

Investigating dreams by strategically presenting sounds during REM sleep to reactivate waking experiences

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ABSTRACT

Dreams may partially reflect the memory reorganizing that occurs nightly, improving the usefulness of what we learn each day. However, solid evidence has yet to link dreaming with adaptive overnight memory reorganization. Establishing this link faces several challenges, including the difficulty of experimentally controlling dream content and the susceptibility of dream reports to distortion and forgetting upon awakening. Fortunately, memory consolidation can be systematically manipulated using Targeted Memory Reactivation (TMR), whereby sensory stimulation during sleep can influence previously acquired memories, often reducing forgetting. Stimuli presented during sleep can also be incorporated into dreams, but the extent to which reactivating memories with TMR can influence dream content is still unclear. In the present study, we enlisted TMR to strategically influence dreams. In the evening, participants performed two distinct tasks designed to be readily incorporated into dreams, each associated with a unique sound. The associations between the two tasks and the two (counterbalanced) sounds were further reinforced in a conditioning phase just prior to sleep. The experimenter then presented one of the two sounds when participants were in REM sleep. Dream reports revealed more incorporation of task elements from the cued task than from the uncued task, though incorporation was high for both tasks. Furthermore, dreaming of a task was linked with decreased negative valence and increased creativity. We conclude that this approach to dream curation provides a promising way to investigate the influence of dreaming on memory storage and other cognitive functions.

1. Introduction

Dreaming is emblematic of sleep; yet, the functions of dreaming remain poorly understood. Dreams can be defined as any subjective experience occurring during sleep (Siclari et al., 2020), but here we focus on the immersive first-person narratives that are common during REM sleep. Among a long list of distinct ideas, REM-sleep dreaming has been hypothesized to (a) help us generalize and forget information (Crick and Mitchison, 1983; Hoel, 2021), (b) update our internal model of the world (Hobson et al., 2014), (c) process emotional memories (Scarpelli et al., 2019; Zhang et al., 2024), (d) rehearse scenarios to prepare for future interactions (Revonsuo et al., 2015; Revonsuo and Valli, 2000), (e) a combination of the above (Zadra and Stickgold, 2021) or (f) have no cognitive functions at all (Vertes and Eastman, 2000). These theories span a wide territory of ideas, whereas empirical support for any of these theories is largely inconclusive. Theories of dreaming based on correlations between REM features and outcomes (e.g., Eagleman and Vaughn, 2021) leave open the question of whether dream experiences actually contribute to these outcomes. The evidence

regarding the specific functions of dreaming is mostly indirect, such as inferences based on computational models or correlations between dream content and subsequent behavior (Bloxxham and Horton, 2024). To put theories of dream function on firmer footing, we need better strategies to experimentally modify dream content.

Whereas some experiments find that dreams incorporate learning tasks performed before sleep, such as a virtual maze, it is impossible with this approach to randomly assign participants to different conditions to dream about one task versus another (Stickgold, 2001; Wamsley et al., 2010). As such, any effects of dreaming about a task are confounded with the variables predisposing certain participants to dream about it, such as their emotional response towards the task, motivation to learn, initial performance, or more. This approach thus faces significant barriers to producing solid inferences about the contributions of dreaming to waking mental function.

A potential pathway to circumvent these problems is to make use of lucid dreaming, which is when an individual is aware they are dreaming while remaining asleep. In such circumstances, dreamers can influence the dream to some extent (Windt and Voss, 2018). Therefore, lucid

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dreamers could go to sleep with the intention of carrying out some predefined experimental tasks (Schädlich et al., 2017). However, when tasks are assigned before sleep, these experiments are subject to the same limitations, because success in the task depends on each dreamers' ability to remember and execute it during sleep. Further, lucid REM sleep is characterized by differences in brain activity compared to non-lucid REM sleep (Baird et al., 2022; Demirel et al., 2025; Dresler et al., 2011), leaving open the question of how the functions of dreaming may be impacted by the brain state associated with lucidity. The metacognition required to influence a dream, for example, may fundamentally change how dreams function, such that any conclusions would not apply to the vast majority of dreams that are not lucid dreams. Without a method to systematically manipulate non-lucid dream content, fundamental questions about dream functions are intractable.

Methods for experimentally controlling dream content have considerable potential for improvement in precision and reliability. REM-sleep dream content can be influenced by interventions before sleep, such as exposing participants to stimuli (eg. Gott et al., 2020; Stickgold, 2001; Wamsley and Stickgold, 2019) or asking participants to focus on a topic before sleep with the intention of dreaming about it, a method known as dream incubation (Barrett, 1993; Horowitz et al., 2023; Saredi et al., 1997). However, pre-sleep interventions introduce confounds when studying the functions of REM-sleep dreaming, such as whether outcomes are influenced by the incubation period itself or memory processes occurring in intervening non-REM sleep. Dreams can also be influenced by stimulation during sleep. For instance, in one study noninvasive brain stimulation of the motor cortex during REM sleep decreased movement in dreams (Noreika et al., 2020). It is also well-established that sensory stimulation, including visual, auditory, and olfactory cues, can get incorporated into ongoing dreams (Salvesen et al., 2024; Solomonova, E. & Carr, M., 2019). However, when stimulation is not connected to a pre-sleep learning paradigm, these techniques are not optimal for testing how dreams impact memory.

Novel applications of targeted memory reactivation (TMR) may be a valuable tool for manipulating dreaming more precisely in real time. In TMR, sounds or smells are first linked with specific learning episodes during wake and then re-presented during sleep to trigger offline memory processing and preferentially boost memory performance for cued information upon awakening (Carbone and Diekelmann, 2024; Hu et al., 2020; Oudiette and Paller, 2013). Using this approach to present cues during non-REM sleep can improve performance on a variety of tasks, such as spatial learning (Rudoy et al., 2009), skill learning (Antony et al., 2012), and anti-bias learning tasks (Hu et al., 2015). Whereas fewer studies have investigated memory manipulation during REM sleep, reactivating memories during REM sleep has been shown to boost complex procedural learning (Picard-Deland et al., 2021a), emotional memory processing (Hutchison et al., 2021), rule abstraction (Pereira et al., 2023), and effectiveness of nightmare therapy (Schwartz et al., 2022).

There is much enthusiasm around the question of whether TMR can reliably induce dreams related to specific memories (Bloxham and Horton, 2024). Applying TMR in either REM or non-REM sleep in a morning nap increased dream incorporation of associated memories in the following days (Picard-Deland and Nielsen, 2022). Administering TMR cues associated with a treatment for nightmares increased positive emotion in dreams reported in a dream diary over a 2-week period (Schwartz et al., 2022) and was linked with therapy-related dream content in a pilot study (Mundt et al., 2024). Pre-sleep sleep training for 20 min to associate cues with a lucid mindset, followed by TMR cues in REM sleep, induced lucid dreams at a high rate (Carr et al., 2023). Additionally, odors, previously associated with rural scenes, presented during REM sleep increased the presence of rural topics in subsequently reported dreams (Schredl et al., 2014). Under what circumstances can TMR modify dream content precisely and reliably?

The goal of this study was to determine if TMR methods could produce a strong influence on dream content. We designed two pre-sleep

tasks with the hope of maximizing dream incorporation. Past studies have generally suffered from low dream-incorporation rates, often less than 10 % of dream reports including incorporation of the target memory (Bloxham and Horton, 2024). The ordinary nature of the pre-sleep tasks used in these studies may be part of the problem. Indeed, many dreams pertain to personally significant events, concerns, and novel experiences (Malinowski and Horton, 2014). For instance, individuals often dream about memories that are social (Revonsuo et al., 2015) and emotional (Malinowski and Horton, 2014; Nielsen and Stenstrom, 2005). In keeping with these ideas, dreams collected in sleep laboratories often incorporate elements of the laboratory setting and personnel (54 % of laboratory dreams in one study referenced personnel; Picard-Deland et al., 2021b).

In light of these considerations, we created pre-sleep tasks that emphasized personal interactions with experimenters in two highly novel scenarios with noteworthy social and emotional components. Furthermore, we also addressed the common limitation of relying entirely on dream reports; dreams are often forgotten or distorted upon awakening. This limitation can be reduced when additional evidence is obtained during a dream, as in interactive dreaming (Konkoly et al., 2021). In our design, each task thus entailed a unique respiratory signature, based on the speculation that respiratory changes could be measured objectively during sleep at the time when memories of these tasks influence dreaming. This tactic has been used successfully in prior studies with lucid dreamers (Konkoly et al., 2024; Oudiette et al., 2018), and is in line with findings that respiration can be dynamically modulated by stimuli presented during sleep (Arzi et al., 2010, 2012).

