



Using Real-time Reporting to Investigate Visual Experiences in Dreams

Karen R. Konkoly¹, Saba Al-Youssef^{2,3}, Christopher Y. Mazurek¹, Remington Mallett¹, Daniel J. Morris¹, Ana Gales³, Isabelle Arnulf^{2,3}, Delphine Oudiette^{2,3}, and Ken A. Paller¹

Abstract

Neuroscientific investigations of human dreaming have been hampered by reliance on dream recall after awakening. For example, a challenge of associating EEG features with post-waking dream reports is that they are subject to distortion, forgetting, and poor temporal precision. In this study, we used real-time reporting to investigate whether one of the most robust features of the waking visual system, increased alpha oscillations upon closing one's eyes, also applies when people dream of closing their eyes. We studied 13 people, four with narcolepsy and nine without, who experienced many lucid dreams—they were aware they were dreaming while remaining asleep. They reported on both their dream experiences (visual percepts present/absent) and dream-eyelid status (open/closed) using a novel communication technique; they produced distinctive sniff-

ing patterns according to presleep instructions. We observed these signals in respiration recordings from a nasal cannula. These physiological signals enabled analyses of time-locked neural activity during REM sleep. We recorded 150 signals over 19 sessions from 11 individuals. Robust increases in alpha power were not found after signaled dream-eye closure. Remarkably, the experience of eye closure while dreaming was associated with fading visual content only about half the time. Comparing the presence versus absence of visual content was possible only in three participants, who showed increased alpha power in association with a momentary lack of visual content. Enlisting dreamers to actively control and report on ongoing dream experiences in this way thus opens new avenues for dynamic investigations of dreams—the illusory perceptions that haunt our sleep. ■

INTRODUCTION

Progress understanding the nature of dreams has been hampered by the limitations of retrospective dream reports. These verbal accounts are subject to forgetting following the sleep–wake transition and provide only a post hoc perspective on experiences that unfolded dynamically during sleep. Relying on retrospective reporting makes it difficult to study the real-time evolution of dream content and the neural processes that underlie dream experiences. A more direct approach is needed: one that captures dream content as it unfolds.

Lucid dreamers, aware they are dreaming while remaining asleep, offer a unique opportunity to overcome these limitations. Prior research has demonstrated that lucid dreamers can communicate from within their dreams, signaling their lucidity (Demirel et al., 2025; Baird, Tononi, & LaBerge, 2022; LaBerge, Nagel, Dement, & Zarcone, 1981), indicating the beginning and end of predefined tasks (LaBerge, Baird, & Zimbardo, 2018; Oudiette et al., 2018; Erlacher, Schädlich, Stumbrys, & Schredl, 2014; Dresler et al., 2011; Erlacher & Schredl, 2004, 2008), and even answering questions (Türker et al., 2023; Konkoly

et al., 2021). A recent review highlighted that this “observable dreaming” is well positioned to advance our understanding of dreaming by allowing for neural analyses time-locked to specific moments within dreams (Mallett, Konkoly, Nielsen, Carr, & Paller, 2024). Several studies have employed such time-locked analyses to study time perception in dreams (Erlacher et al., 2014; Erlacher & Schredl, 2004) or the effect of dreamed events on physiology outside the brain (e.g., LaBerge et al., 2018; Oudiette et al., 2018; LaBerge, 1990; Brylowski, Levitan, & LaBerge, 1989; LaBerge, Levitan, & Dement, 1986; LaBerge & Dement, 1982). However, to date very few studies have leveraged this ability to study neural correlates of dream experiences, other than the experience of lucidity itself (e.g., Demirel et al., 2025; Baird et al., 2022). Of note, one abstract reported neural differences between singing and counting in lucid dreams (LaBerge & Dement, 1982), and one study with two participants revealed that clenching one's fist elicited corresponding activity in the sensorimotor cortex (Dresler et al., 2011). Although these studies both asked dreamers to produce a sequence of signals to indicate the progression of a predefined task, there was no vocabulary of signals. A vocabulary of signals, each with a unique meaning, can allow for flexible reporting, which is necessary for characterizing the unpredictable and dynamically changing nature of dream percepts.

¹Northwestern University, Evanston, IL, ²Sorbonne Université, Paris, France, ³AP-HP, Hôpital Pitié-Salpêtrière, Paris, France

Here, we show proof-of-concept evidence that lucid dreamers can engage a vocabulary of signals to provide real-time reports on specific aspects of their mental content during rapid eye movement (REM) sleep. As a preliminary demonstration of how this real-time dream reporting can contribute to our understanding of the neural correlates of dreaming, we chose to investigate the experience of opening and closing one's dream-eyes within the dream. We selected eye closure because closing one's eyes in the waking state triggers a robust neural response clearly observable in EEG recordings as an increase in occipital alpha power (Hohai, Saurels, Johnston, Yarrow, & Arnold, 2022; Clayton, Yeung, & Cohen Kadosh, 2018; Cooper, Croft, Dominey, Burgess, & Gruzelier, 2003; Berger, 1929). This effect persists even when one's visual experience remains constant with eye closure in complete darkness (Feng et al., 2021; Ben-Simon et al., 2013; Boytsova & Danko, 2010). We thus sought to explore whether dreaming of closing one's eyes elicits the sort of increase in occipital alpha power observed in wakefulness.

We also investigated effects of closing one's dream-eyes on visual experiences in dreams. Dreams often entail vivid visual experiences (Schredl, 2010; Aserinsky & Kleitman, 1953), but there is much to be learned about how these realistic experiences are produced during sleep. Studies using animal models demonstrate that occipital cortex is activated during REM sleep via bursts of activation from the pons (Peigneux et al., 2001). However, these so-called ponto-geniculo-occipital waves have yet to be reliably detected in humans (Gott, Liley, & Hobson, 2017), precluding links with subjective features of dreaming. In humans, sleep physiology features in the minutes prior to awakening suggest that reduced alpha and delta EEG power correlate with heightened visual experiences as described in subsequent dream reports (Stuart & Conduit, 2009; Bértolo et al., 2003; Wollman & Antrobus, 1987). However, the reliance on retrospective reports in these studies makes it difficult to distinguish neural activity related to dream production from that related to memory encoding.

We equipped lucid dreamers with a vocabulary of signals to report on their dream-eyes as open or closed and on the presence or absence of visual content. Note that when we describe people closing their eyes within a dream, we are referring to dream-eyes closing in a virtual dream body, as the eyes in their sleeping bodies are already closed. By analyzing these real-time reports in conjunction with concurrent neural activity, we aimed to investigate how dreaming of opening and closing one's eyes affects both the subjective experience of visual content and the concurrent patterns of occipital alpha power. We achieved extremely high rates of lucid dreaming among the participants in this study because (a) we administered targeted lucidity reactivation (TLR; Carr et al., 2023) to healthy lucid dreamers and (b) we included individuals with narcolepsy, a hypersomnia disorder associated with increased lucid dreaming (Dodet,

Chavez, Leu-Semenescu, Golmard, & Arnulf, 2015; Rak, Beiting, Steiger, Schredl, & Dresler, 2015).

Our results demonstrated that dreamers could use multiple signals to dynamically report on their experiences in real time. We also obtained preliminary evidence on alpha activity during sleep. Dreaming of closing one's eyes was not accompanied by the reliable alpha power increase that occurs during wake. Closing one's dream-eyes often reduced dream visual content but did not do so consistently like during wake. In the subset of three participants who experienced both visual and nonvisual dreams, alpha power was greater during dreams lacking visual content. The overall results strongly support our conclusion that this innovative approach opens new avenues for investigating the neural basis of illusory perception during sleep.

