Research Paper

# Temporal proximity to sleep determines emotional memory interference

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Memory cues can be associated with both positive and negative experiences at different time points, in either a positive-to-negative or negative-to-positive order. While sleep preferentially consolidates recent experiences, its impact on emotional memory across such opposing-valence sequences remains unclear. We tested whether sleep differentially modulates delayed cue affect in positive-to-negative versus negative-to-positive conditions. One hundred twenty participants were randomly assigned to sleep or wake groups and completed both conditions in counterbalanced order. Participants learned pseudoword-picture associations where the same cues were paired with emotional pictures of opposite valence. Emotional valence ratings were collected immediately after encoding and after a 12 h interval (overnight sleep vs. daytime wakefulness). Sleep led to more positive cue ratings in the negative-to-positive condition and more negative ratings in the positive-to-negative condition, compared to wake controls. Stronger positive picture ratings predicted greater positive-valence shifts after sleep in the negative-to-positive condition. These findings indicate that sleep preferentially modulates the affective tone of memories encoded closer to sleep onset, independent of recognition accuracy. This suggests a dissociation between mnemonic and affective consolidation, where sleep selectively biases emotional value according to the temporal order of experience. This principle may inform therapeutic strategies for optimizing emotional outcomes by timing positive experiences before sleep, though clinical applications require further study.

Recollecting positive memories can powerfully aid emotion regulation, alleviating the impact of negative experiences (Joormann and Siemer 2004; Joormann et al. 2007). Research in both rodents and human shows that recalling positive memories elevates positive mood, buffers against stress and depression (Ramirez et al. 2015; Speer and Delgado 2017), promotes social connection (Rasmussen and Berntsen 2009; Wolf and Demiray 2019), and engages brain regions implicated in reward processing (Redondo et al. 2014). In these studies, positive memories are typically introduced after negative experiences, inducing a negative-to-positive sequence that targets the affective experience. Here, we use the term "interference" to refer specifically to affective interference—the competition between opposing emotional valences associated with the same cue—rather than the traditional concept of content-based forgetting. Yet, it remains unclear how the timing of positive memory acquisition—specifically, whether positive memories are acquired before or after negative events—would modulate their interfering effect on the affective tone of negative memories. While theoretical models of memory interference suggest that the temporal order of memory encoding strongly influences how memories interact in terms of retention and accessibility (Mensink and Raaijmakers 1988; Anderson et al. 1994; Murayama et al. 2014), it is less clear whether these principles apply to the modulation of emotional valence. Importantly, most laboratory studies have not systematically manipulated the temporal sequence of positive and negative memory encoding, leaving a critical gap in our understanding of how interference dynamics shape emotional memory.

Sleep is not only essential for mnemonic consolidation (stabilizing memory content), but also plays a central role in affective consolidation (modulating emotional tone) (Walker and van der Helm 2009; Payne and Kensinger 2010; Rasch and Born 2013; Goldstein and Walker 2014; Paller et al. 2021). Several studies report that sleep preferentially consolidates memories encoded close to sleep onset—a phenomenon known as the temporal gradient of sleep-dependent consolidation (Gais et al. 2006; Talamini et al. 2008; Hagewoud et al. 2010; Holz et al. 2012; Cunningham et al. 2014). This selectivity extends to emotionally salient material regardless of valence, with both NREM and REM sleep stages implicated in the reactivation and integration of highly arousing content (Gais et al. 2006; Payne et al. 2008; Talamini et al. 2008; Payne and Kensinger 2010). Crucially, given the temporal gradient of sleep-dependent consolidation, this selectivity raises the possibility that sleep may preferentially strengthen the emotional memory encoded closest to sleep onset. Consequently, sleep could determine which memory—positive or negative—would dominate based on its temporal proximity, thereby modulating positive-memory effects in the negative-to-positive and positive-to-negative conditions. Moreover, sleep is instrumental in emotion regulation, reducing the affective intensity of negative experiences and supporting adaptive emotional processing (Palmer and Alfano 2017; Vandekerckhove and Wang 2018). For example, following negative memory encoding, individuals who sleep showed diminished physiological reactivity to these memories upon re-exposure (Baran et al. 2012; Werner et al. 2015). Conversely, sleep deprivation disrupts adaptive emotional regulation, results in increased

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emotional reactivity and reduced cognitive control (Yoo et al. 2007; Simon et al. 2015; Harrington et al. 2021; Stenson et al. 2021; Palmer et al. 2024).

Targeted memory reactivation studies have demonstrated that replaying memory cues during sleep can bias the competition between conflicting memories (Oyarzún et al. 2017; Antony et al. 2018; Joensen et al. 2022). While this principle has primarily been established in neutral domains, recent work suggests it extends to emotional memory. For example, Xia et al. (2024) found that when participants learned negative associations on day 1 and positive associations on day 2 with the same cues, replaying those cues during the second night of sleep preferentially reactivated positive memories. However, it is unclear whether this selective reactivation was driven by the emotional valence of the positive memories or simply by their temporal proximity to sleep. More broadly, most prior research has relied on such externally cued paradigms or has focused primarily on negative-to-positive sequences, rarely addressing how natural, spontaneous sleep-dependent consolidation interacts with the temporal order of emotional memory encoding. This leaves a critical gap in our understanding: does sleep preferentially consolidate the affective tone of memories based on their emotional valence, their temporal proximity to sleep, or their sequential position in an interference paradigm? Crucially, we aim to disentangle whether such consolidation effects manifest as changes in memory retention or as shifts in emotional reactivity. Addressing this question is essential for elucidating the boundary conditions of sleep-dependent emotional memory consolidation and may inform new approaches to emotional regulation and mental health.

