving by influencing memory reorganization. Specifically, rapid eye movement (REM) sleep primarily enhances novel associations between memories, while non-rapid eye movement (NREM) sleep aids in rule extraction, relational memory formation, and memory integration. The degree to which sleep influences creative problem-solving is further

moderated by changes in sleep architecture, manipulation of memories during sleep, and task type. Among current theoretical explanations, the notion of increased spreading activation during sleep has received less attention, with system- and cellular-level mechanisms becoming mainstream. These include hippocampal-neocortical dialogue, synaptic downscaling, and overlapping memory replay across sleep stages. Through these mechanisms, sleep promotes memory reorganization, thereby aiding creative problem-solving. Future research should expand its scope by diversifying the types of problems requiring creative solutions, while deepening mechanistic investigations through the lens of emotional memory and cross-modal transfer between memory representations.

Keywords: sleep, memory reorganization, creative problem-solving

Sleep is essential for physical and mental health and normal development. Sleep deprivation negatively affects attentional processing, executive function, long-term memory, and emotional processing [?, ?, ?, ?, ?]. Sleep quality also serves as an important predictor of emotional states; for instance, anhedonia in patients with moderate to severe depression significantly correlates with rapid eye movement sleep latency (REML), enabling REML to serve as a biological marker for diagnosing certain depression subtypes [?, ?]. Given sleep's critical role in individual development and its clinical applications, it is necessary to strengthen our understanding of the relationship between sleep and cognitive processing.

Research has found that sleep facilitates creative problem-solving when individuals encounter difficult problems [?, ?, ?]. Creative problem-solving involves the sudden emergence of solutions following a reconstruction of problem understanding, achieved by searching for indirectly relevant and non-obvious information that transcends the original problem representation [?, ?, ?]. Researchers' interest in sleep's role stems from two lines of evidence: behavioral studies show that sleep deprivation impairs executive function, whose shifting and inhibition subsystems are closely related to creative thinking [?, ?], suggesting that sleep deprivation may negatively impact creative problem-solving; and neurophysiological findings reveal that the mesolimbic dopaminergic system (ML-DA) is activated during sleep, providing a neural substrate for cognitive processing. Specifically, activation of the ventral tegmental area (VTA) projects to the hippocampus, which can reposition thinking to facilitate creative output, while elevated dopamine levels during sleep also support creative thinking [?, ?, ?, ?]. These findings establish a preliminary link between sleep and creative problem-solving.

However, controversy remains regarding how sleep influences creative problem-solving. One perspective attributes creative problem-solving to incubation, suggesting that ceasing conscious thought about a problem during an incubation period facilitates solutions, with sleep providing a state similar to incubation [?, ?]. Yet more research indicates that sleep has unique effects beyond incubation: sleep promotes creative problem-solving by facilitating memory reorganization [?, ?]. The representational change theory, which explains creative

problem-solving, posits that difficulty in finding creative solutions stems from inappropriate heuristics in the initial problem representation that lead to an erroneous problem search space. This requires constraint relaxation to transform the problem representation and obtain the correct search space [?, ?]. Thus, creative problem-solving involves two stages: search and reconstruction. The search stage relies on general cognitive abilities such as attention and working memory to explore the problem space based on the original representation, whereas the reconstruction stage reorganizes the original representation to activate the correct problem space. Reconstruction is the critical phase of creative problem-solving and primarily depends on memory reorganization. Since sleep facilitates memory reorganization [?, ?], it may aid creative problem-solving by influencing this reconstruction stage.

Different sleep stages exert distinct effects on creative problem-solving, and the impact of sleep is not uniform, being influenced by participant characteristics, task features, and levels of memory reorganization. This paper aims to synthesize existing research to clarify the mechanisms through which sleep affects creative problem-solving and elucidate the relationships among sleep, memory reorganization, and creative problem-solving. Theoretically, this effort will provide support for representational change theory from a sleep perspective while expanding research on the relationship between sleep and higher-order cognitive processing. Through systematic review of existing theories, it will deepen feasible research directions for theoretical mechanisms. Practically, by manipulating memory reorganization processes, it may be possible to develop more applications of sleep in creative problem-solving and related domains.

2. The Impact of Sleep on Creative Problem-Solving

Sleep consists of rapid eye movement (REM) and non-rapid eye movement (NREM) stages. After falling asleep, individuals first enter NREM sleep, which lasts 60-90 minutes, followed by REM sleep. Different sleep stages influence creative problem-solving differently by affecting distinct forms of memory reorganization. Memory reorganization refers to the flexible combination of memories to generate new memories not directly experienced [?, ?], often occurring alongside memory consolidation. The multi-process model posits that memory reorganization includes three forms: schema formation, integration, and decomposition. Schemas are frameworks that organize memory information. Schema formation primarily manifests as rule extraction; schema integration involves combining new and old memory information to form relational memory; and schema decomposition breaks down existing frameworks to form novel associations [?, ?]. Different sleep stages influence these different forms of memory reorganization, thereby facilitating creative problem-solving.