METHODS

Experimental Design

Participants

We recruited 13 participants: nine healthy participants with lucid dreaming experience through word of mouth (≥ 1 lucid dreams per month; five women, age: $M = 31$ years, range = 21–66) and four lucid dreamers with narcolepsy from patients followed in the National Reference Center for Narcolepsy in the Pitié-Salpêtrière Hospital (≥ 3 lucid dreams per week; three women, age: $M = 31.75$ years, range = 19–45). Lucid dreamers with narcolepsy met the international criteria for narcolepsy (American Academy of Sleep Medicine, 2023b), including (i) excessive daytime sleepiness occurring daily for at least 3 months; (ii) a mean sleep latency lower than or equal to 8 min and two or more sleep-onset REM sleep periods on the multiple sleep latency tests (five tests performed at 08:00, 10:00, 12:00, 14:00, and 16:00); and (iii) no other cause for these findings, including sleep apnea syndrome, insufficient sleep, delayed sleep phase disorder, depression, and the effect of medication or substances or their withdrawal. Only sessions in which participants completed at least one signal during REM sleep were included in the analyses ($n = 11$ participants, 19 sessions). Data from three participants were excluded from spectral analyses because they lacked at least one trial in each condition: Two participants did not perform either eyes-open or eyes-closed signals during REM sleep, and one (CL) had poor data quality for the waking control conditions.

Although our sample size is small, warranting caution in generalizing our findings regarding alpha power, many participants experienced several lucid dreams and completed the task several times (see Table 1), and our statistical approach takes advantage of each trial rather than relying on averaged values per participant. Furthermore, because closing one's eyes while awake increases alpha power so reliably in healthy individuals (Barry, Clarke, Johnstone, Magee, & Rushby, 2007), even single examples of closing one's eyes during dreams can be

Table 1. Number of Sleep Study Sessions and Signals Performed in REM Sleep per Participant

Participant	No. of Sessions	No. of Signals			
		Eyes-Open	Eyes-Closed	Visual Content	No Visual Content
101	3	1	1	0	0
102	6	11	8	17	9
103	1	1	1	0	0
104	6	5	4	3	1
105	1	2	0	2	3
106	1	1	1	0	1
107	2	2	2	2	1
108	1	0	0	0	0
109	1	0	1	0	1
AC	2	16	18	19	4
CL	1	1	4	0	0
VF	1	1	3	0	3
LH	1	0	0	0	0

informative, particularly in healthy individuals with high alpha power reactivity to eye closure (Niedermeyer, 2005). Each sleep study session consisted of electrode application and one or more opportunities to sleep, as described below. Participants completed one to six sleep study sessions each (see Table 1) and were invited back after their first session for subsequent sessions, depending on their interest and availability.

Procedure

Procedures were approved by ethics committees at corresponding institutions (Northwestern University for healthy participants and CPP Ile-de-France 8 for those with narcolepsy). Healthy participants were compensated \$70 for their participation. Participants with narcolepsy were compensated 70€. Upon scheduling, all participants were e-mailed the task they would be asked to complete in the lab, and we suggested that they practice it in advance several times while awake and also during sleep if they had any lucid dreams.

The following steps applied to healthy participants during overnight laboratory sessions. They came to the laboratory about 1.5 hr before their usual bedtime and gave informed consent. Next, they were prepared for polysomnography (PSG) using a NeuroScan SynAmps system with a 1000-Hz sampling rate, including EEG channels F3, F4, C3, C4, O1, Oz, and O2; chin EMG; horizontal and vertical EOG, and a nasal cannula to measure airflow. Before sleep, we checked sound cue intensity, taking note of the lowest volume audible for participants and what they felt would be comfortable for sleep.

Participants then completed waking eyes-open and eyes-closed conditions. They opened and closed their eyes at least twice, for 30 sec each time, while completing the following: relaxing in normal lighting, relaxing while wearing blackout goggles, imagining a vivid visual scene while wearing blackout goggles, and imagining complete darkness while wearing blackout goggles. Healthy participants completed these conditions in this order; participants with narcolepsy completed these control conditions in a randomized order. Four healthy participants completed additional conditions after relaxing in normal lighting (relaxing during visual stimulation with color-changing LED lights blinking on and off, visible through closed eyelids).

Participants were instructed that if they experienced a lucid dream, they should open and close their dream-eyes and report on their progress in real time via sniffing, eye movements, and/or twitching signals. They were told to do the task as many times as they wished and were not given any specific instructions on how long to wait before changing their eyelid position. Healthy participants were given the option to signal when they became lucid using two left–right eye movements; participants with narcolepsy signaled lucidity with alternating corrugator and zygomatic muscle twitches.

Given the novelty of using sniffing for dream communication, the signaling schemes evolved over the course of the study (see Supplement A). In the first six study sessions, participants were instructed to open, close, and then reopen their dream-eyes, signaling at each change in eyelid position by performing between two and four in–out sniffs or left–right eye movements. Thus, the meaning of each signal corresponded to whether it appeared

first (eyes open), second (eyes closed), or third (eyes reopened) in the sequence. In all subsequent sessions, we engaged four different signals each consisting of a separate sniffing or facial twitching pattern to indicate eyes open, eyes closed, visual content, and no visual content. In four sessions, these signals included successive inhales and exhales, in–out sniffs, and breath holding. Because experimenters noted that in–out sniffs were the most distinctive, in the 14 final sessions with healthy participants, signals consisted of one to four in–out sniffs (see Figure 1 for an example). Our success with sniffing signals in healthy individuals prompted a subsequently conducted investigation utilizing our method of sniffing communication, culminating in an article co-authored by some of the present authors (Morris et al., 2025).

All dreamers with narcolepsy utilized the same signaling scheme, which consisted of one or two in–out sniffs to indicate opening and closing one’s eyes and two zygomatic or corrugator twitches to indicate the presence or absence of visual content. These facial twitches have been validated in lucid dreamers with narcolepsy (Türker et al., 2023; Konkoly et al., 2021) and were utilized here to make the signaling scheme easier to remember for those participants.

Healthy participants were told that they would be woken up at 4 a.m. for lucid dreaming training, but to attempt the task if they happened to have a lucid dream in the first half of the night. This awakening was included in the procedure because sleep interruption tends to promote lucid dreaming (Erlacher & Stumbrys, 2020). At 4 a.m., participants practiced the task several times and then underwent training for TLR. In this training, sound cues were repeatedly associated with a lucid state of mind (Carr et al., 2023). The TLR cue was three consecutive pure-tone beeps, each lasting 650 msec, and increasing in pitch from 400 to 600 to 800 Hz. The training typically lasted 20 min, though it was shortened for participants who felt it would be difficult to fall back asleep if the training did not end sooner. One healthy participant (Participant 103) completed an early morning nap instead of an overnight sleep study, so for this participant the training was conducted immediately prior to the nap.

When participants entered REM sleep, TLR cues were quietly presented by experimenters, approximately one cue every 30 sec, to trigger lucid dreams. Experimenters immediately paused cueing if REM sleep showed signs of disruption, such as increased muscle tone, slow rolling eye movements, or increased high-frequency activity. Cueing was resumed when there were no signs of arousal after at least one additional rapid eye movement was observed. If the participant did not begin the task after several TLR cues, we also presented them with verbal reminders to become lucid and complete the task, such as “Remember to sniff and close your eyes,” or “Close your eyes in the dream,” or “Hey [name], listen to this! You may be dreaming” (see Supplement B for an example). Importantly, to avoid cueing-related arousals during task performance, cueing was also paused as soon as a participant produced a signal.