To address these questions, we designed an experiment to test how nocturnal sleep versus daytime wakefulness influences the interference between positive and negative memories. We systematically manipulated the encoding order, such that positive and negative images—each linked to a shared pseudoword cue—were learned in either a positive-to-negative or negative-to-positive order. This allowed us to assess whether the temporal sequence of emotional experiences modulates the extent to which positive memories can buffer (positive-to-negative condition) or overwrite (negative-to-positive condition) negative ones. Participants rated their emotional responses to the cues during acquisition, followed by a 12 h interval of either sleep or wakefulness. At delayed test, we reassessed both emotional valence ratings and recognition memory for the cues. Guided by the "Sleep to Forget, Sleep to Remember" framework (Walker and van der Helm 2009), we specifically aimed to disentangle whether sleep-dependent consolidation manifests as a shift in affective valence (affective consolidation) or as a change in memory retention (mnemonic consolidation). By integrating order manipulation, shared cueing, and sleep/wake comparison, our study directly examines whether sleep preferentially consolidates positive or negative memories as a function of their temporal proximity and emotional salience. Specifically, we asked whether sleep-dependent interference effects would manifest solely as shifts in emotional valence (affective updating) or also extend to memory retention (e.g., negative-to-positive effects leading to forgetting of negative items). This approach provides novel insights into the mechanisms by which sleep shapes the temporal dynamics of emotional memory interaction (Fig. 1).

## Results

### Sleep preserves the emotional valence of more recent memories

First, as a manipulation check, we confirmed that the emotional value of the pictures was successfully transferred to the cues during encoding. A Bayesian regression revealed that the valence ratings of the most recently encoded pictures credibly predicted Immediate Cue Valence Ratings in both the positive-to-negative condition (estimate = 0.142, 95% HDI [0.088, 0.193]) and the negative-to-positive condition (estimate = 0.066, 95% HDI [0.010, 0.121]), indicating that participants effectively learned the emotional associations. To investigate how sleep and the pairing order affect the emotional valence of memory cues, we compared valence ratings of pseudowords between the immediate and 12 h delayed tests. To rule out potential sampling bias, we first examined the raw valence ratings at the immediate test (baseline). A Bayesian analysis confirmed no credible difference between the sleep (M = 5.04, SE = 0.07) and wake (M = 5.12, SE = 0.08) groups ($median_{diff}$ = 0.086, 95% HDI [−0.124, 0.287]). This confirms group equivalence at baseline and ensures that subsequent changes can be attributed to our experimental manipulations.

To account for individual differences in initial ratings, we analyzed the change in valence ratings (delayed minus immediate) at the item level using a Bayesian linear mixed model (BLMM), with group (sleep vs. wake) and condition (positive-to-negative vs. negative-to-positive) as fixed factors and subject as a random effect. In the positive-to-negative condition, the sleep group rated cues significantly more negatively at delay than the wake group ($median_{diff}$ = −0.243, 95% HDI [−0.447, −0.044]; Fig. 2A). Conversely, in the negative-to-positive condition, the sleep group rated cues significantly more positively than the wake group ($median_{diff}$ = 0.252, 95% HDI [0.052, 0.457]; Fig. 2A). The opposing directions of these effects were further confirmed at the model level: bridge sampling indicated extreme evidence for the Condition × Group interaction model over an additive model, $BF_{10}$ = 107.6 (bridge sampling CV < 0.02; Gronau et al. 2017).

We then modeled delayed valence judgments, controlling for immediate valence, with group and condition as fixed factors and subject as a random effect. Results mirrored the change score analysis: in the positive-to-negative condition, sleep led to more negative cue ratings than wake ($median_{diff}$ = −0.290, 95% HDI [−0.530, −0.046]; Fig. 2B). However, in the negative-to-positive condition, there was no significant group difference ($median_{diff}$ = −0.042, 95% HDI [−0.277, 0.213]; Fig. 2B).

These findings indicate that sleep preferentially preserves the emotional valence of memories encoded closer to sleep. Specifically, when negative material is encoded immediately before sleep (positive-to-negative condition), sleep led to a relatively more negative response to cues. Conversely, when positive material is encoded just before sleep (negative-to-positive condition), sleep preserved the updated positive valence, protecting it against the negative drift observed in the wake group. These results highlight the nuanced, order-dependent role of sleep in modulating emotional memory, supporting a sleep-dependent temporal gradient in emotional memory consolidation. To verify the robustness of these findings, we ran a supplementary analysis using an extended random-effects structure that included both item-level random intercepts and by-subject random slopes for the Condition × Group interaction: Valence Changes ~ 1 + Condition × Group + (1 + Condition × Group | Subject) + (1 | Pseudowords). Crucially, the sleep-dependent effects remained robust and credible in both the negative-to-positive ($Median_{diff}$ = 0.254, 95% HDI [0.033, 0.472]) and positive-to-negative conditions ($Median_{diff}$ = −0.246, 95% HDI [−0.493, −0.010]), confirming that the observed modulation is not driven by specific modeling choices. Additionally, given potential gender differences in emotional processing, we conducted a supplementary analysis including gender as a factor. We found no credible main effect of gender (estimate = −0.176, 95% HDI [−0.501, 0.151]) or interactions involving gender (e.g., Condition × Group × Gender: estimate = −0.460, 95% HDI [−1.050, 0.194]). We also verified that the order of task

