Trends in
Cognitive Sciences

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Review

New strategies for the cognitive science of dreaming

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Dreams have long captivated human curiosity, but empirical research in this area has faced significant methodological challenges. Recent interdisciplinary advances have now opened up new opportunities for studying dreams. This review synthesizes these advances into three methodological frameworks and describes how they overcome historical barriers in dream research. First, with observable dreaming, neural decoding and real-time reporting offer more direct measures of dream content. Second, with dream engineering, targeted stimulation and lucidity provide routes to experimentally manipulate dream content. Third, with computational dream analysis, the generation and exploration of large dream-report databases offer powerful avenues to identify patterns in dream content. By enabling researchers to systematically observe, engineer, and analyze dreams, these innovations herald a new era in dream science.

Highlights

The stage is set for breakthroughs in our understanding of dreaming.

Neuroscientific measures can track dream content in real time, thus avoiding sole reliance on subjective dream reports.

Manipulating dream content with sensory stimulation offers a route to test functional accounts of dreaming by using causal methods.

Applying computational language tools to large dream-report databases provides new insights into dream content and its connection to awake experience.

Similarities between neurocognitive representations while awake and during dreaming allow decoders trained on awake data to be applied to dreaming.

Advanced measurement and manipulation of dreams produces applications for the treatment of psychiatric symptoms and sleep disorders.

The barriers to studying dreaming

Thoughts and perceptions occur across the full 24 h cycle, but drastic variation in their neurocognitive features leads to a fundamental separation between thoughts that occur during sleep and wake. Despite significant progress in our understanding of the awake mind over past decades, the empirical study of dreams has remained opaque and challenging. What determines the content of dreams? Do dreams serve one or more functions? What neural processes generate dreams? Do dreams have an impact on health? These and other crucial questions remain largely unanswered, largely owing to methodological limitations.

Prospects for scientifically understanding dreams face various challenges. As with studies of any other human conscious experience, dream research must contend with the difficulty of objectively observing dream experiences, compounded by their seemingly chaotic content structure. However, an empirical science of dreaming is far from futile. We summarize here the historical limitations of studying dreaming as well as recent methodological advances that promise to overcome many of those limitations and usher in a new era for dream science (Figure 1, Key figure).

What is dreaming?

The development of electroencephalography (EEG) and the subsequent discovery of **rapid eye movement (REM) sleep** (see Glossary) led to a surge in dream-related publications from the mid-1950s through to the 1960s [1]. During this era, dreaming was predominantly linked to REM sleep [2], reinforcing the focus of behaviorism on objective measures and supporting definitions of dreaming that were exclusively tied to REM sleep. However, the introduction of experience-sampling methods such as the **serial awakening paradigm** [3,4] expanded our understanding by unveiling a broader spectrum of sleep-related mentation, thus moving beyond traditional narrative dreams. This paradigm shift towards embracing both objective measures and subjective experiences of sleep has mirrored broader changes in cognitive science, and has