If participants began signaling during REM sleep but then stopped, they were prompted with more TLR cues to perform the task again. If the participant did not signal again after repeated attempts, they were woken for a semi-structured dream report interview conducted via two-way intercom. They were asked to report everything they could remember since they last fell asleep, and dream reports were considered to pertain to any signals performed since the preceding dream report. They were asked to give as much detail as possible, particularly about anything pertaining to the task, signals they performed, or what they saw when their eyes were open and closed. Participants slept for as long as they wanted, with the option to return to sleep after each dream report and attempt to lucid dream again. After they finished sleeping, first-time participants completed a questionnaire about their lucid dreaming history and were asked if they would like to participate in subsequent overnight sessions.

Lucid dreamers with narcolepsy followed the same procedure as described for healthy participants, with a few exceptions. Their sleep was measured during several daytime naps instead of overnight. No TLR training or cues were administered. They arrived at the lab in the morning and were asked to stop all medications on the day of the experiment so they could fall asleep more easily. They were prepared for polysomnography using Grael 4 K PSG/EEG (Medical Data Technology, Compumedics) with the same EEG montage plus an electrocardiogram channel, at a 256-Hz sampling rate. They were given five different nap opportunities throughout the day, approximately every 2 hr, in which they were instructed to open and close their eyes within the dream and report on their progress and visual experience. These participants had difficulty staying awake when attempting to perform wake control conditions, so periods of EEG were manually chosen for instances when the participant appeared clearly awake and had their eyes open versus closed.

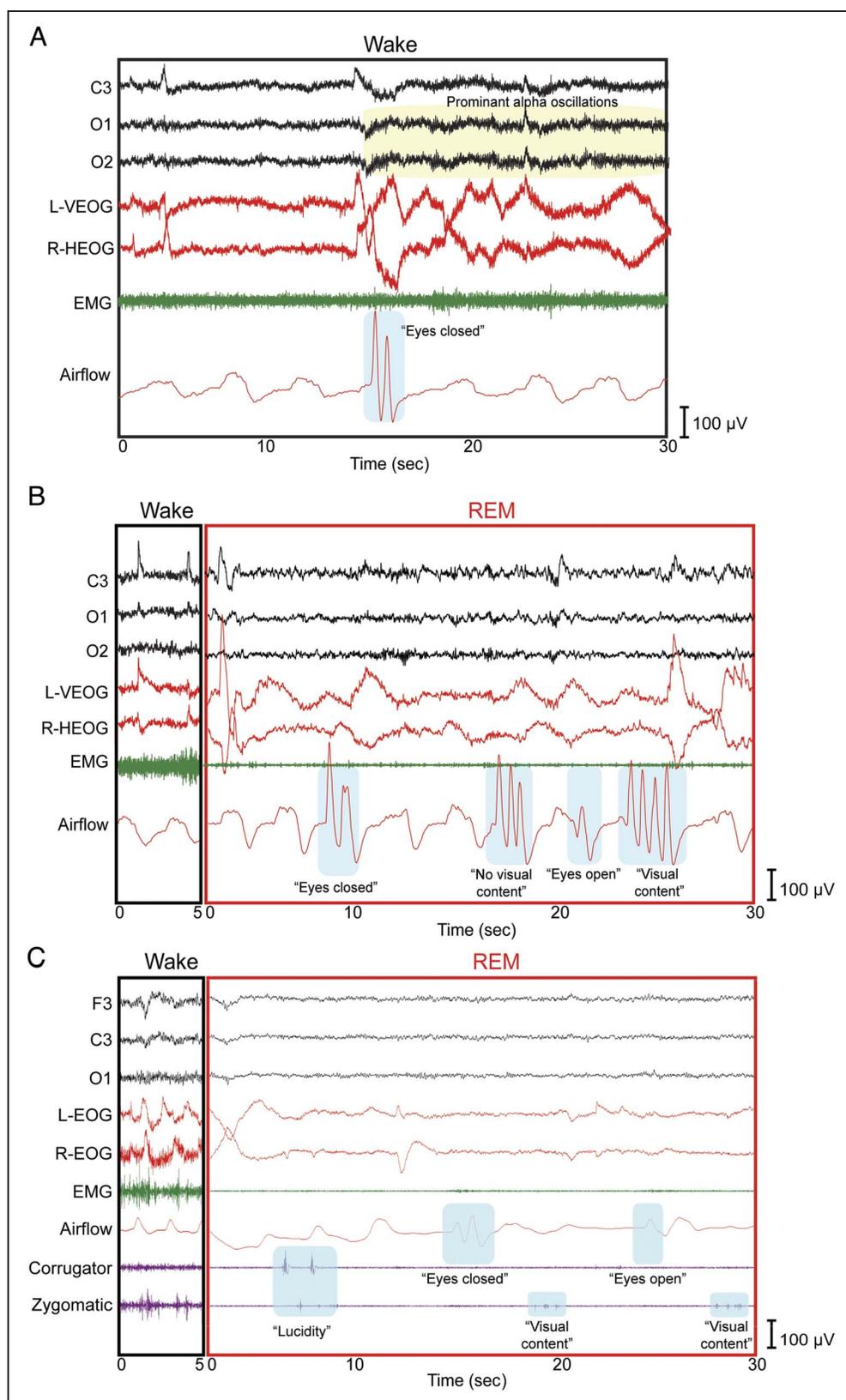
Preprocessing

Sleep was scored by one expert sleep scorer (healthy participants) or by two expert sleep scorers (participants with narcolepsy) according to international guidelines (American Academy of Sleep Medicine, 2023a). For sleep scoring, EEG and EOG data were filtered at 0.3–0.35 Hz, and EMG data were filtered at 10–100 Hz.

Signal Identification

Signals were initially identified by one rater and included if agreed upon by a second rater who was blind to the initial ratings, dream reports, and cues presented. For healthy participants, the second rater reviewed all epochs in REM sleep with potential signals. For lucid dreamers with narcolepsy, the second rater reviewed all recordings. Raters classified each signal and demarcated its start and end time.

Figure 1. Examples of task performance in wake and REM sleep. (A) Example of increased alpha oscillations (highlighted in yellow) upon eye closure during wake. Before signaling eye closure (two in-out sniffs), the participant's eyes were open. (B) Comparing sleep physiology during a 5-sec period of wake (left) and a 30-sec period of REM (right) demonstrates typical characteristics of REM sleep. Data show the same healthy participant from Panel A completing the task during a REM period later that night after receiving a cue to induce lucidity approximately 1 min earlier. The participant performed eyes-closed signaling (two in-out sniffs) and then indicated absent visual content (three in-out sniffs), followed by eyes-open signaling (one in-out sniff) and an indication of visual content (four in-out sniffs). Upon awakening, the participant reported, "I was in a hotel ... I walked up to a wall and ... put my hands on the wall and I was like, look at my fingers, look at the wall, look closely, make it clear, then I did the task, and I think the visuals were like as expected at that point, closing my eyes, and opening them." (C) A lucid dreamer with narcolepsy completing sniff and facial muscle contraction signals. The participant first performed alternating corrugator and zygomatic muscle twitches to indicate lucidity. Then, the participant performed two in-out sniffs to indicate their eyes were closed and then three zygomatic twitches to indicate the presence of visual content. Next, they performed one in-out sniff to indicate their eyes were open and again three zygomatic twitches to indicate that they were still experiencing visual percepts. Upon awakening, the participant reported (translated from French), "I found myself in a building that looks like a company building, I walked around to explore the place, and I did the task several times during my exploration. Each time I closed my eyes, I kept seeing the same visual I had before when my eyes were open and when I opened them again, it was always the same visual."