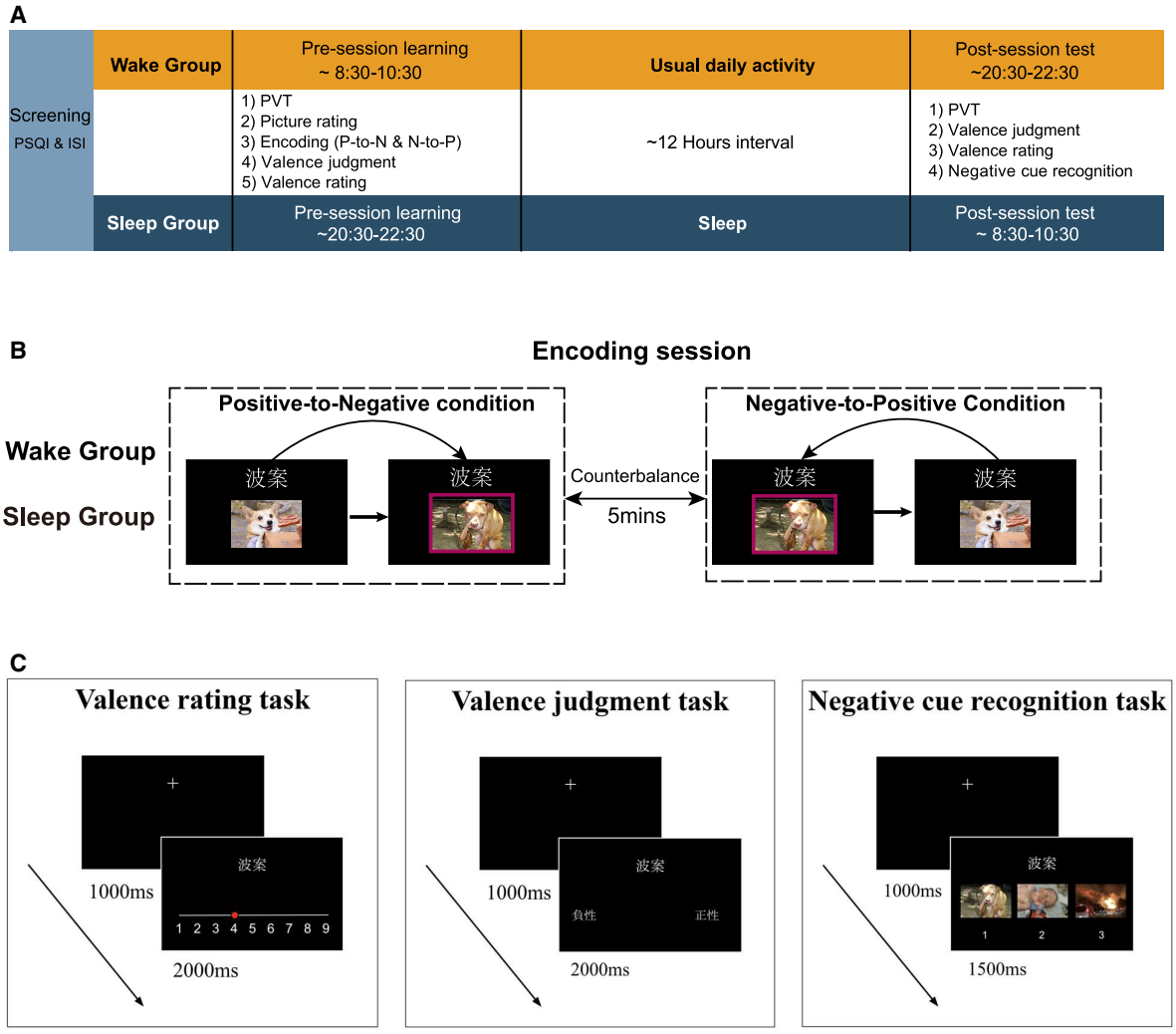


**Figure 1.** Overall experimental procedure and assessment tasks. (*A*) Schematic overview of the experimental timeline for both groups. The yellow section depicts the procedures followed by participants in the wake group, and the blue section illustrates those for the sleep group. The timeline is presented from left to right in accordance with the chronological flow of the experiment. (*B*) Item-level schematic of the encoding session. Each pseudoword was assigned to one condition only and paired with images of opposing affective valence across the two encoding phases: in Phase 1 it was paired with an image of one valence, and in Phase 2 it was re-paired with an image of the opposite valence. Distinct pseudoword sets were used for the two conditions, and the order of encoding blocks was counterbalanced across participants. (*C*) Assessment task examples. Schematic trial structures are shown for the valence rating task, valence judgment task, and post-session cue recognition task. All depicted tasks are assessment measures rather than learning phases. For each task, the assignment of pictures to pseudowords, as well as the sequence of pseudoword presentation, was randomized across participants.

administration (i.e., whether the positive-to-negative or negative-to-positive block was performed first) did not influence these results. A supplementary model including task order as a factor revealed no credible main effect of Order ($Median_{diff} = 0.003$, 95% HDI [−0.301, 0.277]) or interactions (e.g., Condition × Group × Order: $Median_{diff} = -0.261$, 95% HDI [−0.810, 0.328]). This confirms that our counterbalancing procedure was effective and that the brief interval between blocks did not differentially modulate the sleep effect.

## Positive rating of pictures predicts valence change of cues

To test whether the strength of positive or negative picture valence predicted the degree of change in cue valence, we conducted a mixed-effects regression analysis with group (sleep vs. wake), condition (positive-to-negative vs. negative-to-positive), and picture valence rating as fixed effects, and subject as a random effect.