2.1 The Impact of REM Sleep on Creative Problem-Solving

During REM sleep, individuals lose voluntary control of consciousness, exhibit reduced focused attention, and shift from deliberate logical analysis to a highly

associative mode of thought. This supports the formation of unexpected connections between memory elements and generates intuitive, novel problem solutions [?, ?, ?]. Consequently, REM sleep primarily facilitates memory reorganization by strengthening and creating new associations between memories, thereby helping solve problems requiring associative thinking.

The indirect or non-obvious connections between memory representations can hinder reconstruction of original memory representations, and REM sleep's facilitation of association aids this reconstruction process. This is evident in semantic priming effects, where responses to target words are faster when preceded by semantically related primes. Generally, stronger associations produce stronger priming effects, making semantic priming a valuable measure of associative thinking. One study required participants to complete semantic priming tasks before and after sleep, as well as after being awakened from REM and NREM sleep, while manipulating the strength of associations between primes and targets (none, strong, weak). Results showed that before sleep and after NREM awakenings, participants exhibited stronger priming effects for strong associations, whereas after REM awakenings, priming effects were stronger for weak associations [?, ?]. Awakening from sleep often produces sleep inertia, maintaining characteristics of the pre-awakening sleep state. Conducting semantic priming tasks immediately after awakening thus avoids artificially separating sleep from cognitive activities occurring during sleep, establishing a direct link between sleep stages and cognitive processes. These findings demonstrate that REM sleep enhances associative thinking by strengthening connections between memory representations, thereby facilitating creative problem-solving.

This effect also manifests in remote association ability, as evidenced by improved performance on the Remote Associates Test (RAT). The RAT is a classic measure of creative problem-solving that presents participants with three unrelated words and asks them to find a fourth word that connects all three. One study required participants to complete RAT items in pre- and post-tests, categorizing post-test items as repeated-exposure, no-exposure, or primed-exposure based on whether they had been presented before. Additionally, a word analogy task was administered after the pre-test to provide priming words for some RAT items in the post-test. Participants were assigned to no-sleep, REM-nap, or NREM-nap groups between tests. Using a 3 (exposure type) \times 3 (sleep condition) mixed design with sleep condition as a between-subjects factor, the study compared RAT solution rates. Results revealed that for primed-exposure items, solution rates increased by 40% in the REM-nap condition, with no significant improvement in the other conditions. For repeated-exposure items, all groups showed improvement without significant differences, while no-exposure items showed no significant improvement across conditions [?, ?]. By establishing priming conditions before sleep and comparing solution rates across three exposure conditions, this study provided a reasonable explanation for how REM sleep facilitates creative problem-solving by forming novel connections: priming words presented before sleep are incorporated into the memory network and produce stronger spreading activation during REM sleep, activating weaker related connections

and forming new associative networks. Upon re-encountering the problem after sleep, task stimuli are reinterpreted based on this new network, establishing novel connections with solutions and facilitating creative problem-solving.

Thus, when a difficult problem is presented before sleep, REM sleep helps process problem representations by strengthening connections between them. The less obvious and direct the initial connections, the more novel the associations between memory representations become. These associations are unconsciously retained and successfully activated when the problem is encountered again after sleep, emerging as creative solutions [?, ?].

2.2 The Impact of NREM Sleep on Creative Problem-Solving

Traditionally, NREM sleep is divided into four stages, with stages three and four collectively known as slow-wave sleep (SWS). During NREM sleep, individuals generate logically sound problem-solving methods based on existing memories [?, ?]. This stage typically facilitates rule extraction, relational memory formation, and memory integration to accomplish memory reorganization and promote creative problem-solving.

2.2.1 NREM Sleep Facilitates Rule Extraction NREM sleep facilitates rule extraction, particularly the transformation of rules from implicit to explicit knowledge. Rule extraction involves stripping away unnecessary details based on existing problem rules to enable rapid problem resolution. The number reduction task (NRT) is commonly used to investigate how rule extraction aids creative problem-solving. In this task, participants must reduce a sequence of numbers according to given rules, with the final digit serving as the answer. A hidden rule exists: the second digit of the reduced sequence matches the final digit. If participants extract this hidden rule, it indicates memory reorganization has occurred, allowing them to solve the problem creatively rather than through digit-by-digit reduction. The NRT enables clear determination of whether creative problem-solving occurs through memory reorganization and, through reaction times, reveals whether participants' knowledge state is implicit or explicit.