Participants engaged in both tasks in the evening prior to sleeping in the lab, and cues for only one of the two tasks were presented during the night. We hypothesized that cues would infiltrate ongoing dream content, biasing dreams to include more content related to the cued memory and triggering associated respiratory patterns. We predicted that on-task dreaming would impact next-day cognition, boosting theorized functions of dreaming in relation to the dreamt-of memory. By reactivating objectively verifiable, dream-worthy tasks, we sought to define an effective strategy for empirical explorations of the contributions of dreaming to mental function.

2. Methods

2.1. Participants

We recruited 20 participants via an online forum and word of mouth (13 female, 6 male, 1 no response; ages 19–31; $mean = 23.95$ years, $SD = 4.08$). We preferentially selected participants who frequently recalled dreams (17 participants recalled a dream once a week or more, 2 recalled 2–3 dreams per month, and 1 recalled less than 1 dream per month). We recruited frequent dream recallers to maximize the chances that participants would recall dreams during their laboratory session. Demographic information was missing from 1 participant due to technical failure. Participants were compensated \$100 for their participation. The experimental procedures were approved by the Institutional Review Board at Northwestern University, and all experiments were performed in accordance with those guidelines. All participants gave informed consent.

2.2. Procedure

Participants arrived in the lab approximately 3 h before their usual bedtime, or at 9 p.m., whichever was earlier. Upon arriving in the lab, they first gave informed consent and were told that the purpose of the study was to investigate how sounds can impact what memories get incorporated into dreams, and that during sleep we might softly play sounds. Participants then engaged in two different tasks, each lasting for 30 min. Tasks were designed to be memorable, distinctive from one another, and to centrally involve a unique respiratory signature. Each

task took place in a different location, either an office or a lecture hall. Each task was guided by a different experimenter, although the other experimenter was also present to take notes and provide technical support while interacting minimally with the participant. The order of the tasks, location, experimenter lead, and associated musical track were counterbalanced across participants. Fig. 1 shows the experimental timeline.

2.2.1. Tasks

One task was learning to play a harmonica duet with an experimenter using only nasal inhalations. For approximately 25 min, participants had the opportunity to progress through four different harmonica songs of increasing difficulty using a Honer Special 20 Harmonica in G. Musical scores for each song (Fig. S1) were explained to participants, and the experimenter with whom they were learning the duet provided feedback and advice for improvement. The same 45-s musical backing track was used to indicate the start of each rendition, and participants progressed to the next song when the experimenter deemed that they had mastered both parts of the duet. At the culmination of the task, participants performed the most difficult song they learned five more times. During these final rounds, the experimenter sang their portion of the duet to enable a later evaluation of only the participants' harmonica performance. To increase participants' engagement, participants were also told they were being evaluated during these final rounds on their tempo, rhythmic accuracy, musicianship, technique, and tuning. To add another distinctive memory element, several different scented stickers were applied to harmonicas before each session (Horiechaly super scent stickers).

The other task consisted of competing against an experimenter in a bubble-blowing competition. We utilized pop-resistant bubbles that could be held in one's gloved hand (no-pop stunt bubble kit). To ensure a distinctive respiratory component, the rules of the game required competitors to blow a bubble using only a nasal exhalation, to catch the bubble in their gloved hand, and then to guide the bubble towards the target by using at least 3 additional nasal exhalations. Competitors scored more points (options ranged from 0 to 10) as their bubble approached the center of an 80-cm Longbow archery target fastened to a 36x49" tri-fold display board. To allow for scorekeeping, competitors shouted out the point value whenever a bubble landed on the target. The start and duration of each round of competition was indicated by a 45-s musical backing track, and both competitors stood next to each other and competed to land bubbles on the same target during each round. To maximize task engagement, competitors progressed through a series of challenges. For instance, after catching the bubble in their hand, competitors had to spin in a circle or raise the bubble in the air before blowing it towards the target. Other challenges included turning off the lights in the room and an interference round in which nasal exhalations could be used to blow competitors' bubbles off course. Participants were also permitted to introduce their own challenges, with the goal of

maximizing their engagement with the task. For the last 5 rounds, there were no challenges. During these rounds, the experimenter did not compete, and participants were instructed to earn as many points as possible. Their cumulative score for the last 5 rounds was added to a leaderboard.

2.2.2. Post-task surveys

After finishing each task, participants completed a survey regarding their experience. To capture individual associations and idiosyncratic elements of participants' experience during each task, participants were first asked to give a recorded verbal report of approximately 7 min describing their experience. They were asked to include everything they remembered about completing the task, especially any thoughts, feelings, memories, and associations they had. They then used a computer to complete the Positive and Negative Affect Schedule (PANAS; Crawford and Henry, 2004), indicating the extent to which during the task they felt 20 different emotions listed on a Likert Scale from 0 (very slightly or not at all) to 4 (extremely). Half of the scale items were summed to obtain a positive affect score and the other half were summed to obtain a negative affect score. Additionally, participants rated their engagement (same scale) and their overall intensity of emotions from 1 (none) to 4 (strong). Next, participants were given 3 min to type out all the creative, alternative uses they could think of for harmonicas or bubbles, a task-specific variant of Guilford's Alternate Uses Task to measure divergent creativity (Guilford, 1967). Finally, they were given the opportunity to type out any additional memories, feelings, thoughts, or associations they had in relation to the task that they didn't mention in the recording. Participants took a 5-min break after completing the first survey before beginning the second task.

2.2.3. Pre-sleep activities

After completing both tasks and surveys, participants completed a survey on sleep quality. They also completed a 27-item assessment of sensory-processing sensitivity (Smolewska et al., 2006), a trait associated with noticing subtle nuances in the physical environment (Turjeman-Levi and Kluger, 2022). We included this measure, already associated with differences in dreaming (Carr and Nielsen, 2017), to test whether high sensory-processing sensitivity predicts increased incorporation of external stimuli into dreams. Participants additionally answered whether they had any prior experience playing the harmonica (5 yes, 14 no), or prior experience reading sheet music or playing other instruments (all participants said yes). Experimenters then applied electrodes for polysomnography (F3, F4, C3, C4, O1, O2, 2 chin EMG channels, EKG, left horizontal EOG, right horizontal EOG, and a vertical EOG channel, all referenced to the right mastoid). Airflow was measured via a nasal cannula connected to a transducer (biNAPS nasal airflow pressure transducer). EEG data were recorded with a .1–100 Hz band-pass (EMG bandpass was 10–50 Hz; airflow bandpass was .05–50 Hz) and a 1000 Hz sampling rate using a NeuroScan SynAmps system. Before

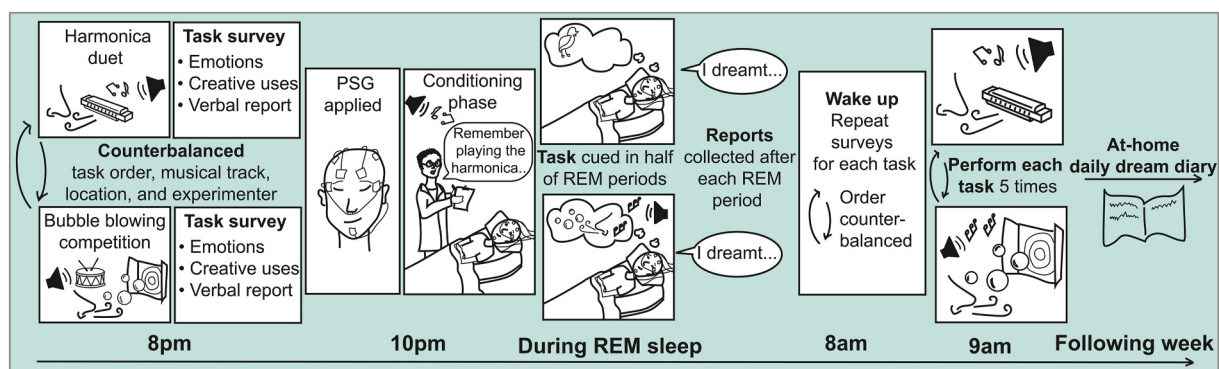


Fig. 1. Experimental timeline.

sleep, participants underwent a final training session to reinforce associations between musical backing tracks, respiration patterns, and task memories. This training was performed while lying down in bed with eyes closed. The two 45-s musical backing tracks were presented with order counterbalanced across participants. At the onset of each track, they were instructed to mentally rehearse the associated task as follows.

“As you hear the music, put yourself back in the room where you were learning to play the harmonica with your nose. You are starting another round of the task. Breathe like you were breathing as you played the harmonica, inhaling for each note. Hear the sound of the tune you were playing with the experimenter, remember what it was like to learn the duet. After the music stops, you can relax.”

“As you hear the music, put yourself back in the room where you were competing to blow bubbles to a target with your nose. You are starting another round of the task. Breathe like you were breathing as you blew the bubbles, 3 quick exhales towards the target. Remember what it was like to catch them and guide them towards the target, competing against an experimenter. After the music stops, you can relax.”