For positive pictures, we found that in the sleep group, higher positive valence ratings significantly predicted a greater increase in cue valence under the negative-to-positive condition ($median_{diff} = 0.147$, 95% HDI [0.039, 0.260]; Fig. 3A), but not under the positive-to-negative condition ($median_{diff} = 0.017$, 95% HDI [−0.088, 0.130]). No significant effects were found in the wake group for either the negative-to-positive condition ($median_{diff} = 0.017$, 95% HDI [−0.086, 0.120]) or the positive-to-negative condition ($median_{diff} = 0.058$, 95% HDI [−0.049, 0.164]) (Fig. 3A). For negative pictures, negative valence ratings did not significantly predict changes in cue valence in any group or condition (all 95% HDIs included zero, Fig. 3B).

This analysis reveals that within the sleep group, the perceived positivity of recently encoded positive memories predicts a greater shift in the emotional valence of associated cues. While this predictive relationship was credible in the sleep group and absent in the wake group, the interaction comparing these slopes was not statistically robust (all 95% HDI included 0). Thus, while sleep

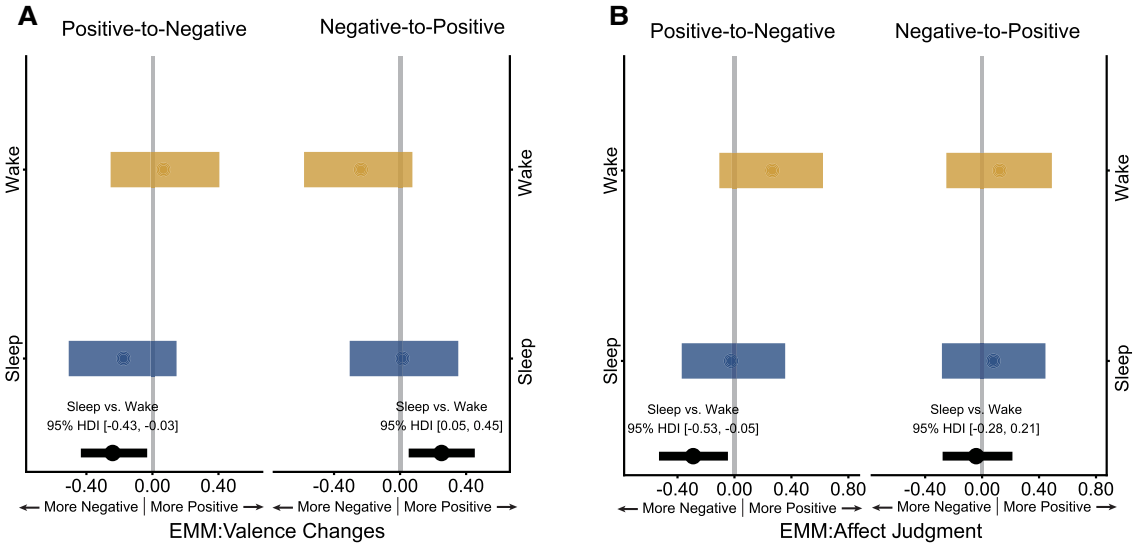


**Figure 2.** Effects of sleep versus wake on emotional evaluation outcomes across the positive-to-negative and negative-to-positive conditions. (*A*) Effect of sleep versus wake on valence change scores in the positive-to-negative and negative-to-positive conditions. (*B*) Effect of sleep versus wake on affect judgment in the positive-to-negative and negative-to-positive conditions. Both valence change scores (calculated as pre-session minus post-session ratings) and affect judgment were analyzed using Bayesian linear mixed models (BLMMs) at the item level. For each analysis, group (sleep vs. wake) and condition (positive-to-negative vs. negative-to-positive) were included as fixed effects, with participant as a random effect. For the affect judgment analysis, pre-session judgment was included as a covariate, and post-session judgment as the dependent variable. In the plots, horizontal yellow (wake group), blue (sleep group), and black (contrast between wake and sleep) lines indicate the 95% highest density intervals (HDIs), with the central dot denoting the median of each HDI. The vertical gray line represents zero. An effect is considered significant if the 95% HDI does not include zero; otherwise, the effect is interpreted as nonsignificant.

appears to facilitate this association, we interpret the group difference with caution.

## Sleep and emotional interference do not modulate recognition memory accuracy for negative memories

First, we confirmed that there were no baseline differences in initial learning. Analysis of accuracy during the encoding phase revealed no credible differences between the sleep and wake groups (all 95% HDIs for group differences included zero). To assess whether sleep influences positive interference effects on recognition memory for negative cues, we administered a cue recognition task at the delayed test only—thereby avoiding repeated testing and any potential influence on valence ratings. Recognition accuracy for negative memories was analyzed using a mixed-effects model with group (sleep vs. wake) and condition (positive-to-negative vs. negative-to-positive) as fixed factors, and subject as a random effect. Descriptive statistics showed comparable recognition