EOG Signals

EOG was scored to detect rapid eye movements as well as left–right lucidity eye signals in healthy participants. For healthy participants, EOG channels in REM periods after sleep interruption were scored by a blind rater. For participants with narcolepsy, the initial rater scored EOG channels in the subset of data where visual percepts and eyelid status were indicated. The rater identified rapid eye movements, defined as a synchronized change of EOG potentials of opposing polarity in the two EOG channels, with the initial deflection lasting less than 0.5 sec and exceeding the threshold of 25 μ V (Maranci et al., 2022). Horizontal EOG channels were used to detect eye movements (with the exception of one healthy participant for whom vertical EOG was used because horizontal EOG recordings were inadequate). If at least one eye movement was present in the interval from 1 to 6 sec after a given signal, that REM sleep period was marked as containing eye movements.

EEG Data

EEG data from healthy participants were preprocessed using the EEGlab toolbox in MATLAB (Delorme & Makeig, 2004) and using the MNE-Python library (Gramfort et al., 2013) for participants with narcolepsy. EEG data were collected with the initial bandpass filtering of 0.1–100 Hz for healthy participants and without any initial bandpass filtering for participants with narcolepsy. Data from individuals with narcolepsy were filtered between 0.3 and 35 Hz prior to analysis. Data were referenced to the right mastoid for healthy participants and to the average of two mastoids for participants with narcolepsy. Channels with poor signal quality upon visual inspection were excluded from analyses. No other cleaning steps were applied given that participants were either asleep or motionless during the analysis periods of interest. Power was calculated from seconds 1 to 6 following each signal in each of four frequency bands (delta: 2.5–4 Hz, theta: 4–8 Hz, alpha: 8–13 Hz, beta: 13–30.5 Hz). Power was calculated using Welch’s method (*pwelch* function in MATLAB). As part of Welch’s method for spectral estimation, within each 5-sec epoch we used 1-sec sliding subwindows and 50% overlap in 0.5-Hz bins, and bins were averaged to obtain the average power for each 5-sec epoch of interest, resulting in one power value in each frequency band for each signal.

Statistical Analysis

Unless noted otherwise, all statistical tests were done in R using the *lmer* function to compute linear mixed models. All mixed models included participant ID as a random intercept to account for variability between participants and the different number of trials per participant. In cases where tests involved an interaction term, we computed ANOVAs on the linear mixed models. Follow-up *t* tests were computed using the *emmeans* and *pairs* functions

in R using the Tukey method to correct for multiple comparisons. Cohen’s *d* effect sizes were calculated with the *eff_size* function from the *emmeans* package in R and partial η^2 effect sizes were calculated with the *F_to_Eta2* function from the *effectsize* package in R. Multiple nonsignificant *p* values are reported using the notation “*ps* >” to indicate that all *p* values are greater than the value indicated.

RESULTS

Real-time Signals of Visual Content in Lucid Dreams

Eleven of the participants (85%) produced task-related signals during REM sleep, totaling 150 signals indicating eyelid position or presence of visual content. This total was obtained in 15 sessions from eight healthy participants plus four sessions from three participants with narcolepsy. Combined, participants completed 43 eyes-closed signals, 41 eyes-open signals, 23 no-visual-content signals, and 43 visual-content signals (see Table 1). In all cases, a dream report confirmed that the participant had attempted the task (examples shown in Figure 1 and Supplement C). For EEG spectral analyses, data were excluded from participants without at least one trial in each condition, resulting in a sample of 38 eyes-closed signals, 38 eyes-open signals, 19 no-visual-content signals, and 41 visual-content signals during REM sleep. We thus accomplished our primary goal of demonstrating that dreamers could dynamically report on actions and changing percepts using a vocabulary of different signals.

The Relationship between Eye Closure and Visual Content in Dreams

We next tested whether closing one’s eyes in a lucid dream reduced the presence of visual percepts, according to real-time reports. There were 49 cases in which an eyes-open or eyes-closed signal was followed within 30 sec by a visual-content or no-visual-content signal (see Table 2 and Figure 2). We ran a logistic mixed-effects model (*glmer*) with visual content (present vs. absent) as the dependent variable and perceived eye position (open vs. closed) as the independent variable. We found that dreaming of closing one’s eyes significantly reduced the presence of visual content ($\beta = 3.18$, 95% CI [0.7, 5.66], $p = .01$). According to dream reports given upon awakening, closing one’s eyes often resulted in a loss of visual experience without mention of any other qualities changing in the dream (for instance, “I was just seeing the landscape with my eyes open as we were driving by. And when I closed my eyes, I could not see the landscape”).

Occasionally, dreamers reported that closing or opening their eyes changed their visual experience without eliminating it (e.g., “I could vaguely make out the outlines of objects ... like I could see through my eyelids” or

Table 2. Breakdown of Event Reports When Dream-eyes Were Open versus Closed

<i>Dream-eyes</i>	<i>Group</i>	<i>No. of Events</i>	<i>Events with Visual Content</i>	<i>Events with No Visual Content</i>	<i>Percent with Visual Content</i>
Open	Healthy	16	13	3	81%
	Narcolepsy	8	8	0	100%
	Total	24	21	3	88%
Closed	Healthy	8	2	6	25%
	Narcolepsy	17	11	6	65%
	Total	25	13	12	52%

Values indicate the number of times eyes-open signals and eyes-closed signals were followed by signals indicating visual content and no visual content.

“before I closed my eyes, I had an image of the supermarket, and when I closed my eyes I saw a person walking forward with a supermarket cart”). However, it was not possible to systematically investigate this point as we did not specifically ask participants to report visual content before closing their eyes, and real-time signals did not differentiate between constant and changed visual percepts. At other times, dream experiences upon eye closure were as if the eyes remained open (e.g., “I could still see everything clearly, it was a bright day”). See Table 3 and Supplement C for more examples of the impact of eyelid status on the dreamers’ experiences.

Occipital Alpha Power following Eye Closure during Wake and REM Sleep

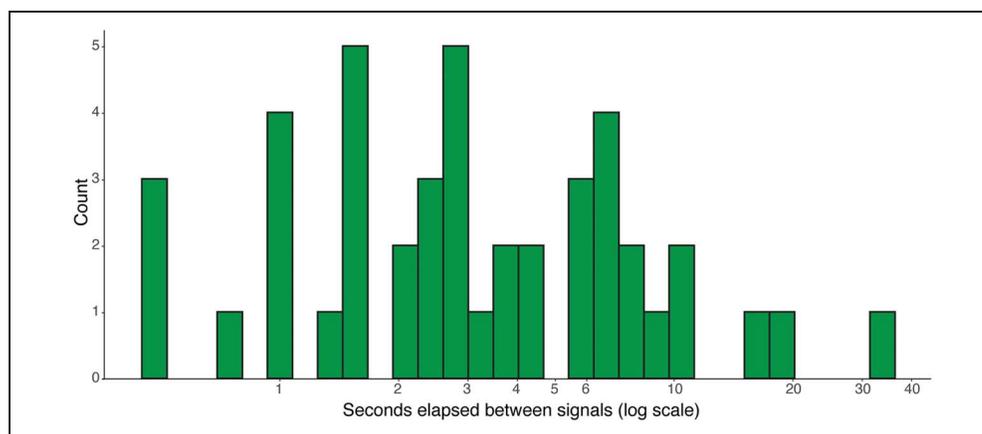
As a preliminary investigation into whether eye closure changed occipital power differently during dreaming and waking, we computed linear mixed models to test whether occipital power in each frequency band (delta, theta, alpha, beta) was predicted by sleep stage (wake, REM), perceived eyelid position (open, closed), and their interaction (occipital power \sim sleep stage * perceived eyelid

position), using the Bonferroni method to adjust p values for these four comparisons.