Wagner et al. (2004) first demonstrated that sleep facilitates creative problem-solving through memory reorganization using the NRT. By controlling for 8-hour nighttime sleep, nighttime wakefulness, and daytime wakefulness conditions, they examined whether participants could use the hidden rule in post-tests. Results showed that the sleep group had twice as many participants gain insight into the hidden rule compared to both wake groups, indicating that individuals reprocessed task representations acquired before sleep, promoting their reorganization to extract the hidden rule and facilitate creative problem-solving. However, this study did not specify the role of individual sleep stages.

Subsequent research addressed this limitation by controlling exposure to REM sleep and SWS through sleep timing to clarify specific stage contributions. Re-

sults showed that approximately half of participants had acquired implicit knowledge of the rule before sleep. More participants in the SWS condition transformed this implicit knowledge into explicit knowledge, while those in the REM condition mostly maintained implicit knowledge [?, ?]. EEG data also indicated that increased alpha and beta activity during SWS predicted the transformation of knowledge states and acquisition of explicit knowledge after sleep [?, ?]. These findings provide behavioral and physiological evidence that NREM sleep facilitates creative problem-solving by transforming implicit knowledge about rules into explicit knowledge, enabling conscious rule application.

Studies using the serial reaction time task (SRTT) also support NREM sleep's role in rule extraction. While the SRTT is commonly used to investigate rule extraction, its results can inform creative problem-solving. In this task, four locations corresponding to response keys are presented sequentially according to a fixed pattern. Reaction time reductions indicate implicit knowledge acquisition, while explicit knowledge is assessed through participants' ability to report the sequence. Although the SRTT separates rule extraction from conscious application, making it more complex and less intuitive than the NRT, research using this task supports sleep's role: when implicit knowledge is acquired before sleep, higher amounts of SWS and sleep spindles correlate with explicit knowledge acquisition [?, ?, ?]. NREM sleep helps transform implicitly acquired rules into explicit states, enabling conscious application of hidden rules to solve problems creatively. However, since acquiring implicit knowledge before sleep is not a prerequisite for subsequent rule use, whether conscious rule application after sleep without pre-sleep implicit knowledge involves NREM sleep and shares mechanisms with knowledge state transformation warrants further investigation.

2.2.2 NREM Sleep Facilitates Relational Memory Formation NREM sleep facilitates the formation of relational memory, which involves identifying commonalities between independent memory representations and using these commonalities as binding nodes to create new, direct connections not previously taught but derived through logical inference [?, ?]. The emergence of relational memory constitutes a form of memory reorganization that helps transform problem representations and facilitates creative problem-solving.

One study used an associative inference task to demonstrate NREM sleep's role in relational memory formation. Participants memorized paired object-face images during learning, with each object sequentially paired with two faces. After a nap or equivalent wake interval, they selected face images associated with a given face during retrieval. Successfully matching two face images indicated relational memory formation between them. Although not a creative problem-solving task per se, successful performance required selecting new creative connections between faces, making it a valid indicator of creative problem-solving. Results showed that the nap group outperformed the wake group in relational memory, with NREM duration significantly correlating with performance

and SWS predicting relational memory [?, ?]. Notably, this type of relational memory resembles novel associations between memories, but closer comparison with REM sleep's role reveals important differences: REM sleep associations form through enhanced activation of existing memories, where pre-sleep representations establish connections with infrequently used representations due to increased spreading activation, promoting associations independent of the hippocampus. In contrast, NREM sleep associations form through processing newly acquired memories, highlighting commonalities between pre-sleep representations to create new connections that depend on the hippocampus. This again supports the view that REM sleep tends to generate solutions through association, while NREM sleep tends to generate solutions through logical reasoning.

However, recent studies using emotionally neutral and negative pictures in associative inference tasks have found beneficial effects of sleep but failed to support the influence of sleep stages on relational memory formation [?, ?]. Therefore, the view that NREM sleep facilitates creative problem-solving through relational memory formation still requires more direct evidence.

2.2.3 NREM Sleep Facilitates Memory Integration NREM sleep facilitates memory integration, whereby existing memory representations may be altered through integration of new representations. One study investigated how NREM sleep spindles affect memory integration using a word memory task. Participants learned new words before a sleep or wake interval, followed by immediate and one-week delayed recall tests. Results showed that the sleep group had significantly higher recall rates in the immediate test, with some participants exhibiting lexical competition effects, and spindle count significantly predicted these effects [?, ?]. Lexical competition effects occur when memory for new words interferes with expression of similar existing memories, indicating integration of new memories into existing networks. NREM sleep spindles provide an optimal state for memory integration, which may alter expression of old memory representations and thereby influence the reconstruction phase of creative problem-solving.