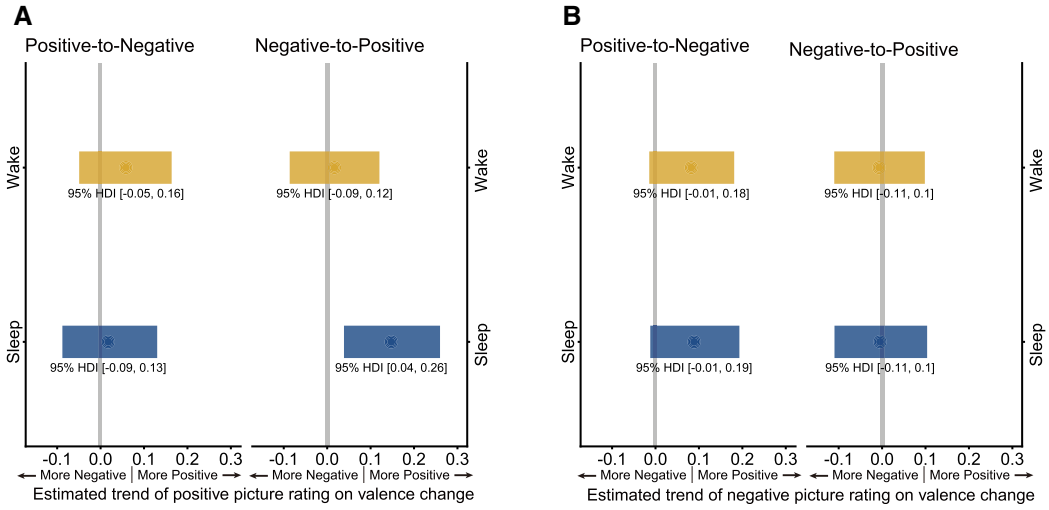


**Figure 3.** Predictive effects of picture valence on changes in pseudoword valence ratings. Results from Bayesian linear mixed models (BLMMs) examining whether picture valence ratings predict changes in pseudoword valence ratings across conditions. (*A*) Estimated effect of positive picture valence ratings on pseudoword valence change scores. (*B*) Estimated effect of negative picture valence ratings on pseudoword valence change scores. In the plots, horizontal yellow (wake group) and blue (sleep group) lines indicate the 95% highest density intervals (HDIs), with the central dot marking the median of each HDI. The vertical gray line represents zero. An effect is considered significant if the 95% HDI does not encompass zero; otherwise, the effect is interpreted as nonsignificant.

accuracy across groups. In the positive-to-negative condition, accuracy was 66.6% (SE = 1.36%) for the sleep group and 63.8% (SE = 1.39%) for the wake group. Similarly, in the negative-to-positive condition, accuracy was 65.2% (SE = 1.38%) for sleep and 62.6% (SE = 1.40%) for wake.

Bayesian analysis confirmed this lack of difference. We found no credible differences in recognition accuracy between the sleep and wake groups in either the positive-to-negative condition ($median_{diff} = 0.136$, 95% HDI [–0.111, 0.400]) or the negative-to-positive condition ($median_{diff} = 0.122$, 95% HDI [–0.140, 0.372]). These findings indicate that, while sleep selectively modulates the emotional valence of memory cues based on their temporal proximity to sleep, it does not differentially affect recognition accuracy for negative memories across these pairing orders. Thus, sleep's effects on emotional memory appear to be specific to affective, rather than recognition-based, aspects of negative memory.

## Discussion

Recalling positive memories enables us to relive joyful moments and counteract the undesirable effects of negative experiences. Here we examined how sleep may facilitate the positive memory effects when positive and negative memories are sequentially paired with shared cues. Crucially, our findings reveal that the temporal proximity of positive memory acquisition to sleep is a pivotal: sleep preferentially preserved the emotional valence of memories acquired immediately before bedtime—stabilizing the updated positivity when positive memories followed negative ones (negative-to-positive condition) and maintaining the dominance of negativity when negative memories were most recently encoded (positive-to-negative condition). Notably, in the negative-to-positive condition, the degree of perceived positivity predicted greater positive emotional shifts after sleep. Collectively, these results suggest that instead of uniformly consolidating daytime learning, sleep selectively preserves the affect tones of memories acquired closer to bedtime. Our study highlights that sleep could facilitate the attenuation of earlier acquired negative memories when positive ones are encoded subsequently (negative-to-positive condition).

While prior research has established that sleep supports emotional memory consolidation and emotion regulation (Walker and van der Helm 2009; Rasch and Born 2013), our study clarifies that these benefits are critically shaped by the temporal proximity of positive and negative experiences to sleep onset, in a manner that resonates with classic interference theory (Mensink and Raaijmakers 1988; Abel and Bäuml 2014). Our findings indicate that sleep modulates the strength and direction of emotional interference: when positive memories are encoded closer to sleep, sleep preferentially stabilizes their positive affective tone, thereby allowing positive interference to counteract the lingering impact of previously encoded negativity. Conversely, if negative memories are learned closer to sleep, sleep tends to preserve their negative affect. This temporally specific modulation of positive interference aligns with and extends established models of sleep-dependent memory consolidation (Gais et al. 2006; Payne et al. 2008; Talamini et al. 2008; Rasch and Born 2013), suggesting that sleep-dependent consolidation is sensitive to the temporal proximity of affective experiences. These insights highlight the potential adaptive value of leveraging sleep's selective consolidation processes to optimize emotional recalibration—for example, by deliberately introducing positive experiences or therapeutic interventions immediately prior to sleep, even in the context of prior negative events.

The importance of temporal proximity is further underscored by our finding that the perceived positivity of memories encoded immediately before sleep predicted beneficial changes in subsequent emotional responses. While we did not observe a credible predictive relationship for negative memories or for memories encoded prior to wakefulness, the primary finding highlights the potential role of temporal proximity and positive emotional valence in gating sleep-dependent consolidation. Specifically, we observed that within the sleep group, the intensity of positive affect encountered immediately prior to sleep onset predicted the degree of valence change, suggesting that sleep may facilitate the stabilization of these salient positive memories. This finding extends prior research on sleep-dependent processing of emotionally salient material (Payne et al. 2008; Payne and Kensinger 2010), revealing that it is the interplay between emotional valence and timing that critically gates the emotional benefits conferred by sleep. Clinically, this interactional temporal window may be harnessed to enhance the efficacy of interventions for affective disorders. For example, deliberately timing positive memory reappraisal, gratitude journaling, or imagery rescripting interventions to occur immediately before sleep could optimize the integration of adaptive emotional content, thereby attenuating the residual impact of earlier negative experiences. These findings underscore the role of sleep in selectively stabilizing positive emotional memories encoded proximal to sleep.