As shown in Figure 3A, power was lower in REM sleep than in wake for both occipital alpha, $F(1, 178.59) = 19.09$, $p = .0008$, partial $\eta^2 = .1$, and beta, $F(1, 179.59) = 41.43$, $p < .0004$, partial $\eta^2 = .19$. Power also varied with perceived eyelid position for both alpha, $F(1, 176.71) = 25.25$, $p < .0004$, partial $\eta^2 = .13$, and beta, $F(1, 177.56) = 12.71$, $p = .002$, partial $\eta^2 = .07$. There were also significant interactions indicating that being awake versus asleep influenced the degree to which perceived eye closure affected alpha, $F(1, 176.77) = 25.32$, $p < .0004$, partial $\eta^2 = .13$, and beta, $F(1, 177.63) = 11.52$, $p = .003$, partial $\eta^2 = .06$. Follow-up comparisons showed significant power increases upon eye closure during wake for alpha, $t(177) = 7.93$, $p < .0004$, Cohen’s $d = 1.5$, and beta, $t(177) = 5.48$, $p < .0004$, Cohen’s $d = 1.04$, whereas these effects were not observed during REM sleep ($ps > .99$). Occipital power in the delta and theta frequency bands did not change depending on sleep stage, eyelid position, or their interaction ($ps > .4$).

Because 37 of the 76 REM sleep trials contained subsequent signals during the analysis window (see Figure 2), we checked whether these additional signals impacted

Figure 2. Time between signals in REM sleep. Histogram of seconds elapsed between eyelid position and subsequent visual content signals within given dreams. Includes data from 50 signal pairs from eight participants. Signals about visual content always followed eye position signals within 30 sec, except for one participant who produced a no-visual-content signal 35 sec after an eyes-closed signal and one participant (data not shown) who produced a no-visual content signal 675 sec after an eyes-open signal. Overall, the 6-sec analysis period following eyes-open or eyes-closed signals, 37 out of the 81 eyelid position trials contained another signal. Thirty-five of these signals indicated visual content or no visual content, and in two cases they indicated a change in eyelid position.



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Table 3. Examples of Reported Task Performance in Dreams

<i>Real-time Signals</i>	<i>Dream Report Excerpts</i>
Eyes-open Visual content Eyes-closed	I was driving in a car, I was in the backseat, and all three people in the car were geese. I was a goose, I was a goose, as well. We were just driving along and I realized I was in a dream. I was just seeing the landscape with my eyes open as we were driving by. And when I closed my eyes I could not see the landscape.
Visual content Eyes-closed No visual content	I was walking down the stairs ... I kind of flew/bounced and lost gravity in the dream. Then you cued me, and I was like, "Okay I'm lucid." I could see things ... When I closed my eyes, I couldn't see anything.
Eyes-closed Eyes-open Visual content	I was on my phone, and I was reading ... I noticed the experimenter sleeping on the floor ... I was like, "Hey hey hey! I think I'm dreaming, I'm not sure" ... When my eyes were open, I had visuals of the room, and when my eyes were closed, I didn't have visuals.
No visual content Eyes-open No visual content Visual content No visual content Visual content Eyes-open	There was no dream at the beginning, it was all black, so I tried to close my eyes ... I opened my eyes but there was still no visual ... I started trying to move around and trying to get visuals to appear. I started singing a song, "I can see clearly now the rain is gone," and nothing was happening so I started floating around, and I left the lab room. Then I noticed that I could start seeing things, because I left this room and saw you, so once I could see visuals ... I closed my eyes ... I think now even when I closed my eyes there were still visuals.
Eyes-closed Eyes-open No visual content	I had a false awakening where the experimenter came in to open the door to get me up ... and I realized that it was a dream ... I closed my eyes in the dream, and the scene dissolved, but it was accompanied by a very loud sound, like a humming or like a vibration or something ... I then signaled that my visuals were gone. And then I signaled reopening my eyes, and no visuals reappeared, so I signaled that there were no visuals.
Eyes-closed No visual content Eyes-open Visual content Eyes-closed Visual content Eyes-open Visual content Eyes-closed Visual content Eyes-open Eyes-closed Visual content Eyes-open Eyes-closed Visual content Eyes-open Visual content	... It was an L-shaped room ... while I was exploring it ... it turned blue ... When I closed my eyes ... at first I couldn't see anything, but then 2–3 seconds later I started to have a visual, a part of a face ... I started to open my eyes again. At first I saw nothing, and then I started to walk, and I told myself I should tell them I can see something now. Then I entered another blue room ... I closed my eyes, I had visual content ... I think it was a screen or something. When I opened my eyes, my surroundings had changed ... now there were PCs ... I saw a moving walkway ... I went through, there were people with weird heads, they were like zombies ... I closed my eyes, I could still see visuals, but when I opened my eyes, I remembered there were a lot more zombies than before, ... isolated myself in a corner and closed my eyes. I had a visual of a room with furniture, it looked like a classroom. When I opened my eyes, the visual took 1 or 2 seconds to stabilize, but my surroundings had completely changed. Now I was in a room where a cooking class was taking place ...
Eyes-closed Visual content Eyes-open Visual content Eyes-closed Visual content Eyes-open Visual content Eyes-closed Visual content Eyes-open Eyes-closed Eyes-closed No visual content Eyes-open	... I think I did the task at least 5 times. The general pattern was that when I closed my eyes, I still saw what was in front of me before I closed my eyes, and when I opened my eyes, I still saw what was before. ... So, I asked myself, was I really closing my eyes? And what made me think that I was closing my eyes? So, I tried to concentrate, and I noticed that I had a little tactile feedback when I closed my eyes, but even that feeling started to fade after a while.

Examples of signals observed during REM sleep and the relevant excerpts of subsequent dream reports. The first five examples are from healthy participants, and the final two are from participants with narcolepsy.