After this guided portion, they were told to continue mentally rehearsing each task each time they heard its musical backing track. For the remainder of the experiment, shortened sound cues were presented consisting of the first 10 s of each musical backing track. Five more cues were presented for each task in an alternating order over the next 15 min (inter-cue intervals 65, 70, 70, 65, 60, 75, 75, 90, 120 s).

2.2.4. Cueing procedure

Participants were then randomly assigned to be presented with either the bubble-task cue or the harmonica-task cue overnight. An experimenter monitored polysomnography, and each time the participant entered a period of stable REM sleep, the experimenter presented either task cues or silent sham cues, both associated with event markers inserted into the EEG recording. Task versus silent sham cues were presented individually by an experimenter approximately every 30 s in alternate REM periods throughout the night and their order was counterbalanced across participants.

The experimenter attempted to maximize the amount of cueing in REM sleep while equalizing the number of task and silent sham cues presented and to collect reports as soon as possible following periods of cueing. In the first two REM periods, we presented an average of 8.36 cues ($SD = 4.05$, $range = 1-17$); in the next two, we presented an average of 14.76 cues ($SD = 4.83$, $range = 3-23$); and in subsequent REM periods, we presented an average of 17.32 cues ($SD = 6.4$, $range = 1-29$). About 2–5 s after the final cue was presented, participants were awoken and prompted for a dream report. We also woke them for dream reports after a clear instance of task-related breathing (e.g., at least three successive inhalations or exhalations), if they appeared to be leaving REM sleep, or if they awoke naturally.

In each dream report, participants verbally responded to the following questions via 2-way intercom.

- 1) Can you tell me everything you can remember?
- 2) Did anything in your dream relate to the sounds or the tasks?
- 3) Do you remember anything else?
- 4) (if relevant) Please try to recount in as much detail as possible how your dream related to the sounds or tasks.
- 5) During your dream, how aware were you that you were dreaming: from 0 (not at all) to 4 (very much so)?
- 6) During your dream, how much were you able to control your actions or what happened: from 0 (not at all) to 4 (very much so)?

2.2.5. Morning

Participants were allowed to sleep for as long as they wished. In the morning, electrodes were removed and participants freshened up. Next, participants repeated both post-task surveys from the evening in a

randomized order, including the verbal report of their task memory, PANAS, and alternate-uses task. Finally, participants again attempted 5 rounds both the bubble-blowing and harmonica tasks so that we could later assess changes in performance.

For a week after the session, participants completed an at-home dream diary each morning. In the diary, participants were asked to describe everything they could remember from their dreams and/or other experiences during sleep, including any details they could remember such as the sequence of events, thoughts, sensations, and/or feelings. They were also asked if they could see any ways in which their dreams incorporated aspects of the bubble-blowing or harmonica-playing tasks, and if so to describe them.

2.3. Data preprocessing

Polysomnographic data for each participant were scored by a trained expert according to standard procedures ([AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications Version 3, 2023](#)). EEG channels were filtered from .3 to 35 Hz for sleep scoring. The expert also manually reviewed the respiration channel to identify instances of task-related breathing during REM sleep.

Next, we parameterized breathing in the 15 s before and 15 s after each cue onset marker to test whether there was a tendency for cues to induce breathing changes corresponding to the associated task. We chose this time window because it encompassed the distinctive respiratory signature for each task during wake. We used a peak-finding algorithm (*FindPeaks*) to extract the number of inhalation peaks and exhalation troughs in each window ([Gorodisky et al., 2024](#)). In addition, we used the *BreathMetrics* toolbox in MATLAB to compute the total number of breath cycles in each window ([Noto et al., 2018](#)), as well as calculate six respiratory features for each breath, which were averaged across each 15-s period. These metrics were the inhale peak height, exhale trough height, inhale duration, exhale duration, inhale volume, and exhale volume.

All dream reports were independently coded by two raters blind to which task was cued and to the design of alternating task and silent sham cues across REM periods. For dreams reported during the laboratory session, raters first coded whether a dream report contained veridical incorporation of sound cues, henceforth referred to as cue-sound incorporation (e.g. “The drum sound was playing from a beatbox in my dream.”). Next, for all dreams, raters coded each dream report for the presence of elements directly and indirectly related to each task based on the prespecified criteria detailed below. Direct incorporations consisted of any mention of elements that were physically present during each task, such as harmonicas or bubbles. Indirectly incorporated elements were those that pertained to a task abstractly by incorporating a concept associated with a task, such as music or competition. See the supplementary material for the complete codebook given to blind raters.

Direct incorporations for the harmonica task included any mention of the dream containing the harmonica task (e.g. “A dream character was talking about the harmonica task”), harmonicas (e.g. “I was at a harmonica show”), breathing in (e.g. “My dream self tried to sniff in when I heard the music”), sheet music (e.g. “I was trying to read a piece of sheet music”), scented stickers (e.g. “Someone gave me a smelly sticker”), the song melodies (e.g. “I heard them playing the notes from the second harmonica song”), and duets (e.g. “My partner and I were singing together”). Indirect incorporations included references to music (e.g. “I was part of a musical production”), instruments (e.g. “I was playing the guitar”), collaboration with another person (e.g. “My friend and I were both painting on the same canvas”), a performance by the participant or another person (e.g. “I was acting in my school play”), and being evaluated (“I was applying for a new school, and I got an email saying I made it to the second round”). Direct incorporations for the bubble task included any mention of the dream containing the bubble task (e.g. “people were playing the bubble game but with beanbags”), of

either bubbles, bubble wands or bubble fluid (e.g. “I was blowing bubbles with my gum”), breathing out (e.g. “I was blowing out birthday candles”), a target (e.g. “The tree had a target in it”), gloves (e.g. “I was bundling up a kid in a winter coat and gloves”), a leaderboard (e.g. “Everyone’s scores were displayed on a screen”), the plastic sheet used to protect the furniture (e.g. “The couch was covered in plastic”), shouting out the score (e.g. “The fans were all shouting out the score”), or a direct reference to one of the challenges in the task such as bubble interference or lights off (e.g. “We were playing frisbee but the rules were like the interference challenge”). Indirect incorporations included references to archery or darts (e.g. “I was at the archery range with my brother”), a carnival-like game (e.g. “We were playing ski ball”), other types of games (e.g. “We were playing this weird game picking candied fruit”), competitions (e.g. “I was in an indoor soccer tournament”), time pressure (e.g. “I was going to an event and there was a strong sense of urgency”), or wands (e.g. “I was a witch casting a spell with my wand”).

Raters also coded also rated whether dream reports contained any direct or indirect references to counterbalanced elements of each task. Direct incorporation included whether the dream directly mentioned the task location (e.g. “I was in the room where we did the harmonica task”) or the experimenter leading the task (e.g. “I dreamt Daniel came in and unhooked me”). Indirect incorporation of an experimenter occurred if the dream contained a concept associated with the lead experimenter, such as the idea of a researcher that shares a characteristic mentioned by the participant (e.g. “The dream character’s laugh sounded exactly like Karen’s”). Indirect incorporation of a task location included incorporation of a concept associated with the task location (e.g. “I dreamt I was in an office, but I didn’t recognize it” or “I dreamt of listening to a lecture”).

In addition to these incorporations that applied to all participants, raters also assessed incorporations unique to the individual. To do so, before reviewing each participant’s dream reports, raters read the transcripts of the 7-min verbal reports completed after each task. At their discretion, raters denoted individual associations in which a participant’s dream involved a memory or association mentioned in their verbal report (e.g. After reporting thinking about their little brother throughout the task because he plays the harmonica, they reported dreaming, “My little brother was asking me a question.”). To assess the length of dream reports, text was extracted from dream report transcripts pertaining only to the content of the reported dream, removing questions posed by the experimenter, verbal fillers, or other commentary or conversation that was not a part of the recalled dream. Two separate blind raters evaluated the dreams reported at home after the laboratory session. Sets of raters met and were instructed to agree on a consensus for any discrepancies. These consensus ratings were used in the analyses.

A separate blind rater evaluated participants’ responses in the Alternate-Uses Task. The number of unique responses from each participant was quantified, and morning responses were discounted if they were repeated from the evening before (Guilford, 1967). This rater also evaluated performance on the final five harmonica performances in the evening and morning. Participants received one point for each note they correctly hit, and notes that occurred during inaudible parts of the audio recording (e.g. due to talking) were subtracted from the total possible points available.