Our findings also align with and extend recent evidence from TMR paradigms. Xia et al. (2024) showed that when memory cues associated with both positive and negative experiences were presented during sleep, positive memories encoded closer to the TMR session were preferentially reactivated and strengthened. Our present results demonstrate that even in the absence of external cues, sleep naturally prioritizes the consolidation of positive memories acquired immediately before sleep, amplifying their influence on emotional outcomes. This convergence between spontaneous and cue-driven consolidation highlights a general temporal principle: sleep-dependent memory processing is exquisitely sensitive to the timing of learning, whether through natural experience or targeted intervention.

Our findings refine existing models of sleep-dependent emotional memory consolidation by demonstrating that sleep's influence is temporally gated, preferentially reinforcing positive affect when such memories are encoded immediately prior to sleep. This selectivity likely reflects a dynamic interplay between hippocampal-neocortical reactivation during NREM sleep and limbic-prefrontal circuits engaged during REM, as supported by recent electrophysiological and neuroimaging studies (Diekelmann and Born 2010; van der Helm et al. 2011; Rasch and Born 2013; Vijayan et al. 2017). Importantly, our results show that sleep modulates emotional intensity without compromising memory accuracy. It is worth noting that unlike prior studies focusing on inherently emotional items (e.g., Payne et al. 2008), our paradigm assessed memory for neutral cues associated with emotional stimuli. The absence of a sleep benefit for recognition accuracy suggests that while sleep effectively consolidated the affective association (as reflected in valence ratings), it did not preferentially enhance the verbatim retention of the neutral cues themselves. This pattern reflects a dissociation between two distinct processes: mnemonic consolidation, which preserved the factual content of memories, and affective consolidation, which selectively attenuated negative emotional salience—particularly when positive memories were acquired before sleep. This dissociation between emotional and informational aspects of memory further aligns with the "sleep to forget and sleep to remember" model, which posits that sleep, especially REM, weakens the affective tone of negative memories while retaining their core content (Walker and van der Helm 2009; Goldstein and Walker 2014). Notably, this mechanism is also consonant with therapeutic frameworks such as Cognitive Behavioral Therapy (CBT), which aim to reduce emotional distress while preserving accurate memory (Hayes 2015; Hayes et al. 2017).

Collectively, our findings thus support the use of sleep-informed strategies for optimizing emotional processing in trauma or affective disorders, by leveraging the time-dependent properties of sleep-based memory consolidation.

Limitations of the current study warrant consideration. First, although the within-subjects design enhances statistical power and controls for interindividual variability, it may still introduce order or carryover effects that are not fully eliminated by counterbalancing. Future research employing between-subjects or crossover designs, as well as systematically varying the temporal interval between positive and negative encoding (and the interval between learning and sleep onset), will be essential to more precisely delineate the temporal boundaries and directionality of sleep's selective consolidation effects. In the current study, the scheduling of sessions resulted in limited variability in the learning-to-sleep interval, precluding a sensitive test of whether shorter delays predict stronger consolidation effects. Second, the absence of objective sleep EEG data in our protocol precludes direct examination of the specific sleep stages or neural oscillatory dynamics that may underlie the observed behavioral effects. Although we examined correlations between self-reported sleep parameters (e.g., total sleep time, sleep onset latency) and behavioral outcomes, we did not observe credible associations—likely due to the limited variability in our healthy, good-sleeping sample (restriction of range). Therefore, incorporating objective polysomnography to analyze NREM and REM sleep architecture, as well as oscillatory activity such as slow oscillations and spindles, would provide deeper mechanistic insight into the neural substrates supporting temporally selective emotional memory updating. Third, while the use of pseudoword cues enabled careful experimental control, it may limit ecological validity and generalizability to real-world emotional experiences. Future studies should extend these findings by utilizing more naturalistic, sensory-rich, or autobiographical stimuli to assess whether the observed effects generalize to emotionally salient events encountered in daily life. Finally, future work should also consider individual differences in personality traits (e.g., neuroticism or extraversion), which may modulate susceptibility to sleep-dependent emotional interference.

In summary, our study demonstrates that it is not sleep per se, but the temporal proximity of positive memory encoding to sleep, that determines whether sleep preserves or reshapes the emotional landscape of memory. By strategically timing positive learning or interventions before sleep, it may be possible to harness sleep's selective consolidation mechanisms to promote adaptive emotional processing—offering a novel and practical principle for enhancing resilience following negative experiences.

## Materials and Methods

### Participants

We recruited a sample of 120 Cantonese-speaking participants (38 male, 82 female; age range: 18–28 years, M = 22, SD = 2). This sample size ($n = 60$ per group) substantially exceeds those typically found in recent studies using similar sleep/wake paradigms (e.g., $n \approx 20$–30 per group; Ashton et al. 2020; Harrington et al. 2021), ensuring robust parameter estimation. Participants were randomly assigned to the sleep group ($n = 60$; 16 male, 44 female) or the wake group ($n = 60$; 22 male, 38 female).