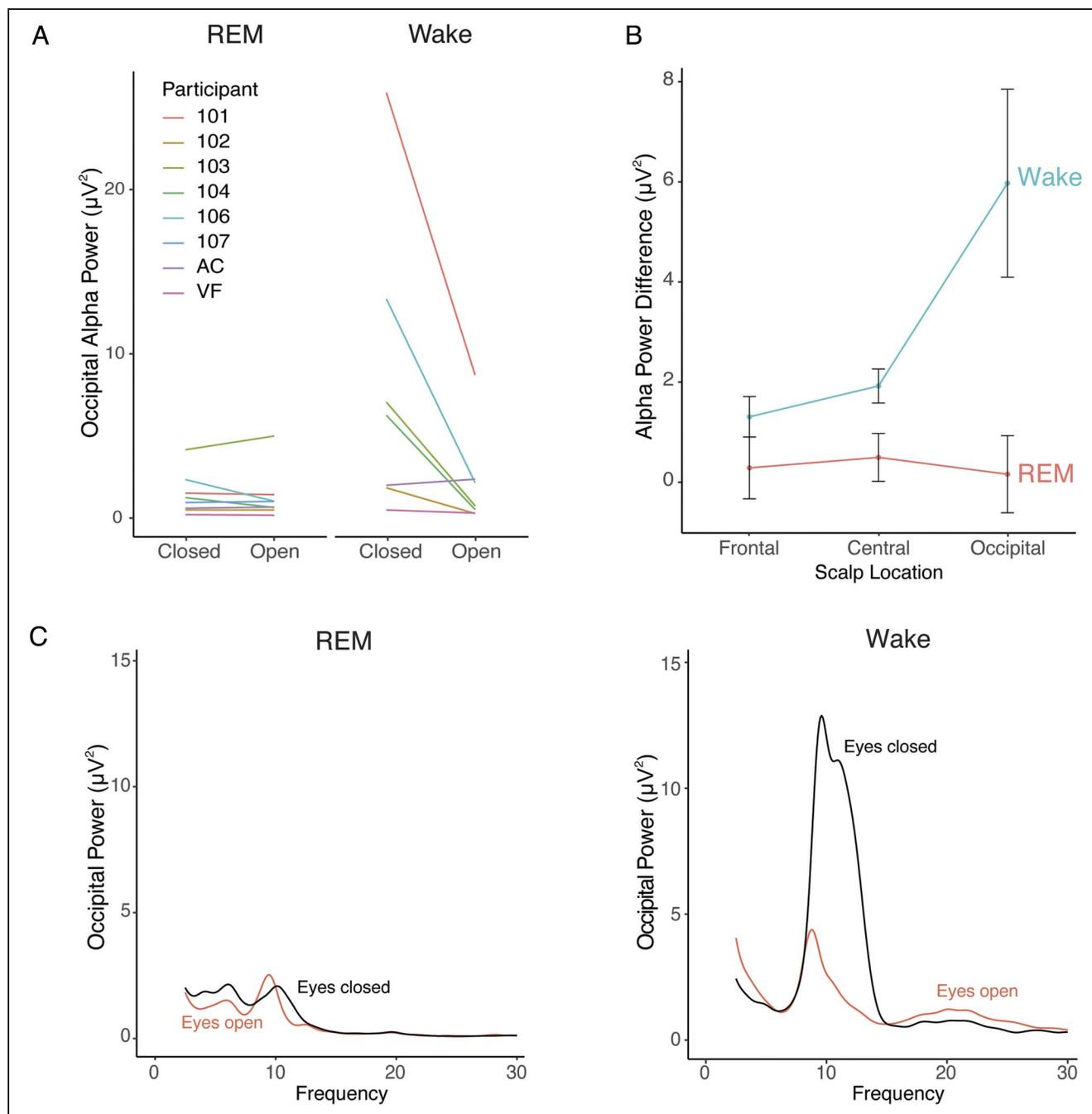


Figure 3. Alpha power as a function of eye closure and sleep stage. Data are from seconds 1 to 6 following eyes-open or eyes-closed signals. (A) Occipital alpha power increased upon eye closure during wake but not during REM sleep. Lines connect each participant's average alpha power when the eyes were open and closed. (B) Grand averaged alpha power difference (eyes-closed minus eyes-open) in frontal, central, and occipital channels. Error bars represent within-subject standard error of the mean. (C) Grand averaged EEG power spectrum when the eyes are perceived to be open versus closed in occipital channels.

power. We separately tested whether occipital delta, theta, alpha, and beta power were predicted by perceived eyelid position (open/closed), the presence of a signal during the analysis window (signal/no signal), and their interaction (occipital power \sim perceived eyelid position \times subsequent signal). We used the Bonferroni method to adjust p values for these four comparisons. We did not find evidence that these additional signals or their

interaction with perceived eyelid position impacted power in any band ($ps > .05$).

Figure 3B shows results from different scalp locations. To analyze the topography of alpha and beta power changes upon eye closure, we calculated each participant's difference in alpha and beta power (eyes-closed minus eyes-open) in frontal, central, and occipital channels. We then tested whether differences in power upon

eye closure were predicted by sleep stage (wake, REM), scalp location (frontal, central, occipital), and their interaction (average power difference \sim sleep stage * scalp location), Bonferroni correcting for these two comparisons. The difference in alpha power upon eye closure was predicted by sleep stage, $F(1, 30) = 13.62, p = .001$, partial $\eta^2 = .31$, and the interaction between sleep stage and scalp location, $F(2, 30) = 4.23, p = .048$, partial $\eta^2 =$

.22. Specifically, the increase in alpha power upon eye closure during wake was greater in occipital channels than central channels, $t(30) = -3.14, p = .02$, Cohen's $d = -1.7$, and frontal channels, $t(30) = -3.61, p = .006$, Cohen's $d = -1.9$. During REM sleep, the difference in alpha power upon eye closure did not vary based on scalp location ($ps > .9$). Regarding beta power, there were no topographic differences upon perceived eye closure