Furthermore, research using video game tasks has confirmed NREM sleep's memory integration role in creative problem-solving. Solving these tasks requires logical reasoning based on holistic problem understanding, necessitating integration of problem memories into prior networks to formulate solutions. Participants solved levels sequentially until encountering an unsolvable level, after which they entered sleep or wake intervals before attempting the unsolved level again. Results showed the sleep group had twice as many participants successfully solve the level compared to the wake group, with those obtaining SWS being more likely to solve it [?, ?]. This task's advantage lies in minimizing declarative and procedural memory demands, limiting memory content to the task itself. During sleep, individuals flexibly organize problem-related memories through integration, achieving comprehensive problem understanding to

facilitate creative problem-solving. The correlation between successful problem solvers and SWS further indicates that SWS supports this process. Thus, NREM sleep's impact on creative problem-solving can be accomplished through memory integration, generating new holistic memory representations that expand the memory network and enable search within a broader problem space.

Research on NREM sleep typically uses spatial and visual tasks that depend more on processing newly acquired pre-sleep memories, whereas REM sleep research typically uses verbal tasks that depend more on processing old memories. Each sleep stage has unique functions: NREM sleep primarily helps solve problems requiring logical reasoning, while REM sleep mainly helps solve problems requiring association. However, simple division of sleep stages has clear drawbacks. First, complete separation of sleep stages cannot be guaranteed, as interactions between stages always exist. Second, sleep as a whole involves not only individual stages but also transitions between them, which is easily overlooked. For example, one study found that dynamic interactions between NREM and REM sleep predicted the rate of transformation from implicit to explicit knowledge after sleep [?, ?], suggesting that memory reorganization may not be influenced by single sleep stages alone. Moreover, some forms of memory reorganization have been linked to different sleep stages; for instance, relational memory formation becomes associated with REM sleep when emotional content is added [?, ?] and shows sleep-dependent but stage-independent effects [?, ?]. Therefore, rigid division of sleep stages is unwise, and future research should focus on overall sleep architecture, such as transitions between stages and their interactions, to understand their impact on creative problem-solving.

3. Factors Influencing Sleep's Effects

Sleep does not always produce positive results for creative problem-solving [?, ?, ?], suggesting other factors may interfere with its effects. Current research has identified factors influencing the magnitude of sleep's impact based on factors affecting memory reorganization, including changes in sleep architecture, memory manipulation during sleep, and task type.

3.1 Changes in Sleep Architecture

Aging produces changes in sleep duration and structure: total sleep time decreases, sleep onset latency increases, fragmented sleep reduces sleep efficiency, SWS significantly decreases, and sleep spindles show reduced number, amplitude, and density [?, ?, ?, ?]. These age-related changes in sleep architecture affect sleep's role in creative problem-solving.

Most studies using young adults have demonstrated positive effects of sleep on creative problem-solving. However, with age-related changes in sleep architecture, sleep's impact becomes non-significant. One study first examined how sleep affects creative problem-solving across age groups [?, ?]. Young sleep, older sleep, and older wake groups completed the NRT before and after their

respective sleep or wake conditions. Results showed that, after controlling for basic cognitive abilities, more young adults than older adults could creatively solve the NRT after a night of sleep, with no significant difference between sleep and wake conditions in older adults. However, there was no age difference in acquiring implicit knowledge of the hidden rule during the pre-test. As the only study investigating sleep's impact on older adults' creative problem-solving, these results support the influence of sleep architecture changes: both age groups could acquire implicit knowledge of the hidden rule before sleep, and SWS could facilitate its transformation to explicit knowledge. Young adults successfully transformed implicit knowledge into explicit knowledge to consciously apply the rule, but older adults' reduced SWS was insufficient for this process, rendering sleep ineffective for creative problem-solving.

Research in this area remains limited in quantity and depth, with age-related sleep architecture effects attributed only to SWS reduction. However, research on sleep-dependent memory consolidation in aging suggests additional mechanisms. One study found that reduced spindles in older adults impair sleep-dependent memory consolidation [?, ?], and since spindles are key brain waves for memory consolidation, their reduction may also impair memory reorganization that accompanies consolidation. Future research should examine how age-related spindle changes affect creative problem-solving, extending the focus from macro-level sleep architecture to micro-level changes in specific brain waves. Additionally, research on sleep's impact on episodic memory consolidation in older adults found that reduced sleep effects were unrelated to SWS duration but rather to age-related impairment of hippocampal and prefrontal cortex functions during sleep, leading to disrupted memory reactivation and diminished sleep effects [?, ?]. This suggests that pre-sleep experiences may cause changes in sleep architecture or microstructure, and that research should identify more fundamental influencing factors beyond quantitative changes in sleep structure. It also indicates that age-related sleep architecture changes may not be the sole reason for diminished sleep effects, warranting expanded research perspectives.