2.4. Statistical analysis

Unless noted otherwise, all statistical tests were two-tailed and done in R using the *lmer* function to compute linear mixed models with participant ID as a random intercept or the *lm* function to compute linear regressions. In cases where tests involved an interaction term, we computed ANOVAs on the linear models. Follow-up t-tests were computed using the *emmeans* and *pairs* functions in R using the Tukey method to correct for multiple comparisons. Wilcoxon signed-rank tests were completed using the *wilcox.test* function in R. For the analysis of respiration, we used the Bonferroni method to correct for multiple

comparisons, multiplying each p-value by 9 (the number of respiration measures), including those from the pairwise t-tests. The statistical models and number of observations per predictor are summarized in Table S1.

3. Results

We collected an average of 5.1 ($SD = 2.67$, $range = 1-9$) dream reports per participant following REM periods (including those with TMR cues and sham cues). Of the 20 participants, 19 had dream incorporation of at least one task. A further breakdown showed that 14 participants incorporated elements from both tasks, 1 incorporated elements from only the bubble task, and 4 incorporated elements from only the harmonica task.

Averaged across participants, 52 % of the reported dreams (i.e., 53 of the 102 dreams) contained at least one element related to a task ($SD = 21$ %, $range = 0-100$ %). Dreams with incorporation contained an average of 1.94 task elements per dream ($SD = 1.24$, $range = 1-7$ total elements). This value included an average of .81 directly related elements ($SD = 1.1$, $range = 0$ to 5 elements per dream), .72 indirectly related elements ($SD = .61$, $range = 0$ to 4 elements per dream), and .40 individual incorporations unique to the participant ($SD = .46$, $range 0$ to 2 per dream).

We separately analyzed dream incorporation that referenced the specific sound that was presented. Eight participants (40 %) reported cue-sound incorporation in a total of 9 dream reports. In one case, no sounds had been presented in the immediately prior REM period, but the participant reported hearing a task cue that had been presented earlier in the night. In all other cases, participants correctly reported the cue sound that had been presented in that REM period, although in 2 cases they also reported hearing the sound that was not cued. Fig. 2 provides examples of task and sound cue incorporation.

We conducted a Wilcoxon signed-rank test to check whether participants found one task to be more engaging than the other according to their evening ratings. The two tasks were rated as similarly engaging ($M = 3.5$ and 3.55 on a 1 to 5 scale for bubble and harmonica tasks respectively, $p = .82$, effect size $r = .007$).

For each dream, we calculated the total number of memory elements incorporated for each task, summing the number of direct, indirect, and individual incorporations. We checked whether there were differences in the number of harmonica versus bubble task elements incorporated into dreams ($number\ of\ incorporated\ elements \sim task$), and found that elements from each task were incorporated into dreams at similar rates ($M = .42$ and $.53$ elements incorporated per dream for bubble and harmonica tasks respectively ($t(178.44) = 1.03$, $p = .3$). These absolute rates of incorporation depend on the leniency of the rating system, and determining the chance rate of spurious incorporation would require evaluating dreams without prior task exposure, which we did not collect in this dataset. Thus, our most convincing results concern our well-controlled manipulations of presenting cues for only one task in only certain REM periods, while blinding participants to which cues were presented and when, aside from any inferences they might have made due to cue-sound incorporation.

We tested whether the number of incorporated elements was predicted by the task cued that night (cued task vs. uncued task), the REM period cued (cued vs. silent REM periods), and their interaction ($number\ of\ incorporated\ elements \sim task\ cued * REM\ period\ cued$). Dreams throughout the night incorporated more memory elements pertaining to the cued task than to the uncued task ($M = .64$ elements of cued task; .38 elements of uncued task; $F(1176.53) = 4.68$, $p = .03$; Fig. 3A and C). The prediction that we could use cues to alter dream reports was thus substantiated. Despite this significant overall effect, the effect was not apparent in every participant’s recalled dreams. As shown in Fig. 3B, 12 participants dreamed of more elements from the cued than uncued task, 6 dreamed of an equivalent number of task elements across the two tasks, and 2 dreamed of more elements from the uncued task than the

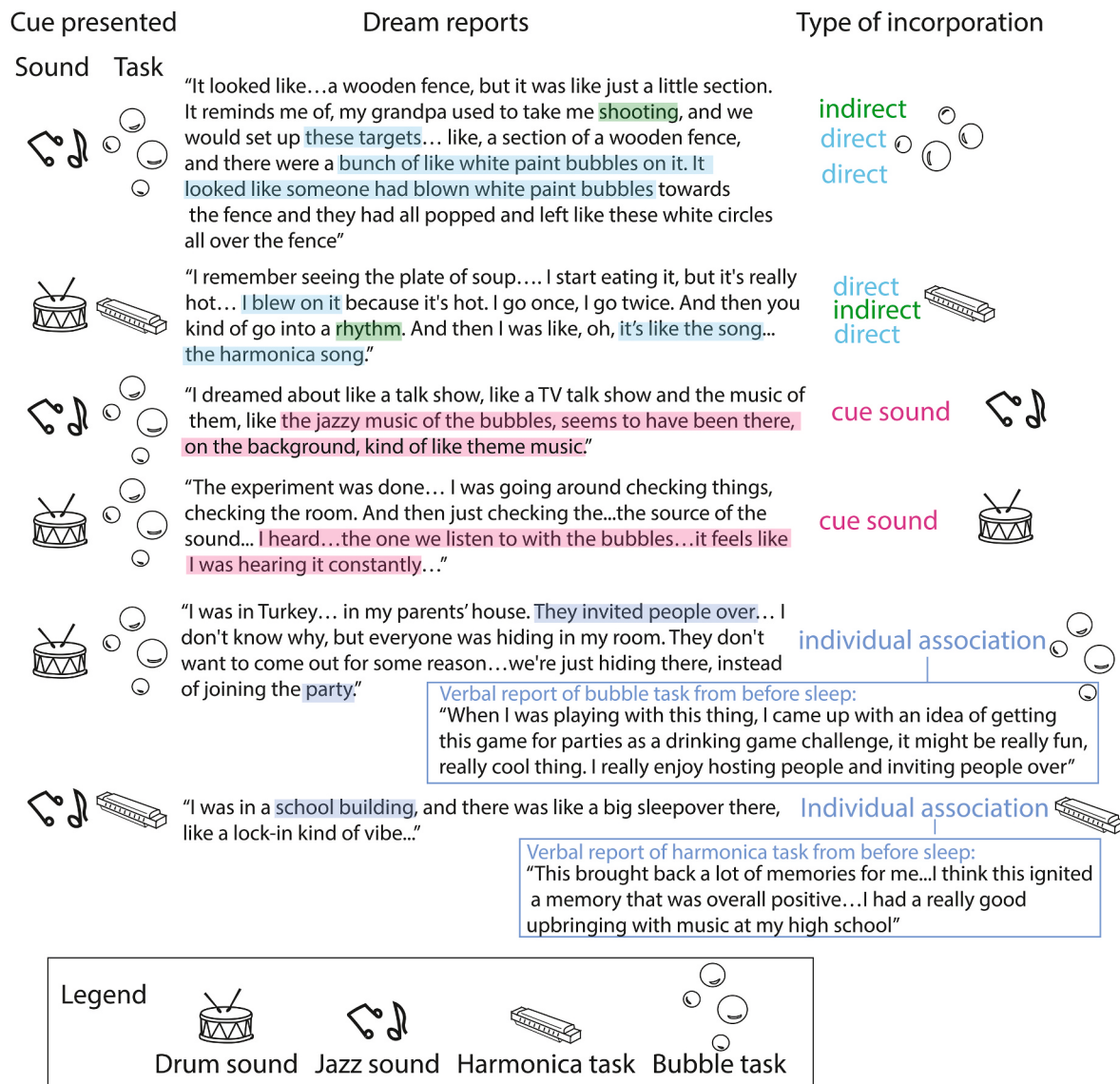


Fig. 2. Examples of dream incorporations of cued tasks. The first example was reported following the third REM period of the night, which was silent but preceded by a cued REM period. All other examples are from reports directly following cued REM periods. These examples are from 6 different dreams from 5 participants.

cued task.

Incorporation did not vary significantly during cued versus silent REM periods ($F(1181.18) = .14, p = .7$), and there was no interaction between the task cued and whether or not cues were presented in the REM period preceding the dream report ($F(1176.53) = .06, p = .81$; Fig. 3C). We also tested whether these variables predicted the length of reported dreams ($\text{word count} \sim \text{task cued} * \text{REM period cued}$). Interestingly, there was a main effect of the cueing status of the REM period, indicating that longer dreams were reported following cued REM periods compared to silent REM periods (cued REM periods $M = 103.36$ words, $SD = 94.06$; silent REM periods $M = 81.17$ words, $SD = 96.47$; $F(174.56, 1) = 4.18, p = .04$).