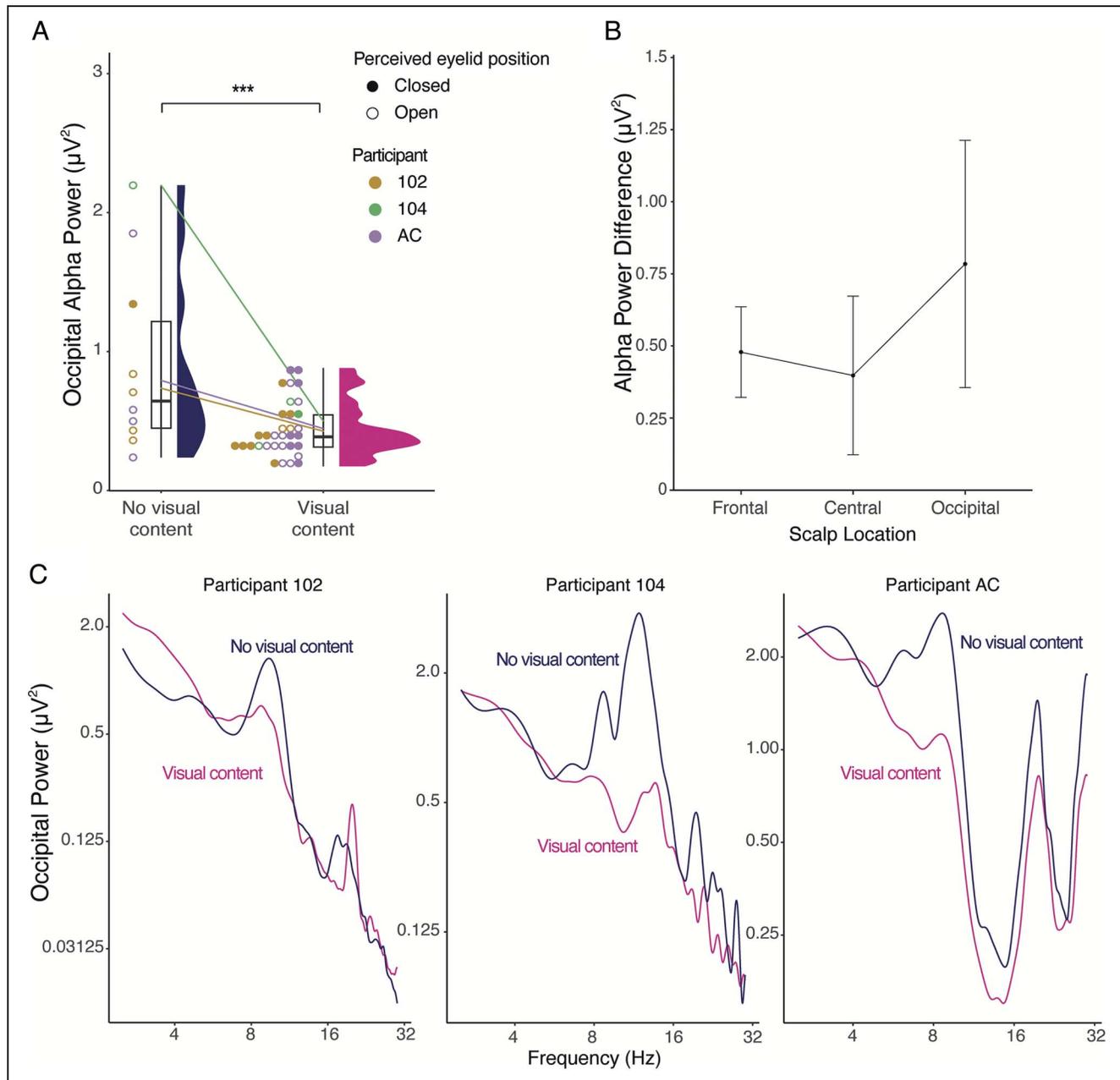


Figure 4. Alpha power depending on REM sleep visual content. Power during seconds 1–6 after opening or closing one's eyes depended on whether the dream subsequently contained visual content or not. These analyses included three participants who indicated both the presence and absence of visual content following changes in eyelid position: participant with narcolepsy AC and healthy participants 102 and 104. (A) Alpha power increased when visual content was absent from dreams. Points represent binned values for each trial during REM sleep, and lines connect average values for each participant. Half-violin plots show the distribution. (B) Mean difference in alpha power (no visual content minus visual content) in frontal, central, and occipital channels. Points represent grand averages, and error bars show within-subject standard errors of the mean. (C) The EEG spectrum for each participant included a difference in the alpha band for visual content versus no visual content. *** indicates statistical significance at $p < .001$.

Table 4. Visual Experiences in Association with Rapid Eye Movements

<i>Rapid Eye Movements</i>	<i>All Events</i>	<i>No Visual Content</i>	<i>Visual Content</i>	<i>Percent Visual Content</i>
With	22 (9 with narcolepsy)	4 (2 with narcolepsy)	18 (7 with narcolepsy)	82%
Without	27 (16 with narcolepsy)	11 (4 with narcolepsy)	16 (12 with narcolepsy)	59%
% with eye movements	44.9%	27%	53%	

The table details the frequency with which participants indicated visual content versus no visual content during the 1–6 sec period after each eyes-open or eyes-closed signal depending on whether it contained rapid eye movements or not.

based on sleep stage, scalp location, or their interaction ($p_s > .3$).

Note that participants with narcolepsy did not exhibit the characteristic alpha power increase upon eye closure during wake (Figure 3A). Previous research described alpha power increases upon eye closure in individuals with narcolepsy (Türker et al., 2023), but this effect was not always found (Alloway, Ogilvie, & Shapiro, 1997) and may depend on participants' level of drowsiness.

Alpha Power in Dreams without Visual Content

A third experimental goal was to compare REM sleep EEG data as a function of visual content. All 11 lucid dreamers produced eyes-open or eyes-closed signals, often repeatedly, but only three subsequently reported experiencing both the presence and absence of visual content. Accordingly, we conducted a preliminary analysis of data restricted to the three participants who indicated experiencing both visual and nonvisual dreams within 30 sec after indicating a change in eyelid position. We tested whether occipital alpha power was predicted by the presence or absence of visual content (occipital alpha power \sim visual content). As shown in Figure 4, visual content was predicted by decreased occipital alpha power, $t(1, 38.05) = -3.66, p = .0008$, Cohen's $d = 1.33$.

To assess topography, we tested whether occipital alpha power was predicted by visual content (present vs. absent), scalp location (frontal, central, occipital), and their interaction (occipital alpha power \sim visual content * scalp location). We found a main effect of visual content, $F(1, 38.99) = 20.74, p < .0001$, partial $\eta^2 = .65$, but no interaction with scalp location ($p > .8$). As shown in Figure 4B, the effect was clear at each scalp location.

Time Association of Visual Experiences with Rapid Eye Movements in REM Sleep

We used a Fisher's exact test to test whether visual content was related to the presence of rapid eye movements in the 5-sec interval beginning 1-sec after dreamers signaled opening or closing their dream-eyes. Table 4 shows that there was a pattern for visual content to more often be associated with periods of rapid eye movements than periods without rapid eye movements, but this pattern was nonsignificant ($p = .12$, odds ratio = 3.02).

DISCUSSION

We employed a novel approach to extract EEG data time-locked to dynamic reports of experiences within dreams. Real-time reports from lucid dreamers have been used to indicate lucidity and the temporal progression of predefined tasks (e.g., LaBerge et al., 2018; Erlacher et al., 2014; Dresler et al., 2011) but have not been used flexibly to inform neural analyses of unpredictable dream percepts. Here, we take a step forward by demonstrating that a vocabulary of signals can be used dynamically by people to report on their dream actions and changing dream perceptions.

We also demonstrated that people can communicate from within dreams using sniffing signals. This methodological advance builds on two related findings, a published abstract of a polysomnographic recording of a lucid dreamer executing rapid sniffs (LaBerge & Dement, 1982) and a Russian-language publication of a lucid dreamer responding to math questions using respiration (Mironov, Sinin, & Dorokhov, 2018). Whereas it was previously shown that respiration can correspond to dreamt events in the case of lucid dreamers holding their breath in their dreams (Oudiette et al., 2018), here we took the additional step of demonstrating that dreamers can execute specific sniffing patterns as a means of volitional communication from dreams. Note that sniffing signals were also recently utilized to indicate the start and end of a dreamed task in one of our subsequent studies that was premised on the results reported here (Morris et al., 2025). We also used signals of facial muscle contractions, known to be an effective communication strategy in participants with narcolepsy (Türker et al., 2023; Konkoly et al., 2021). These methods are advantageous for studying the dreaming visual system because they sidestep the necessity of eye movements signaling, which has been considered the "gold standard" in lucid dreaming research (Baird, Mota-Rolim, & Dresler, 2019) but likely changes visual system functioning at the time of signaling.

While prior studies emphasized converging neural correlates of dreaming and waking experience, we demonstrated preliminary evidence of divergence: Dreaming of closing one's eyes did not coincide with the increased alpha power seen during wakefulness. This divergence may reflect the neurophysiology of REM sleep, which could limit visual cortex inhibition and the accompanying alpha oscillations typical of eye closure. Additionally, body representations may be weakly activated in dreams, such

that dreamt proprioceptive representations of eyelids (compared with actual eyelids) are less capable of influencing inhibition in visual cortex. Indeed, one dreamer who signaled closing their dream-eyes reported upon awakening that they wondered how they could be sure they were actually closing their dream-eyes (Table 3; Supplement B). A prior study found that about 18% of dreams occur from a third-person perspective (Erdeniz, Tekgün, Lenggenhager, & Lopez, 2023), so it would have been interesting to query all dreamers on the perspective by which they experienced the dream. Note that we also found an increase in beta power upon waking eye closure that did not occur in REM sleep, which appeared to be driven by increased power at frequencies below 15 Hz and likely also reflects reduced visual processing (Barry et al., 2007). Although our results should be interpreted with caution given our small sample size, it is worth noting that many dreamers completed the task several times, and by using mixed models we increased our power to detect effects compared with a conventional ANOVA comparing only averaged values for each participant.

Another possibility for why eye closure during dreams did not reliably increase alpha is that there was distinctly more experiential heterogeneity compared with eye closure during waking. When we are awake, closing our eyes reliably reduces visual experience. Not so during a dream. In our study, eye closure eliminated visual content about half of the time. How can this heterogeneity across trials be explained? Lucid dream experiences are influenced by expectations about what is likely to happen (Windt, Harkness, & Lenggenhager, 2014; Gackenbach, 1988). We found that dreamers with narcolepsy continued to experience visual percepts 65% of the time after closing their dream-eyes, compared with only 25% of the time in healthy participants. In narcolepsy, expectations of reduced vision upon closing the eyes may be weakened, given that eye closure while awake often leads rapidly to hypnagogic imagery and sleep. However, expectations may not be the only factor influencing dream experiences; cortical activity may also be critical.