3.2 Memory Manipulation During Sleep

In the context of creative problem-solving, manipulating memories during sleep can influence the strength of sleep's effects. Compared to unmanipulated sleep, targeted reactivation of problem-related memories acquired before sleep can effectively enhance post-sleep creative problem-solving performance. The targeted memory reactivation (TMR) paradigm enables such manipulation by pairing stimuli with specific cues during initial presentation and re-presenting those cues during sleep to selectively activate memories.

Early research in this area used olfactory cues to target memory activation. One study used the unusual uses task, a common creative problem-solving measure requiring participants to list possible solutions for a problem and select the most creative one for expert evaluation. Participants received the task with an odor

before sleep, which was then re-presented during sleep under three conditions: task-matched odor, non-matched new odor, or no odor. Results showed that presenting the task-matched odor during sleep produced better creative problem-solving performance than the other conditions [?, ?]. This study first demonstrated the possibility of manipulating memories during sleep to aid creative problem-solving. Subsequent research shifted to more flexible auditory cues due to the limited controllability of olfactory cues, yielding positive results [?, ?]. One study used creative problem-solving riddles as tasks, pairing them with auditory cues during initial testing, then re-presenting these cues during SWS to target memory reactivation, with control groups receiving non-matched cues or no cues. After a full night's sleep, unsolved problems were presented again, with solution rate as the outcome measure. Results showed that presenting riddle-matched auditory cues during sleep produced higher solution rates than control conditions, indicating that targeted memory activation during sleep can further facilitate creative problem-solving by promoting preferential reorganization of specific memories. However, whether targeted activation enhances target memory reactivation or suppresses irrelevant memory activation remains unresolved, warranting further investigation into the underlying mechanisms.

Targeted memory reactivation during sleep offers a non-invasive, low-cost method to enhance sleep's impact on creative problem-solving. However, not all memory reactivation cues have positive effects. Cue duration, timing, and whether cues partially overlap with the problem can produce varying positive or negative effects on post-sleep creative problem-solving [?, ?, ?, ?]. Future research should therefore focus on developing more effective TMR methods.

3.3 Task Type

Sleep's impact on creative problem-solving may be limited by task type. Different tasks require different types of memory reorganization, and sleep shows positive effects in tasks requiring rule or structure extraction and association. However, sleep's effects are not significant for insight problems involving set-breaking. Creative problem-solving often involves "fixation," where individuals adopt fixed cognitive tendencies that focus on seemingly relevant but actually obstructive representations [?, ?]. Such fixation hinders problem resolution. Common tasks for studying set-breaking include classic insight problems such as the nine-dot problem and the eight-coin problem.

Brodts et al. (2018) examined whether sleep and incubation benefit creative problem-solving using visual change detection, classic riddles, and anagrams. Visual change detection requires identifying differences between two sequentially presented similar images and, while not a standard creative problem-solving task, involves the "Aha" experience common to insight. Classic riddles require shifting conventional solution approaches, while anagrams require forming different words from given letters, primarily assessing divergent thinking and associative ability. Three tasks were presented sequentially with fixed time limits. The incubation group entered sleep or wake states after pre-testing and com-

pleted unsolved tasks in post-testing, while the no-incubation group completed both tests after equivalent sleep or wake intervals. Results showed no significant differences between sleep and wake conditions in problem-solving, and incubation between tests did not affect performance except for riddle tasks. This suggests that unconscious processing during incubation benefits riddle solving, but sleep does not show unique effects. Schönauer et al. (2018) similarly found that sleep and wake incubation did not benefit classic insight problems or magic trick solutions.

These findings may reflect two factors. First, set-breaking problems involve cognitive constraints that cannot be overcome by rule extraction and association alone; they require first releasing constraints imposed by current problem representations, decomposing the representation, and then actively reorganizing it. Sleep may not support this decomposition process. Second, when TMR is used during sleep to target specific memories, sleep can help solve riddle-type problems [?, ?], suggesting that natural sleep's broad memory processing may be insufficient for set-breaking problems but can be focused on specifically activated memories through external induction, enabling more precise memory processing to facilitate problem-solving. This indicates the limited nature of natural sleep's memory processing and its potential to aid set-breaking problems when guided by external factors, though this hypothesis requires future verification.