We then fit a linear model to check whether participants' total scores on the sensory-processing sensitivity questionnaire interacted with cueing to predict dream incorporation ($\text{number of incorporated elements} \sim \text{sensory processing sensitivity score} * \text{task cued}$). In this model, we found a nonsignificant main effect that dreams incorporated elements from the cued task ($F(1) = 3.86, p = .058$), but no main effect of sensory processing sensitivity or interaction ($ps > .4$). We also fit a linear model to test whether previous harmonica experience interacted with cueing to predict incorporation of the harmonica task ($\text{number of incorporated}$

$\text{harmonica task elements} \sim \text{harmonica task cued} * \text{previous harmonica experience}$). Of the 5 participants who had previously played the harmonica, 3 received cues for the harmonica task. We found a nonsignificant main effect indicating that previous harmonica experience predicted less incorporation ($F(1) = 3.33, p = .089$), and no effect of cueing or interaction ($ps > .3$).

Given that dreaming in the lab was influenced by the sound cues, as predicted, we next analyzed dream reports over the following week to determine if the same pattern was apparent at home. On average, participants reported recalling a dream on 3.9 of the 7 nights following the experiment ($SD = 1.89, \text{range} = 1-6$), and 31 % of these dreams incorporated at least one task element ($SD = .28$). We tested whether cues impacted these dreams ($\text{number of incorporated elements} \sim \text{task cued} * \text{days elapsed since session}$). Dreams incorporated an average of .71 elements from the cued task ($SD = 1.82$) and .46 elements from the uncued task ($SD = 1.23$), and this disparity was strongest on nights 2 and 3, when dreams contained an average of 1.8 elements from the cued task ($SD = 1.29$) and .7 elements from the uncued task ($SD = 1.5$). As shown in Fig. 3D, there was a main effect indicating that incorporation varied based on the number of days since the session ($F(6, 135.4) = 3.6, p = .002$), but there was no main effect of the task cued ($F(1127.13) = 2.54$,

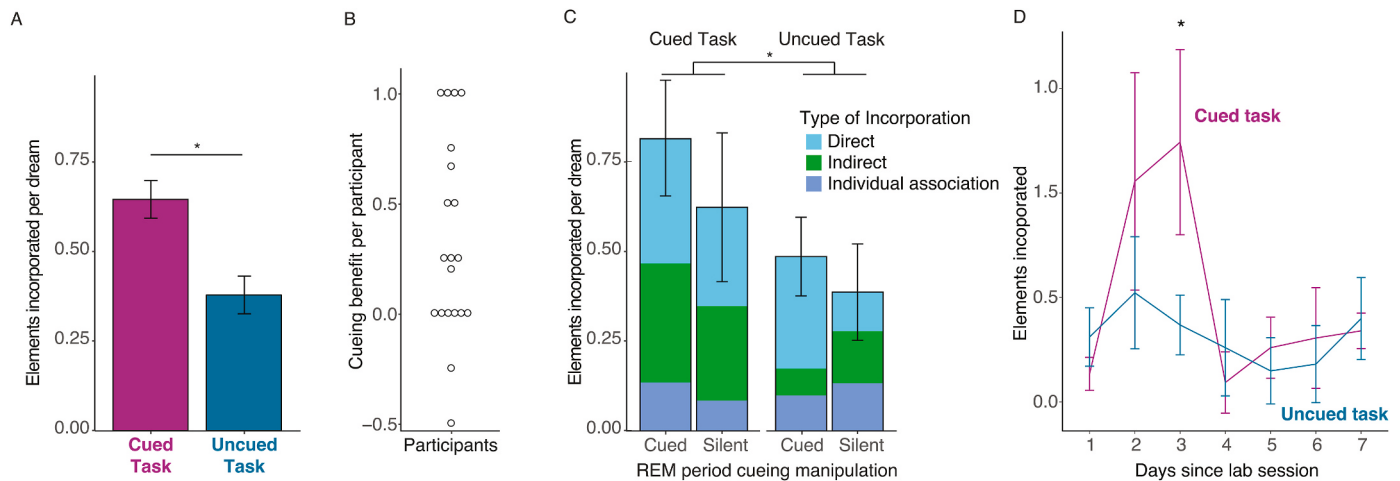


Fig. 3. Task incorporation into dreams. A) During cued REM periods, dreams incorporated more memory elements pertaining to the cued task than the uncued task. B) There was variability in cueing effectiveness across participants. The y-axis indicates the mean number of elements incorporated from the cued task minus elements incorporated from the uncued task across all REM periods. Circles represent values from each participant. C) This graph shows the number of directly, indirectly, and individually associated memory elements into dreams during cued REM periods and uncued REM periods for the cued and uncued task. D) More elements from the cued task appeared in dreams reported at home on the third morning after the laboratory session. Bar heights represent grand averages and error bars represent the within-subjects standard errors of the mean. * indicates significance at $p < .05$.

$p = .11$) or interaction ($F(6127.13) = 1.59, p = .16$). Because a previous study found that cues boosted incorporation only after specific multi-day delays (Picard-Deland and Nielsen, 2022), we separately tested the cueing effect for each night. These t-tests indicated that the cued task was incorporated more often on the third day after the laboratory session ($t(124) = 2.74, p = .007$), but not on other days ($p > .08$).

Next, we tested how cues impacted respiration during wake and REM sleep. Although 53 of the 102 dream reports collected were related to the tasks, only 4 referenced breathing changes, perhaps because various other interesting components of the tasks overshadowed the respiratory components in participants' memories. For example, one participant reported a dream of blowing out birthday candles with her nose while the bubble task cue was being presented. Manual inspection of the preceding REM periods revealed no clearly identifiable respiratory signatures, contrary to findings that lucid dream reports match respiratory content (Konkoly et al., 2024; Oudiette et al., 2018; Morris et al., 2025). As such, we tested whether there was a general tendency for cues to induce breathing changes congruent with the associated task. During wake, we tested whether each measure of breathing differed before versus after the cue depending on which task was cued (*measure of breathing ~ task cued * pre-cue or post-cue*). During REM sleep, given the unknown duration of cue-induced breathing changes, we focused our analysis only on the 15-s after cues compared to silent sham cues, which were always presented in separate REM periods. For each metric, we compared whether the task cued, REM period cued, and their interaction predicted breathing changes (*measure of breathing ~ task cued * REM period cued*).

During wake, six of the nine metrics of breathing changed after cue presentation compared to beforehand (number of inhale peaks ($F(1, 488.4) = 19.51, p = .0001$), number of exhale troughs ($F(1, 487) = 29.6, p < .0001$), exhale trough depth ($F(1, 488.63) = 24.02, p < .0001$), inhale volume ($F(1, 488.30) = 7.85, p = .048$), exhale volume ($F(1, 488.07) = 13.33, p = .003$), and exhale duration ($F(1, 488) = 17.68, p = .0003$). We focus our results on the height of the inhale peak and depth of the exhale trough, the measures which best differentiated the two tasks' breathing signatures during wake. For all results see Table S2 and Fig. S2.

As shown in Fig. 4, during wake there was a significant interaction indicating that the inhale peak height differed after cue presentation compared to beforehand depending on which task was cued ($F(1, 488.03) = 29.26, p < .0001$). Follow-up comparisons indicated higher

inhale peaks after harmonica-task cues ($t(488) = 4.49, p = .0009$) but not bubble-task cues ($t(488) = -2.78, p = .05$), consistent with the harmonica task requiring strong inhalations. There was also a significant interaction indicating that the exhale trough depth differed after cue presentation compared to beforehand depending on which task was cued ($F(1, 488.63) = 15.24, p = .001$). Pairwise comparisons indicated deeper exhales following bubble-task cues ($t(488) = -6.23, p = .0009$) but not harmonica-task cues ($t(488) = -.71, p = 1$), consistent with the bubble task requiring strong exhalations.

During REM sleep, there were main effects indicating that several measures varied depending on which task was cued, including exhale trough depth ($F(1, 1216.50) = 32.64, p < .0001$), inhale volume ($F(1, 1219.4) = 14.13, p = .002$), and exhale duration ($F(1, 1218.6) = 17.6, p = .0003$). However, there were no main effects or interactions with whether task cues or silent sham cues were presented. Thus, these differences may reflect variability between the group that received bubble-task cues and the group that received harmonica-task cues. Perhaps reflecting an orienting response to sounds presented during sleep, pairwise comparisons indicated that exhale troughs were shallower after harmonica-task cues ($t(1215) = -4.3, p = .0009$) compared to after silent sham cues. After bubble-task cues, exhale troughs were also shallower ($t(1217) = -3.77, p = .002$), exhale duration was longer ($t(1219) = -3.93, p = .0009$), and inhale volume was greater ($t(1221) = -4.14, p = .003$) compared to after silent sham cues. Results from all statistical tests can be found in Fig. S2 and Table S2.