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Key figure

The multimodal future of dream science

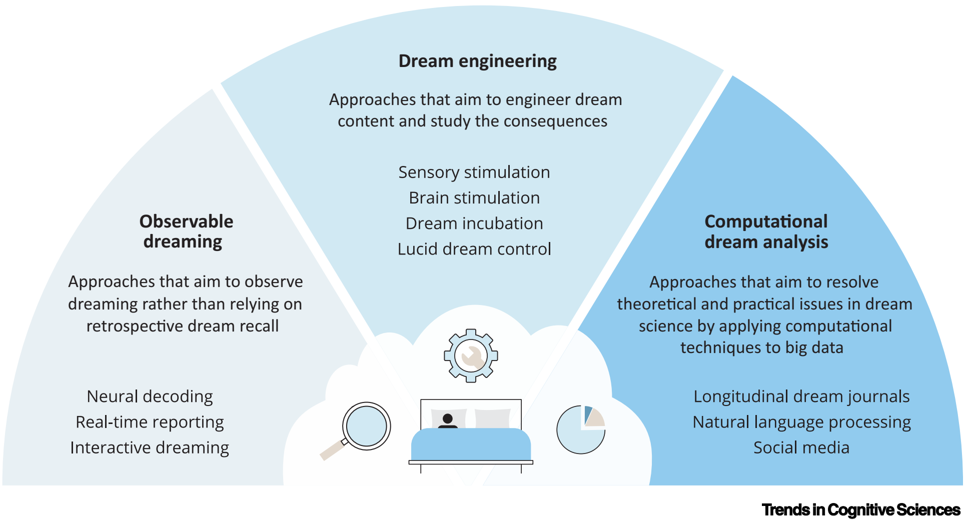

Figure 1. Three classes of methodological advances now enrich dream science. Observable dreaming (left) includes methods such as neural decoding, real-time dream reporting, and interactive dreaming, thereby offering a new window into dreams and removing the sole reliance on post-awakening dream recall. Dream engineering (middle) includes methods such as sensory stimulation and lucid dreaming to change dream content, offering the ability to design controlled studies where treatment groups differ in their dream content with no confounding differences before cue presentation in sleep. Computational dream analysis (right) complements these approaches by viewing dreams 'in the wild' – removed from artificial laboratory confines. Big data sources overcome individual variability, machine-learning tools overcome subjective rater bias, and the ability to track population dreams over time (e.g., during a pandemic) improves the study of how dreams are influenced by awake experiences.

revealed a more nuanced understanding of dreaming that recognizes the variety of experiences across different sleep states and throughout the night.

This shift prompted theoretical advances aimed at differentiating between various sleep experiences that have influenced the development of a taxonomy of dreaming – a crucial step towards a unified theory of dreaming. For instance, a prominent conceptual model distinguishes between narrative dreams, which simulate real-world spatiotemporal environments, and other minimal sleep experiences, such as hypnagogic imagery, that do not qualify as dreams [5,6]. Thus, although sleep is universally acknowledged to be necessary for dreaming, it is not always deemed to be sufficient on its own.

Despite these complexities, the methods highlighted in this review are largely agnostic regarding the specific nature of the dream experience. Instead, they aim to observe, manipulate, and quantify all types of experience during sleep. These methods are essential for advancing such theoretical frameworks and subsequently testing the hypotheses derived from them. Thus, for the purpose of this review, we define dreaming broadly as any conscious experience during sleep [7,8]. This encompasses everything from detailed narrative dreams to basic perceptual thinking, within a context where sleep itself is defined as a state of reversible behavioral quiescence with distinct electrophysiological features [9]. This inclusive definition facilitates further exploration and refinement of our understanding of dreaming by supporting the continuous dialectic between empirical and theoretical advances in the science of dreaming.

Glossary

Computational dream analysis: the use of big data, computational methods, and statistics to resolve theoretical and practical issues in dream science.
Dream engineering: the intentional manipulation or shaping of dream content, often through cognitive techniques or technological interventions.
Dream incorporation: the integration of external stimuli or experiences from the awake world into the content of dreams.
Dream incubation: the practice of focusing on a specific topic or question before sleep to influence or induce related content in dreams.
Dream-lag effect: the phenomenon where events while awake are incorporated into dreams after a delay of about 1 week.
Dream report: a subjective account or description of a dream, often documented upon waking, that details dream experience.
Dream rescripting: the process of modifying a recurrent dream through rewriting or mental imagery while awake, aiming for these changes to persist into sleep, an approach often used in nightmare therapy.
Interactive dreaming: a method in the laboratory that involves real-time information passed between the awake researcher and asleep dreamer.
Lucid dreaming: the experience of being aware that one is dreaming and potentially having control over the content of a dream's, and that occurs on a continuum from minimal awareness to full control.
Neural decoding: the use of computational methods to infer cognitive or sensory experiences, such as thoughts or perceptions, from patterns of brain activity.
Observable dreaming: a suite of neurophysiological approaches that allow the objective observation of dream content.
Polysomnography (PSG): a suite of measures that record brain waves, eye movements, muscle activity, and heart and respiratory rates to analyze sleep patterns and diagnose sleep disorders.
Rapid eye movement (REM) sleep: a sleep stage characterized by rapid movement of the eyes, increased brain activity, and vivid dreams, during which most skeletal muscles experience temporary paralysis.

Overcoming limitations of post-sleep recall with observable dreaming

Perhaps the most fundamental limitation to a fully fledged science of dreaming is the inability to observe dreams directly [10]. Current studies often depend on retrospective **dream reports**, which may not fully represent dream experiences. Between the generation of dream content and the dream report is a complex series of cognitive operations, each of which adds further potential information loss to the final dream report (Box 1). Whereas dreaming occurs during sleep, reports of the dream experience are provided during wake using retrospective memory retrieval. Although there are reasonable arguments for trusting the validity of dream reports [11], the constructive nature of retrospective memory and its susceptibility to distortion or complete forgetting [12] places a fundamental limitation on their reliability [13]. There are a host of personality trait differences and other contextual influences, such as reporting style [14], that are thought to have an impact on dream recall [15] and limit the reliability of post-awakening subjective dream reports. Notably, these concerns are not inherently unique to the study of dreaming. The science of daydreaming, mind-wandering, and other forms of awake thought also relies on subjective reports, but reporting dreams has traditionally exacerbated these concerns because the time between experience and reporting is longer and there is a state change between the experience and the report. The drastic neurochemical shift that occurs between dream generation and reporting [16] might be a reason for longer-lasting skepticism in the study of dreaming. Even reports that no dreams occurred must be taken with some skepticism owing to the possibility of retrieval failure. However, advances in neuroimaging have led to innovative approaches that complement post-awakening retrospective dream recall and concomitant memory errors. Two approaches in particular – content decoding and real-time reporting – can offer paths forward for **observable dreaming**.