4. Theoretical Explanations of Sleep's Impact on Creative Problem-Solving

Sleep's influence on creative problem-solving can be attributed to its facilitation of memory reorganization, which enables flexible transformation of pre-sleep problem representations and promotes successful reconstruction. Researchers have proposed several theories to explain how sleep affects memory reorganization to aid creative problem-solving.

4.1 Complementary Learning Systems Model

The complementary learning systems model posits that individuals possess two memory systems: the hippocampus and neocortex. Newly acquired memory representations are encoded in the hippocampus and gradually transferred to the neocortex during sleep through hippocampal-neocortical connections, eventually becoming independent of the hippocampus. This information transfer process not only aids memory consolidation but also facilitates memory reorganization that accompanies consolidation, thereby supporting creative problem-solving [?, ?, ?]. Specifically, during sleep, coupling of slow oscillations, spindles, and hippocampal ripples enables synchronized memory replay between hippocampus and neocortex. This replay involves spontaneous reactivation of neurons encoding problem-related memories in the hippocampus, with reactivated memories being transmitted to the neocortex for consolidation. Differential replay

patterns induced by each rhythm modify memories, producing reorganization that can be used for creative problem-solving [?, ?, ?, ?].

According to this model, problem-related memories are encoded in the hippocampus before sleep, when hippocampal activity is stronger during problem processing. During sleep, these memories are transferred to the neocortex, so that post-sleep problem processing shows stronger neocortical activity and reduced hippocampal activity, with behavioral manifestations of memory reorganization and improved creative problem-solving. One study using a statistical learning paradigm directly verified this model. The paradigm, commonly used to assess rule extraction, requires participants to learn auditory sequences with underlying statistical structures before entering wake or sleep groups. In a subsequent test phase, participants judged whether given sequences conformed to the structure. Results showed that the sleep group better distinguished structured sequences, with SWS predicting this effect. fMRI data revealed stronger connectivity between the striatum and medial temporal lobe in the wake group, whereas after sleep, participants showed stronger striatal-temporal plane connectivity [?, ?]. This finding confirmed that memory transfer from hippocampus to neocortex aids rule extraction: connectivity with the striatum shifted from medial temporal lobe to temporal plane, directly supporting information transfer during sleep and accompanying rule extraction. Although this study did not further verify whether extracted rules were consciously applied, it provided preliminary and intuitive evidence for the complementary learning systems model.

This model suggests that memory reorganization aiding creative problem-solving occurs alongside consolidation, focusing more on NREM sleep while neglecting REM sleep's role. Clearly, REM sleep is also an important stage for memory reorganization. Despite this limitation, the model provides a system-level explanation of how sleep aids creative problem-solving and offers a foundational framework for subsequent theoretical developments.

4.2 Spreading Activation Theory

Spreading activation theory posits that enhanced activation spreading during sleep facilitates creative problem-solving. When solving creative problems, individuals search for answers within the problem search space. Problem-relevant information becomes activated in the memory network, subsequently activating connected memories; stronger connections are more easily activated. Activation spreading during sleep is stronger than during wakefulness. During sleep, problem-related memories are spontaneously reactivated, and enhanced spreading activation helps activate larger associative networks, expanding the problem search space and highlighting novel connections to facilitate creative problem-solving [?, ?]. This increased activation spreading is primarily mediated by changes in neurotransmitter levels. Changes in acetylcholine and norepinephrine levels during sleep alter neocortical connectivity [?, ?], enabling new connections to form within the neocortex when hippocampal-neocortical activity is desynchronized. Studies using associative tasks support this theory. For

example, research using RAT problems of varying difficulty found that, compared to wake groups, sleep groups improved performance on difficult problems post-sleep [?, ?]. When facing RAT problems, individuals first activate stimulus words, then spread activation to target words (solutions). Difficult problems have fewer direct connections from stimulus to target words, requiring broader activation that sleep's enhanced spreading activation can provide, enabling successful solutions.

Despite experimental support, this theory has clear limitations: its explanation is one-sided and cannot account for creative problem-solving requiring rule extraction or memory integration. Moreover, supporting evidence is largely indirect, with no direct verification under controlled activation spreading levels during sleep. Consequently, recent research has rarely used this theory to explain findings.

4.3 Synaptic Homeostasis Hypothesis

The synaptic homeostasis hypothesis proposes that sleep-dependent synaptic desaturation aids memory reorganization. During wakefulness, synaptic strength gradually increases as individuals acquire information from the environment, leading to synaptic saturation. However, limited brain space cannot accommodate unlimited information, so sleep performs synaptic desaturation through synaptic downscaling. Electrophysiological evidence shows that after sleep onset, reduced external interference and altered neuromodulation cause synapses to proportionally downscale to baseline total strength [?, ?, ?].