Given the hypothesis that dreaming is related to memory consolidation, determining if dreams were associated with systematic memory change from evening to morning is a reasonable goal. However, the present experimental design was not focused on providing highly sensitive measures of retrieval accuracy. Also, the tasks were so unusual that participants did not forget what happened in the morning. Nevertheless, we analyzed data from the 7-min free recall periods. In the evening, reports contained on average a similar number of words for the task later cued (934 words, $SD = 215$) versus the task not cued (998 words, $SD = 179$). In the morning, when participants were recapitulating their memories of completing each task the evening prior, reports again contained a similar number of words for the cued task (805 words, $SD = 121$) and the uncued task (843 words, $SD = 212$). We then computed the overnight change in word count (morning word count – evening word count) for each task and participant to test whether it was impacted by cueing or dreaming (*overnight change in word count ~ task*

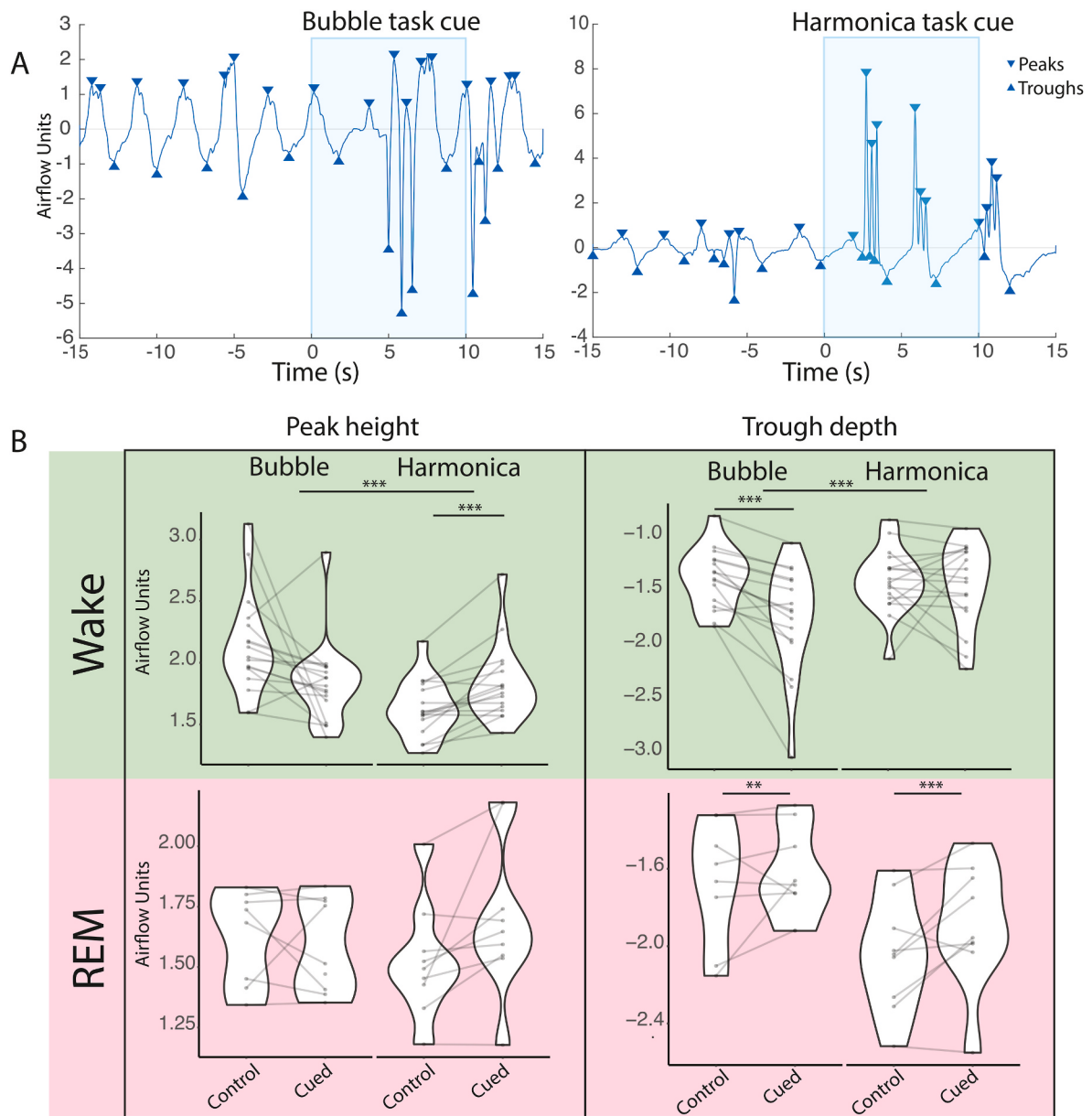


Fig. 4. Respiration changes following task cues in wake and REM sleep. A) Examples of each task's distinctive respiratory signature during wake rehearsal. Shaded boxes indicate when task cues were presented. Arrows indicate peaks and troughs identified by the FindPeaks algorithm. B) Lines connect the average peak height and trough depth in each 15-s period for each participant. For the wake comparisons, "Control" refers to the 15-s period preceding task cues, and for REM sleep "Control" refers to the 15-s following silent sham cues. In all cases, "Cued" refers to the 15-s following task cues. Note that 3 participants were excluded from the analysis of breathing during wake, and 2 from the analysis of breathing during REM sleep, due to insufficient gain on the respiration channel to compute breath metrics or technical failure to record cue time stamps. * indicates $p < .05$, ** indicates $p < .01$, *** indicates $p < .001$.

cued that night * total number of incorporated elements), and we did not find any main effects or interaction ($ps > .2$). Note that this analysis excluded data from 4 participants for whom morning free recall reports were unavailable due to technical difficulty ($n = 3$) or misunderstanding instructions ($n = 1$).

We then tested whether cueing and dream incorporation predicted another facet of memory consolidation, overnight changes in emotional memory relating to each task. Participants' ratings of their emotions pertaining to each task significantly declined following sleep for both positive emotions ($M = 26.7$ and 22.9 in the morning and evening, respectively, $p < .001$, $r = .24$) and negative emotions ($M = 6.5$ and 4.1 in the evening and morning, respectively, $p < .0001$, $r = .26$). We then computed the change in positive and negative emotion for each task by subtracting each participant's evening score from their morning score

and separately tested whether positive and negative evening emotions predicted overnight changes ($emotion\ change \sim evening\ emotion$). Likely because there was more potential for high scores to decrease than low scores, we found that the decline in negative emotion was greater for tasks initially rated higher in negative affect ($t(31.31) = 3.96$, $p = .0004$), although this was not true for positive affect ($t(25.42) = -1.75$, $p = .09$).

We next tested whether the overnight change in negative emotion was predicted by whether the task was cued, the total number of dream elements incorporated, and their interaction ($negative\ emotion\ change \sim task\ cued * number\ of\ incorporated\ elements$). Here, we report results pertaining only to negative emotion because there was insufficient variability in positive emotion change in our dataset to fit statistical models. We found that the overall amount of incorporation (the total

number of direct, indirect, and individual incorporations), whether the task was cued, and their interaction, did not predict changes in negative emotion ($ps > .4$). As a post-hoc exploratory analysis, we also considered direct and indirect incorporation as separate factors, testing whether the number of directly and indirectly incorporated elements differently predicted changes in negative emotion (*negative emotion change* ~ *task cued* + *number of directly incorporated elements* + *number of indirectly incorporated elements*). As shown in Fig. 5A, we found that reduced negative emotion was predicted by direct incorporation ($t(11.54) = -3.42, p = .006$), but not indirect incorporation ($t(19.89) = 1.55, p = .13$) or cueing ($t(21.8) = -1.49, p = .15$).

We also tested whether each participant's total REM duration was related to their change in negative affect (*negative emotion change* ~ *REM duration*), as well as their absolute scores of negative affect in the evening (*evening negative emotion* ~ *REM duration*) and the morning (*morning negative emotion* ~ *REM duration*). Overnight changes in negative emotion were not correlated with the duration of REM sleep ($t(15.17) = 1.43, p = .17$). However, high negative affect in the evening predicted shorter REM durations ($t(17.6) = -3.23, p = .005$), consistent with prior findings that pre-sleep negative emotions reduce REM sleep (Vandekerckhove et al., 2011).