To ensure comparable baseline characteristics, all participants completed the Pittsburgh Sleep Quality Index (PSQI) and the Insomnia Severity Index (ISI) during initial screening (inclusion criteria: PSQI < 12, ISI < 14). Participants were excluded if they reported irregular sleep-wake schedules, defined as: (1) current shift work or transmeridian travel (>2 time zones) in the past month; (2) habitual bedtimes later than 02:00; or (3) irregular sleep timing (weekday-weekend difference >2 h). Participants also completed the Depression, Anxiety, and Stress Scales (DASS) prior to the experimental sessions.

Bayesian analysis confirmed that the groups were well-matched. There were no credible between-group differences in PSQI scores ($\text{Median}_{\text{diff}} = 0.53$, 95% HDI [−0.27, 1.34]) or ISI scores ($\text{Median}_{\text{diff}} = 0.96$, 95% HDI [−0.14, 2.06]). Similarly, no credible differences were found for DASS depression ($\text{Median}_{\text{diff}} = 0.94$, 95% HDI [−1.20, 3.07]), anxiety ($\text{Median}_{\text{diff}} = 1.30$, 95% HDI [−0.78, 3.36]), or stress subscales ($\text{Median}_{\text{diff}} = 2.24$, 95% HDI [−0.26, 4.75]). Sustained attention and alertness were assessed with the psychomotor vigilance task (PVT) administered both before learning and at the 12 h delayed test. A Bayesian linear mixed model revealed no credible main effect of group, session, or group × session interaction (all 95% HDI included 0). Collectively, these results confirm that the sleep and wake groups were well-matched on baseline sleep quality, mood, and sustained attention.

### Experimental design

This study investigated the effects of sequential positive-to-negative (positive–negative sequence) and negative-to-positive (negative–positive sequence) pairings on the consolidation of negative memories, with a particular focus on the modulatory role of sleep in these processes. A mixed factorial design was employed, with Sleep Group (sleep vs. wake) as a between-subjects factor and Condition (positive-to-negative vs. negative-to-positive) as a within-subjects factor. Participants were randomly assigned to either the sleep or wake group, and all participants completed both conditions in a counterbalanced order. The primary dependent variables were changes in affective valence, assessed via valence rating and valence judgment tasks administered both before (pre-session) and after (post-session) the sleep or wake interval, and negative memory accuracy, which was assessed only during the post-session using a cue recognition task. A note on terminology: we refer to our conditions only by the temporal order of the positive and negative pairings—positive-to-negative and negative-to-positive. Because each pseudoword was paired sequentially with two pictures of opposite valence, both pairing orders inherently permit bidirectional associative competition; our design therefore does not dissociate classical proactive from retroactive interference, and we do not make such a claim.

### Materials and tasks

Forty two-syllabi pseudowords were created by randomly pairing two neutral characters which were selected from the Chinese affective words system (Wang et al. 2008). These pseudowords have been successfully used in previous studies (Xia et al. 2023, 2024) to assess emotional memory associations.

Eighty emotional pictures (40 negative and 40 positive) were selected, balanced across four categories: animals, babies, people, and scenery (10 pictures per category). Images were sourced from standardized affective picture databases—International Affective Picture System (IAPS, Bradley and Lang 2017), Nencki Affective Picture System (NAPS, Marchewka et al. 2014), Open Affective Standardized Image Set (OASIS, Kurdi et al. 2017)—and supplemented with comparable images from the public domain.

To monitor and control for potential sleep-related confounds, participants in the sleep group were provided with a standardized paper sleep diary. They recorded bedtime, time spent in bed, sleep onset latency, and wake time for the duration of the study. These measures allowed for verification of compliance with the sleep manipulation and assessment of potential individual differences in sleep parameters. Participants in the wake group were explicitly instructed to refrain from napping, strenuous exercise, and alcohol consumption during the 12 h retention interval. Compliance was verified via a structured verbal report at the beginning of the post-session.

### Psychomotor vigilance task (PVT)

A modified version of the psychomotor vigilance task (PVT) was used to assess participants' vigilance. Each trial began with a

fixation cross, which disappeared randomly after 2000–10,000 msec. Upon disappearance, a counter appeared, and participants were instructed to press the SPACE bar as quickly as possible. Reaction time feedback was provided after each response. If a response exceeded 3000 msec, the message "sleep attack!" was displayed for 2000 msec. The PVT lasted ∼5 min.

### Picture valence rating task

Participants rated each of the 40 negative and 40 positive images on a 9-point Likert scale (1 = extremely negative, 9 = extremely positive). Each trial began with a 1000 msec fixation, followed by the image and rating scale displayed centrally. Images from all four categories (animals, babies, people, scenery) were presented in randomized order, and participants provided ratings via mouse click.

### Negative and positive encoding tasks

Participants completed both the positive-to-negative and negative-to-positive encoding conditions, in which 20 negative and 20 positive images were paired with 20 pseudowords. The same set of pseudowords was used across both conditions to serve as consistent memory cues. Each encoding task comprised two phases. In the passive viewing phase, each trial began with a 1000 msec fixation, followed by the presentation of a pseudoword for 2000 msec. Subsequently, the pseudoword and its corresponding image were displayed together for an additional 2000 msec. After participants had viewed all 20 pseudoword–picture pairs in a condition, a 15 sec break was provided. In the subsequent feedback recognition test phase, each trial presented a pseudoword alongside three images (all previously shown during the passive phase). Participants were required to select the correct pairing by pressing the "1," "2," or "3" key within a 2000 msec window. After their response, the correct pseudoword–picture pairing was displayed for 2000 msec as feedback. Recognition accuracy for the entire phase was shown to participants at the end of the test. Pairings and presentation order were fully randomized for each participant. The order of the positive-to-negative and negative-to-positive conditions was counterbalanced: odd-numbered participants began with the negative-to-positive condition, while even-numbered participants started with the positive-to-negative condition. A break of ∼5 min was provided between the two conditions.