This hypothesis emphasizes that synaptic downscaling during sleep aids memory reorganization, but that new connections produced by reorganization are already present in memory; sleep's role is to make these connections salient rather than create entirely new associations. Specifically, when problem-related memories are encountered before sleep, overlapping memories receive multiple activations. Stronger overlap produces more activation and stronger synapses. During sleep downscaling, stronger synapses are more likely to be preserved, retaining overlapping memories and facilitating rule extraction. Additionally, newly acquired memories receive stronger activation due to overlap with existing memories, making overlapping components more likely to be preserved and integrated into existing memory networks after sleep downscaling. This reorganization helps obtain larger, clearer associative networks that benefit creative problem-solving, a view supported by computer simulation results [?, ?].

This theory provides the first cellular-level explanation of how sleep affects creative problem-solving. However, it has clear limitations: synaptic changes during sleep are not limited to overall strength reduction; sleep also facilitates associative synaptic plasticity, enabling fine-tuned local adjustments. One study using transcranial magnetic stimulation (TMS) and EEG examined synaptic changes during sleep and sleep deprivation, finding that sleep deprivation increased overall synaptic strength while reducing associative plasticity, resulting

in poorer performance on associative memory tasks [?, ?]. This provides evidence for dissociation between synaptic homeostasis and associative plasticity during sleep. Sleep not only maintains synaptic homeostasis for rule extraction but also readjusts associative plasticity to support novel memory connections and behavioral improvement. Future research should combine synaptic homeostasis and associative plasticity, clarifying plasticity changes across sleep stages to develop a more comprehensive theoretical explanation.

4.4 BiOtA Model

The BiOtA model (broader form of the information overlap to abstract model) proposes that overlapping memory replay alternating between REM and NREM sleep facilitates creative problem-solving. This model emphasizes that memory replay occurs in different locations across sleep stages, producing different types of memory reorganization that affect different problem types. During NREM sleep, replay primarily occurs in the hippocampus to strengthen connections with the neocortex, with commonalities or overlaps between hippocampal memory items being transmitted to the neocortex. This stage primarily facilitates creative problem-solving by aiding rule extraction and relational memory formation. During REM sleep, replay primarily occurs in the neocortex, where overlapping representations extracted during NREM are replayed again to identify commonalities with information already stored in the neocortex, yielding more compressed, abstract representations. These abstract representations differ markedly from those acquired during encoding and are therefore uncommon and novel for the individual, constituting a form of novel association. Thus, this stage primarily facilitates creative problem-solving by aiding novel association formation [?, ?].

Based on this model, one can predict that artificially inducing memory replay during different sleep stages would produce different types of memory reorganization and solve different problem types. Multiple studies support this model. For example, one study using the SRTT found that cuing statistical regularity memory replay during SWS led to more participants gaining explicit knowledge of the statistical rules compared to no replay, enabling them to use these rules to solve subsequent problems [?, ?]. Another study found that cuing face picture memory replay during REM sleep produced creative associations based on replayed content, yielding more generalized memories that transcended original face pictures [?, ?]. fMRI research using the SRTT also showed that cuing replay during SWS enhanced connectivity between the hippocampus and caudate nucleus related to sequence learning, while replay during REM sleep increased activation in motor cortex and cerebellum [?, ?], supporting regional differences in memory replay across sleep stages.

In summary, NREM and REM sleep repeat multiple times throughout the night, potentially leading to extreme abstraction and compression of information, promoting detection of shared structures across markedly different memories, and facilitating formation of more unexpected associative networks and memory gist

to aid creative problem-solving. As the most recently proposed theoretical explanation, the BiOtA model integrates the complementary learning systems model and synaptic homeostasis hypothesis, combining system- and cellular-level mechanisms while distinguishing memory replay locations and functions across sleep stages. Most importantly, it explicitly proposes that overlapping alternation between sleep stages contributes to creative problem-solving, emphasizing the importance of overall sleep architecture.

Reviewing existing literature on sleep and creative problem-solving, most studies converge on a common conclusion: sleep promotes creative problem-solving by facilitating memory reorganization. This underscores the importance of balancing work and rest, with appropriate sleep being essential for flexibly applying knowledge to solve problems creatively. However, direct empirical research investigating the relationship among sleep, memory reorganization, and creative problem-solving remains limited, and future studies should increase direct verification of this relationship. Additionally, several issues require further refinement and resolution.