A remarkable finding, albeit also a finding in need of confirmation as it was based on evidence from only three participants, was greater alpha power when dreams momentarily lacked visual content. This finding is consistent with prior reports of reduced alpha power in the moments preceding awakenings in which visual dreams are reported (Stuart & Conduit, 2009; Bértolo et al., 2003). Whereas these studies relied on retrospective reports to assess visual dreaming, our finding provides evidence that reduced alpha power during visual dreaming is not due to other cognitive factors affecting retrospective dream recall (Esposito, Nielsen, & Paquette, 2004). However, as this analysis was only possible in a subset of three participants (those who signaled both the presence and absence of visual dream content), conclusions based on these findings must be considered quite tentative.

In this context, it can be helpful to consider how dreaming differs from waking imagination. During a lucid dream, individuals can perform smooth pursuit eye movements when tracking a visual target, but this is not possible during waking imagination (LaBerge et al., 2018). In our study, participants opened and closed their eyes while awake and relaxing, imagining a visual scene, or imagining darkness under various lighting conditions. In these waking circumstances, EEG analyses revealed higher occipital alpha power under normal lighting compared with blackout goggles, but no differences based on the relaxation or imagination task (Supplement E). We suspect that this finding primarily reflects decreasing alpha modulation to repeated eye closures (Adrian & Matthews, 1934), but this part of our experiment suffered from our inability to obtain trials from participants with narcolepsy in these conditions and the lack of counterbalanced order of conditions in healthy participants. Other studies have found lower alpha power during perception (Webster & Ro, 2020) and hallucinations (Romei et al., 2008), but higher alpha power during demanding visual imagination tasks (Cooper et al., 2003). The evidence for lower alpha power during visual dreaming in the present study and others (Stuart & Conduit, 2009; Bértolo et al., 2003; Wollman & Antrobus, 1987) suggests that suppressed alpha power supports perceptual experiences in both wake and REM sleep, differentiating the physiology of dreaming and perception from that of waking imagination.

Eye movements are another index of visual system activation in REM sleep (Gott et al., 2017; Andrillon, Nir, Cirelli, Tononi, & Fried, 2015; Hong et al., 2009), and there is a longstanding debate about whether they reflect dreamers looking around the dream environment or automatic activation contributing to the creation of dream percepts (Arnulf, 2011). Here, we found a trend for visual dreams to occur more often during periods with rapid eye movements, but the relationship was variable, in line with the mixed literature on awakenings after REM sleep with and without rapid eye movements (Stuart & Conduit, 2009; Hong et al., 1997; Antrobus, Kondo, Reinsel, & Fein, 1995; Foulkes & Pope, 1973; Molinari & Foulkes, 1969). Nevertheless, this finding adds to the evidence that eye movements often correspond to dream experiences but do not always accompany them (Arnulf, 2011; Leclair-Visonneau, Oudiette, Gaymard, Leu-Semenescu, & Arnulf, 2010; Zhou & King, 1997).

The methodology for communicating during dreams was well suited to our experimental goals, and although lucid dream induction and task performance were highly successful, many participants did not execute the full task in sequence. Importantly, we ceased presenting cues during task performance, given that sensory stimulation can produce alpha increases and arousals. Importantly, two variants of alpha oscillations during REM sleep have been described (Cantero, Atienza, & Salas, 2002). One variant occurs in bursts and is associated with environmental monitoring and slight arousal (Cantero, Atienza, & Salas,

2000); the other is more subtle, appearing as suppressed occipital alpha power during eye movements, thought to relate to dream experiences (Cantero, Atienza, Salas, & Gómez, 1999). Changes in alpha power in the present study can be attributed to visual system functioning as opposed to merely the arousal associated with signaling, given the task requirements. That is, the presence and absence of visual content occurred with equivalent signaling demands, as did closing and opening the eyes.

Our study relied on real-time reports from dreamers, which indicated the sequence of task performance in dreams. In some cases, real-time reports did not perfectly conform with dreams reported upon awakening (see Table 3 and Supplement C). These discrepancies could be due in part to the difficulty of executing dream signals, resulting in occasional ambiguous signals incorrectly identified by blind scorers. The potential for incorrectly executed or identified signals adds a source of variability in our REM sleep data, lessening our ability to detect electrophysiological differences based on dreamt eye closure. However, such cases represent a minority of trials and are unlikely to fully explain the dramatic differences observed between the neural response to eye closure in REM sleep and wake. Also, some discrepancy likely reflects failures or distortions in dream recall. For instance, many dreamers expressed uncertainty about their retrospective recall, whereas the objective record allowed us to retrieve details the dreamer may have missed. Indeed, the finding that dreamers correctly answered questions while remaining asleep substantiates the reliability of real-time signals (Türker et al., 2023; Konkoly et al., 2021).

In summary, we conclude that equipping lucid dreamers with a small vocabulary of signals to report on their dream actions and perceptions provides a new avenue for studying the neural basis of dreams. Our electrophysiological findings must be interpreted with caution given our small sample size, albeit one comparable to or larger than those in prior lab-based studies of psychophysiological correlates of task performance within lucid dreams (LaBerge et al., 2018; Schädlich, Erlacher, & Schredl, 2017; Erlacher et al., 2014). Our methodological advances open the door to many follow-up studies in many more people, including those not already proficient in lucid dreaming. For example, dynamic signaling about emotions within dreams could shed light on how emotions fluctuate within dreams and the role of dreaming in emotional processing. The present findings also demonstrate the value of improved methods for soliciting lucid dreams and communicating with dreamers—methods now poised to expand the neuroscience of conscious experience.

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Corresponding author: Karen Konkoly, Department of Psychology, Northwestern University, 2021 Sheridan Road, Evanston, IL 60208, e-mail: karenkonkoly@gmail.com.

Data Availability Statement

Data from healthy participants and analysis scripts are available from the authors upon reasonable request. Data from lucid dreamers with narcolepsy cannot be shared due to no institutional review board approval for data sharing. Supplemental Material can be accessed on this article's homepage: <https://doi.org/10.1162/JOCN.a.107>.

Author Contributions

Karen R. Konkoly: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing—Original draft; Writing—Review & editing. Saba Al-Youssef: Data curation; Formal analysis; Investigation; Visualization; Writing—Review & editing. Christopher Y. Mazurek: Investigation; Writing—Review & editing. Remington Mallett: Investigation; Writing—Review & editing. Daniel Morris: Data curation; Writing—Review & editing. Ana Gales: Data curation. Isabelle Arnulf: Funding acquisition; Resources; Supervision; Writing—Review & editing. Delphine Oudiette: Conceptualization; Funding acquisition; Methodology; Resources; Supervision; Writing—Review & editing. Ken A. Paller: Conceptualization; Funding acquisition; Methodology; Resources; Supervision; Writing—Review & editing.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience (JoCN)* during this period were $M(\text{an})/M = .407$, $W(\text{oman})/M = .32$, $M/W = .115$, and $W/W = .159$, the comparable proportions for the articles that these authorship teams cited were $M/M = .549$, $W/M = .257$, $M/W = .109$, and $W/W = .085$ (Postle and

Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this paper report its proportions of citations by gender category to be: M/M = .617; W/M = .149; M/W = .085; W/W = .149.

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