### Valence rating and judgment tasks

In the valence rating task, participants evaluated each of the 40 pseudoword cues on a 9-point Likert scale, where 1 indicated "extremely negative" and 9 indicated "extremely positive." Participants were explicitly instructed to rate each cue based on their first intuitive feeling or the first image that came to mind, without overthinking. Each trial began with a 1000 msec fixation, after which the pseudoword and the rating scale were presented on the screen until a response was made. The presentation order of pseudowords was randomized for each participant to minimize order effects. In the valence judgment task, participants made binary affective judgments (negative or positive) for the same set of 40 pseudoword cues. Each trial started with a 1000 msec fixation, followed by a 2000 msec presentation of the pseudoword, during which participants were instructed to indicate their judgment by pressing the left (negative) or right (positive) key within the 2000 msec response window. The order of trials was randomized for each participant.

### Negative memory cue recognition

In the post-session, participants completed a recognition task for negative pseudoword–picture pairs only. Each trial presented a pseudoword with three images (previously encoded); participants had 1500 msec to select the correct image (keys "1," "2," or "3"). The order was randomized. This selective test targeted the study's primary focus: the effect of positive interference on negative memory.

## Procedure

The experiment consisted of two sessions: a pre-session and a post-session, scheduled to align with each participant's individual sleep–wake cycle. For the wake group, the pre-session took place in the morning (typically between 08:30 and 10:00), scheduled ∼1–2 h after their usual wake time. In contrast, for the sleep group, the pre-session occurred in the evening (typically between 20:30 and 22:00), scheduled 1–2 h prior to their typical bedtime. The sequence of experimental tasks within the pre-session was counterbalanced across participants based on subject number to control for potential order effects. During this session, participants first completed the Depression Anxiety Stress Scale (DASS-21), followed by the psychomotor vigilance task (PVT), the picture valence rating task, and the emotional encoding tasks (with the positive-to-negative and negative-to-positive conditions presented in counterbalanced order). Subsequently, participants performed the valence judgment task and the valence rating task. The valence judgment task (speeded response) was administered first to capture rapid, automated affective categorization, followed by the valence rating task (self-paced) to assess conscious, fine-grained emotional intensity. Notably, no standalone memory recognition task was administered at the end of the pre-session (beyond the immediate feedback trials during encoding). This omission was deliberate to eliminate additional exposure to the stimuli, thereby minimizing potential testing and interference effects.

The post-session was scheduled to occur after either a period of wakefulness or a night of sleep, depending on group assignment. For the wake group, the post-session was conducted in the evening (20:30–22:00, 1–2 h before their regular bedtime), whereas the sleep group returned to the laboratory the following morning (08:30–10:00, 1–2 h after waking). In the post-session, participants completed the psychomotor vigilance task (PVT), the valence judgment task, the valence rating task, and finally, the negative memory cue recognition task, in that fixed order. Additionally, participants in the sleep group were asked to complete a sleep diary to document their sleep quality and duration during the intervening night.

## Statistics

Bayesian linear mixed models (BLMMs) were used to examine the effects of sleep and interference on single-trial valence ratings, affect judgments, and recognition accuracy. We chose the Bayesian framework because it facilitates the fitting of maximal random effects structures without the convergence issues often encountered in frequentist approaches, and it offers direct probabilistic interpretations of parameter estimates (e.g., 95% highest density intervals) without relying on asymptotic assumptions (Barr et al. 2013; Kruschke 2013). Analyses were conducted in R using the brms package. Demographic differences between groups were tested with independent-samples $t$-tests ($\alpha = 0.05$). For valence ratings, the main outcome was the change in valence (post-session minus pre-session) per trial, modeled as:

$$\text{Valence Changes} = 1 + \text{Condition} \times \text{Group} + (1|\text{Subject}) + (1|\text{Pseudowords})$$

To explore the impact of positive picture ratings, we specified a model including the three-way interaction between Condition, Group, and Positive Picture Rating, along with all constituent lower-order interactions and main effects:

$$\text{Valence Changes} = 1 + \text{Condition} \times \text{Group} \times \text{Positive Picture Rating} + (1|\text{Subject}) + (1|\text{Pseudowords})$$

For valence judgment, the BLMM included pre-session judgment as a covariate:

$$\text{Valence Judgment} = 1 + \text{Condition} \times \text{Group} + \text{Pre-session Judgment} + (1|\text{Subject}) + (1|\text{Pseudowords})$$

Continuous outcomes were modeled with a Gaussian family; binary outcomes (affect judgment, recognition accuracy) with a Bernoulli family. Binary outcomes (recognition accuracy, affect judgment) were modeled using a Bernoulli family with a logit link function. For the recognition task, the model included fixed effects for Group, Condition, and their interaction, along with random intercepts for subjects. Four Markov Chain Monte Carlo (MCMC) chains were run per model (5000 samples each; first 500 as warm-up). Convergence was verified using the Gelman–Rubin R-hat statistic (<1.1). Statistical significance was determined by the 95% highest density interval (HDI) of the posterior; effects were considered credible if the HDI excluded zero. This approach provides robust, interpretable Bayesian estimates throughout. To provide a model-level index of evidence, we additionally computed a Bayes factor ($BF_{10}$) comparing the full Condition × Group interaction model against an additive model (Condition + Group) with identical random-effects structures, using bridge sampling via the bridgesampling R package (Gronau et al. 2017).

### Data access

Data and code are available upon request.

### Competing interest statement

The authors declare no competing interests.

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