5.1 Strengthening Research on Sleep's Impact on Ill-Defined Problems

Existing research has primarily used well-defined problems such as the NRT and RAT to investigate sleep's impact on creative problem-solving, rarely employing ill-defined problems. Well-defined problems have clear initial and goal states but are uncommon in real life. In contrast, ill-defined problems, which have unclear initial and goal states that change over time, are more common. Their solutions are multidimensional, requiring extensive knowledge networks and flexible application of existing knowledge across multiple levels, as well as cooperation among cognition, emotion, and motivation [?, ?]. Solving ill-defined problems is among the most needed future capabilities, making it more important to investigate whether and how sleep affects their resolution.

Initial research has begun examining sleep's impact on ill-defined problems, but results remain controversial. One survey study investigating how dream content during sleep influences real-life problem-solving found that approximately 80% of participants reported dreams providing insights for real-world problems [?, ?]. In contrast, an experimental study using computer-based interactive complex crime stories found no significant differences between sleep and wake conditions in post-test problem-solving performance compared to pre-test [?, ?], providing the first direct experimental evidence that sleep does not benefit ill-defined problem-solving. Given that survey results rely on subjective recall with limited precision, while experimental tasks are rarely encountered in real life with potentially limited generalizability, the impact of sleep on ill-defined problems remains unclear. Future research should first enhance ecological validity to determine whether sleep helps solve ill-defined problems. Additionally, it should investigate how sleep promotes creative resolution of ill-defined problems. Given the complexity of cognitive processes underlying such problem-solving, memory reorganization may not fully explain sleep's effects, necessitating examination of

sleep' s impact on specific cognitive components required for solving ill-defined problems.

5.2 Investigating the Role of Emotional Memory in Sleep' s Impact on Creative Problem-Solving

Current research assumes that spontaneous replay of problem-related memories during sleep triggers memory reorganization necessary for creative problem-solving but overlooks the role of emotional memory. Emotional memory refers to memory for experienced emotions and feelings. Individuals inevitably experience emotional changes when facing difficult problems, such as anxiety or anger, making problem-related memories also emotional memories. Research on emotional memory has found that, compared to neutral memories, sleep preferentially consolidates emotional memories by enhancing their replay, with stronger emotional content producing greater replay, particularly for negative memories [?, ?, ?]. Stronger memory replay can facilitate creative problem-solving [?, ?]. Based on this, one might speculate that when individuals experience negative emotional memories of difficult problems before sleep, these memories are more strongly activated during sleep, triggering preferential reorganization and promoting creative problem-solving, with stronger emotional experiences producing more pronounced sleep effects. However, no study has directly tested emotional memory' s role in sleep' s impact on creative problem-solving. Investigating this mechanism through the lens of memory reorganization could expand existing mechanistic research, making it an important future direction.

5.3 Focusing on Cross-Modal Transfer of Memory Information During Sleep

Current research has focused on how sleep facilitates reorganization of unimodal memory information to promote creative problem-solving, examining physiological mechanisms in terms of specific brain region functions and dynamic inter-regional coordination during unimodal memory reorganization. However, individuals acquire information from multiple modalities, and information gained in one modality may be applied to another—for example, reorganizing auditory memories to solve visual problems. Such cross-modal transfer may produce more creative solutions, making it necessary to investigate sleep' s impact on cross-modal transfer. By expanding the scope of memory reorganization to include recombination between different memory types, we can deepen mechanistic understanding of sleep' s influence on creative problem-solving.

One study used a statistical learning paradigm to investigate sleep' s impact on cross-modal transfer of statistical information. Compared to a 30-minute wake interval, after a 24-hour interval with sleep, more participants could extract statistical structures and apply rules learned from auditory sequences to visual sequences, with SWS predicting this effect. fMRI data showed significant striatal activation related to rule learning in the 24-hour group, and functional connectivity analysis revealed enhanced connections between the precuneus, mid-

dle occipital gyrus, and left putamen that partially correlated with SWS. This suggests that during sleep, involvement of visual-spatial mental imagery and multi-channel integration networks facilitated cross-modal rule transfer [?, ?]. This study first demonstrated that sleep facilitates cross-modal transfer of reorganized auditory memories for solving visual problems. However, because the two experimental conditions differed in duration, time and sleep effects may be confounded. Future research should therefore: first, precisely control potential confounding factors to clarify the relationship among sleep, cross-modal transfer, and creative problem-solving; second, investigate dynamic brain activation during cross-modal transfer in sleep, as existing research has not proposed a complete mechanism despite evidence that cross-modal transfer is driven by specific cognitive control mechanisms [?, ?]; and third, employ technologies providing high spatiotemporal resolution, such as simultaneous EEG-fMRI, as current fMRI research offers poor temporal resolution despite providing information about brain activation during sleep.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv –Machine translation. Verify with original.