Next, we tested whether cueing and dream incorporation impacted another aspect of memory incorporation, creative divergent thinking in relation to each task. We tested whether the number of novel alternative uses participants listed for each task was predicted by task dream incorporation, cueing, or their interaction (*number of responses in morning* ~ *task cued* * *number of incorporated elements*). We found that participants generated more novel alternative uses for bubbles and harmonicas in the evening compared to the next morning ($M = 7.81$ and 5.1 in the evening and morning respectively, $p < .0001, r = .88$), a logical finding given that participants reported their most readily accessible ideas during the initial evening session. As shown in Fig. 5B, in the morning, the number of novel alternative uses given was significantly predicted by the total number of elements incorporated into their dreams ($F(1,28.52) = 9.19, p = .005$), but not whether the task was cued ($F(1,22.41) = .99, p = .33$) or their interaction ($F(1,23.39) = 2.26, p =$

.15). As a post-hoc exploratory analysis, we also considered cueing and the number of directly and indirectly incorporated elements as separate factors predicting the number of responses (*number of responses in morning* ~ *task cued* + *number of directly incorporated elements* + *number of indirectly incorporated elements*). We found that the number of alternative use responses was predicted by indirect incorporation ($t(37.25) = 2.09, p = .04$), but not direct incorporation ($t(31.74) = -.08, p = .94$), or cueing ($t(23.22) = -.03, p = .98$).

Finally, we tested whether dreaming or cueing impacted performance on the two tasks. For the bubble task, we summed the total number of points earned on the final five rounds of the bubble task in the evening and morning. For the harmonica task, we computed the percentage of notes hit out of all possible notes. We then separately compared scores for each task based on the time (morning vs. evening), whether the task was cued, the number of incorporated elements, and their interactions (*score* ~ *time* * *task cued* * *number of incorporated elements*). There were no changes in bubble task scores based on time of day, whether the task was cued, the number of bubble elements incorporated, or their interactions ($ps > .1$). Unfortunately, due to a technical failure of the recording software, evening and morning harmonica scores were only available for two participants so these data could not be analyzed.

4. Discussion

In this study, we were successful in using softly presented auditory cues to influence dreaming. Before sleep, participants performed two exceedingly engaging tasks, each linked with a distinct sound that was presented again later, during REM sleep. While prior studies have reported single examples of cues triggering incorporation of associated memories (Antony et al., 2012) or of cues influencing dreaming over multiple days (Picard-Deland and Nielsen, 2022; Schwartz et al., 2022), here we showed that auditory cues can systematically bias ongoing dreams towards specific memories, building on the finding that olfactory cues can increase dreaming of a previously associated theme (Schredl et al., 2014). The distinctive nature of the two pre-sleep tasks

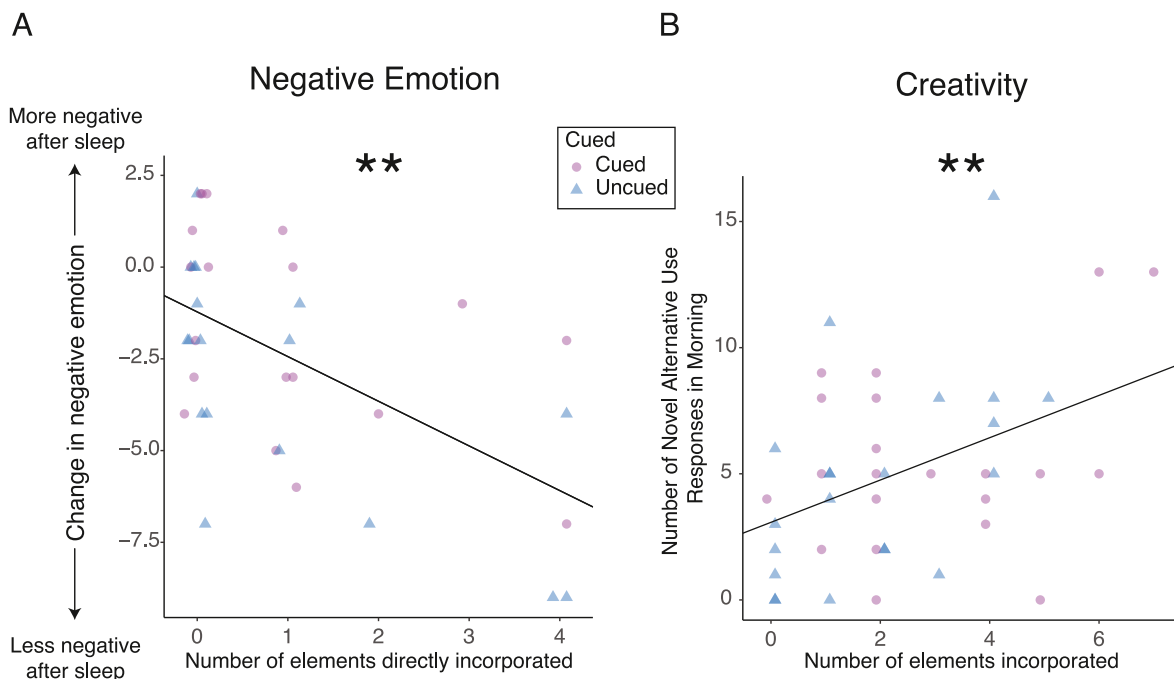


Fig. 5. Changes in cognition related to dreaming. Points represent each participant's values for each task and overlapping points are jittered slightly. A) Overnight reduction in negative emotion (morning minus evening PANAS negative affect score) was predicted by the number of elements directly incorporated into dreams. B) The number of novel alternative uses for bubbles and harmonicas participants thought of in the morning was predicted by the total number of corresponding task elements incorporated into their dreams. ** indicates p values $< .01$.

was probably responsible for both tasks finding their way into dreams, but components of the cued task appeared in dream reports more often than components of the uncued task.

A previous study found no effect of cues on dream content during a morning nap, despite also employing a highly engaging task (Picard-Deland et al., 2021a). One explanation for this discrepancy is that our design included the within-subject comparison of testing whether the reactivated task was dreamt of more often than the uncued task, increasing our power to detect an effect compared to a between-subjects design. Further, our all-night serial-awakenings design allowed for many opportunities to measure the influence of cues on dream content in each participant (5.1 dream reports collected on average), whereas only one dream report was collected per participant at the end of the nap in the previous study. Likely because we recruited participants who frequently recalled dreams, nearly every awakening yielded a dream report, further increasing our power to detect changes in content. Finally, our participants engaged in an explicit rehearsal session before sleep in which they were guided to mentally re-enter each task scenario whenever they heard a cue. By asking participants to volitionally call a task to mind each time they heard its cue, this part of the procedure also served as dream incubation (Horowitz et al., 2023; Mallett et al., 2024; Saredi et al., 1997), and this potential synergy between TMR and dream incubation may have been critical for driving effects.

Our findings bring several questions to the fore regarding how memory reactivation may impact dreaming. We were intrigued to find that dream reports were longer following REM periods with TMR cues compared to those without. This finding could reflect richer dreams due to increased memory reactivation or more elaborate reports of dreams that contained study-relevant information. Further, even though we showed that cues can bias individuals to dream of certain memories, we had no control over how cues or memories were incorporated. Some cues had no apparent influence, others were heard directly by dreamers, some provoked dream incorporation of veridical task elements, and yet others biased dreams towards more distantly related themes associated with the task. One potential explanation is that incorporation manifests differently depending on whether stimulus processing is relegated to sensory areas or whether it reactivates mnemonically associated information in other brain regions, as well as how much the areas engaged by sensory stimulation are already active in support of endogenous dream content (Salvesen et al., 2024). Future studies could explore the factors that determine the form of incorporation, such as the strength of the relationship between the cues and associated memory. Whereas our cues were present throughout each task and indicated the start of each trial during wake, perhaps presenting cues more central to each task could further increase memory incorporation (e.g., presenting the melody of the harmonica song as a cue).

Another point to consider is whether there is an optimal level of task salience for associated cues to maximally influence dreams. It could be that less-engaging tasks leave more room for cues to increase processing, similarly to how weak memories are especially likely to benefit from TMR (Cairney et al., 2016). Yet, our two highly engaging tasks were often incorporated into dreams regardless of whether they were cued, and we found that cues further increased incorporation. One interpretation is that high baseline rates of task incorporation in dreams may boost TMR's ability to influence dreaming. According to the idea of informational gating, sensory decoupling during sleep occurs because attention is sequestered away from sensory stimuli due to competition from endogenous cognitive processes, such as dreams (Andrillon and Kouider, 2020). A hypothesis derived from this theory is that the more congruent a stimulus is with endogenous dream content, the more likely it is to get incorporated (Salvesen et al., 2024). Cueing tasks that are also likely to appear in endogenous dream content would thus increase the likelihood that the ongoing dream is compatible with the cue presented.

Our study also allowed us to investigate whether cues had a delayed influence on dreams in subsequent, non-cued REM periods. A previous

study found that presenting cues (traffic sounds) in an early REM period also increased dreams of that topic in a later REM period (Rahimi et al., 2015), perhaps because dream themes tend to recur throughout the night (Picard-Deland et al., 2023). Here, we found a numerical difference that dreams contained more elements of whichever task was cued that night even in silent REM periods (Fig. 3). The modest sample size in our study ($N = 20$) and variable observations per participant (1–9 dreams reported) likely limited our statistical power to detect this effect, as well as other effects. Further, only half of our participants reported a dream before any cues had been presented (those randomly assigned to receive silent sham cues during their first REM period), but future studies could conduct serial awakenings and initiate cue presentation during only single REM periods at varying delays to better test the temporal precision with which cues influence dreaming.

Additionally, we found that the cued task was incorporated more often in dreams occurring at home three days after the laboratory session, in line with prior evidence that cues in REM sleep can have a delayed effect. For instance, one study found that cueing during REM sleep in a morning nap increased incorporation of the associated task on the two nights afterwards (Picard-Deland and Nielsen, 2022). Another found that cues in REM sleep improved performance on a memory abstraction task, but only after a weeklong delay (Pereira et al., 2023). REM sleep has been hypothesized to play a role in slower plasticity events, such as myelination and memory trace stabilization in the cortex, which may explain these multi-day delayed effects of cues (Konkoly et al., 2023; Pereira and Lewis, 2020).

Our design allowed us to confirm that cues operated with conceptual specificity, increasing dreams of the associated task more than the other task during cued REM periods. The slightly greater incorporation of the uncued task during cued REM periods compared to silent REM periods (see Fig. 3C) could reflect conceptual slippage between tasks, but this contrast was not significant. When designing our tasks, we endeavored to make the tasks as distinctive as possible, knowing that TMR reactivates the context associated with memories (Schechtman et al., 2023) and that REM sleep in particular may promote memory abstraction (Pereira et al., 2023) and remote semantic associations (Stickgold et al., 1999). Tasks were led by different experimenters and occurred in different locations outside of the sleep laboratory. Participants also took a 5-min break between tasks as an additional event boundary, towards the goal of making the tasks as distinctive as possible. Nevertheless, the overlapping features of the two tasks, such as the respiratory focus and social novelty, could have reduced the incorporation differences between conditions. Additionally, although we counterbalanced the experimenter lead for each task, the other experimenter was also present for administrative purposes (keeping score and starting the music), and participants also interacted with experimenters during electrode application and dream report collection. In our scheme for evaluating task incorporation, we included a mention of a task's lead experimenter as incorporation of the associated task. Additional interactions with the same experimenters thus introduce noise but not systematic bias since dreams were coded by raters blind to cue presentation as well as experimental leaders for each task.

Our tasks were designed to optimize dream incorporation rather than to detect subtle changes in memory strength, but we nevertheless collected evening and morning verbal reports of participants' experiences to assess how their memories might have changed. We did not find differences in the length of reports based on whether the corresponding task was dreamt of or cued, but this broad stroke is unlikely to reveal subtle memory operations that may have been at work. We also did not use these reports to assess memory strength due to participants' likelihood of being at ceiling for these memorable tasks, as well as because our instructions did not emphasize a veridical retelling of the sequence of events. Nevertheless, sleep has been shown to boost memory for the sequence of real-world events (Diamond et al., 2025), and it will be important for future studies to identify tasks that are both amenable to dream incorporation and can sensitively measure memory changes.

Our findings do partially support the hypotheses that REM sleep and dreams play a role in ameliorating negative affect attached to a memory (Hartmann, 2010; Levin and Nielsen, 2009; Malinowski and Horton, 2015; Perlis and Nielsen, 1993; Walker, 2009) and promoting creativity (Deperrois et al., 2022; Lewis et al., 2018). We found that only direct incorporations of task elements were linked with this overnight reduction in negative emotion. This finding supports the hypothesis that memory fragments appear in dreams in novel contexts as a sort of exposure therapy to desensitize negative emotions (Levin and Nielsen, 2009; Perlis and Nielsen, 1993).

We also found that dreams promoted creativity in relation to a prior memory, which is another aspect of memory consolidation hypothesized to occur in REM-sleep dreams. We found that the more total task elements incorporated into dreams, the more novel alternative uses for bubbles or harmonicas participants thought of the next morning. Interestingly, this effect was driven by the number of indirectly incorporated elements, those related to the tasks with a degree of abstraction. This finding is consistent with evidence that REM sleep promotes broad semantic associations (Cai et al., 2009; Stickgold et al., 1999) and suggests that dream content reflecting this greater semantic distance may be particularly relevant for creativity. It is worth noting that we only measured creative fluency, the number of novel alternative uses each participant thought of, and a more nuanced scoring system would have better captured other facets of creativity such as how original responses were or the number of conceptual categories they spanned (Vartanian et al., 2019).

An important caveat is that although we were able to bias dream content in favor of specific memories, on-task dreaming did not require or always accompany TMR. Neither emotional processing nor creativity was predicted by cueing or its interaction with dreaming. As such, the evidence we garnered in favor of these functions of dreaming is, like prior evidence, correlational. We cannot dismiss the possibility that third variables, such as participants' motivation, both enabled on-task dreaming (independently, or in response to cues) and caused changes in cognition. Nevertheless, it may be useful for future studies to evaluate whether concrete versus associative memory incorporation determines the role of dreaming in emotional processing and creativity.

Our tasks were selected because they were highly novel and featured real-world scenarios requiring distinctive breathing patterns. As such, the performance measures that could be obtained for each of the two tasks were not optimal. We did not find evidence that performance on the bubble task improved after sleep depending on cueing or dream incorporation. We suspect this analysis is underpowered because our study and tasks were not designed to sensitively measure changes in procedural memory. Other studies do suggest that REM sleep and dreaming aid consolidation of complex procedural memories (Picard-Deland et al., 2021a; Smith et al., 2004).

The study design had the advantage that just one of the two tasks was cued during sleep, and participants were systematically kept from knowing that the experimenter was always cuing just one task. Likewise, the dream raters were blind to which task had been cued during which REM periods. Yet, this study faced the methodological challenge of how to quantify incorporation of memories into dreams. We chose to pre-define a discrete number of elements that would count as memory incorporation, specifying in advance what dream content would be considered direct and indirect task incorporation. This method allowed us to differentiate between dreams that contained many and few task elements, and it was thus suitable for addressing our main question of whether cues boosted incorporation of the associated task relative to the other task and to dreams from REM periods without cues. However, it failed to capture further nuances, which is a common conundrum in task-related dream research. A complementary method that future studies could employ is to ask participants to identify the memory sources of their own dreams (Picard-Deland et al., 2023), as that may improve upon the sensitivity with which we can detect whether task-reactivations are influenced by cueing, so long as participants

remain blind to what cues were presented.

Objectively verifiable breathing patterns were central to each task, but many dreams incorporated task elements without mentioning a change in breathing. This discrepancy highlights the fact that memories were only partially reactivated — and here the respiratory component could have been considered merely a minor component by some participants. Further, the tasks' respiratory signatures were not readily identifiable during sleep even when participants did mention task-related breathing in their dream report. Although lucid dreamers can modify their respiration while sleeping by holding their breath or performing sniffs within lucid dreams (Konkoly et al., 2024; Oudiette et al., 2018; Morris et al., 2025), this may often not be true of non-lucid dream content. Nevertheless, we found that respiration in REM sleep was modulated subtly by cues. When either task was cued, participants tended to exhale more shallowly. Additionally, participants receiving the bubble-task cue tended to inhale a greater volume of air and exhale more slowly. However, none of the measures suggested a significant interaction between breathing changes to cues and which task was cued. As such, we interpret these results as reflecting an orienting response to sounds, consistent with prior work showing slower breaths following an auditory stimulus in REM sleep (Johnson and Lubin, 1967), rather than as reflecting task-related breathing changes due to memory reactivation. It may still be that occasional cues did provoke task-related breathing changes that our analysis of responses to all cues did not detect. Perhaps the high variability of respiration during both cued and non-cued REM sleep makes it difficult to identify such instances. Nevertheless, seeking real-time evidence of TMR via breathing changes is still an interesting research direction. Future studies seeking to identify memory reactivation with respiration could engage more easily measured respiratory changes, such as apneas, and employ within-subjects designs in which multiple memories with distinct breathing signatures are reactivated in a single session.

In conclusion, we demonstrated that auditory TMR can be used to bias dreams towards specific memories. This investigation serves as a starting point for future empirical tests of putative functions of dreaming.

CRedit authorship contribution statement

Karen R. Konkoly: Writing – review & editing, Writing – original draft, Visualization, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniel J. Morris:** Writing – review & editing, Methodology, Investigation, Data curation. **Matthew Cho:** Writing – review & editing, Visualization, Formal analysis. **Kaitlyn Hurka:** Writing – review & editing, Data curation. **Susana G. Torres-Platas:** Writing – review & editing, Investigation. **Lourdes Baehr:** Writing – review & editing, Data curation. **Ken A. Paller:** Writing – review & editing, Supervision, Resources, Funding acquisition.

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Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuropsychologia.2025.109229>.

Data availability

Data will be made available on request.

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