Observing dreams with content decoding

The development of methods for **neural decoding** has provided cognitive neuroscientists with increasingly efficient ways to classify or reconstruct stimuli being viewed or imagined from patterns of neuroimaging data. A pioneering fMRI study used this approach to identify statistically probable objects within **sleep-onset dreams** from neural patterns collected during wakeful object viewing [17]. However, the application of fMRI to sleep studies, especially investigations of REM sleep, is limited because of intrinsic constraints such as loud noise and discomfort (*cf* [18]). Thus, a crucial advance has been the decoding of dreaming using **polysomnography (PSG)** (Figure 2). Recent breakthroughs have shown how neural patterns derived from EEG tracings can be used to decode cognitive features of reported dream content. Specifically, faces and locations in reported dreams are directly related to the amount of high oscillatory activity in temporo-occipital and parietal electrode sites, respectively [19], which coincide with neural correlates of awake perceptual experience. Levels of anger in dream reports also correspond to measurable EEG patterns of frontal oscillatory activity [20].

In addition to neural activity measured with EEG, other measures of sleep physiology can reveal the content of dreams. Despite **REM atonia**, subtle electromyography (EMG) measures of minor muscle twitches of the face reveal correspondences with affective dream content reported upon awakening [21]. Similarly, speech muscle EMG activity precedes awakenings when speech is retrospectively reported in dreams [22,23]. The pattern of eye movements in REM sleep are consistent with those during awake scene perception [24], and reflect at least partial correspondence with dreamer gaze direction [25,26]. Patients with REM sleep behavior disorder (RBD) lack REM atonia, and the resulting observable movements appear to correlate with dreamt movements [27–31]. Although direct experimental validation remains scarce [32,33], this method of 'dream enactment' might be a viable way to observe dreaming [34].

Current methods that aim to observe dreaming with content decoding suffer from several limitations, notably the dependence on accurate retrospective memory recall of the dream experience

REM atonia: the physiological state of muscle paralysis occurring during REM sleep that prevents individuals from acting out their dreams.
Serial awakening paradigm: an experience-sampling technique that involves repeatedly awakening participants throughout the night and probing for any conscious experience.
Sleep-onset dreams: dreams that occur during the transition from wakefulness to sleep or during stage 1 non-REM (N1) sleep, sometimes referred to as hypnagogia, and that typically have less immersive qualities than REM dreams.
Targeted dream incubation (TDI): a protocol aiming to incorporate a target memory or stimulus into dream content via prompts presented during sleep onset.
Targeted memory reactivation (TMR): the selective enhancement of specific memories during sleep by re-exposing the sleeper to associated cues such as sounds or smells.

Box 1. The complex process of dream recall

Dream research has traditionally relied on post-sleep recall as the primary method to access dreaming. Successful dream recall hinges on four steps: dream generation, storage, retrieval, and reporting (Figure I). Understanding the brain mechanisms of these steps is key to unraveling the mysteries of dreaming because retrospective dream reports are only accurate to the extent that each step is successfully completed.

Dream generation is driven, in part, by activity in the posterior regions of the brain [19]. EEG and fMRI studies show heightened activity in visual, auditory, and other sensory areas during REM sleep [109], suggesting that these regions support dream content generation. The intensity or vividness of dreams, likely influenced by activation in these areas [110], may affect memory encoding and subsequent recall.

Dream storage involves transforming the generated dream experience into a stable memory trace that can be later retrieved while awake. This step is thought to rely on activity in the prefrontal [111] and hippocampal regions [112] which are important for memory and undergo neurochemical changes during sleep. Successful dream storage may also depend on the transition from sleep to wake because global brain connectivity during sleep inertia is predictive of increased dream recall [113].

Dream retrieval occurs when the memory traces formed through the process of storage are accessed while awake. Retrieval depends on attention, motivation, and context, and distractions post-waking lead to reduced dream recall. State-dependent memory studies underscore the challenge of recalling dreams during wakefulness. Immediate post-awakening reports are influenced by the cognitive deficits of sleep inertia [16]. In survey settings, longer delays between dream storage and retrieval might introduce additional memory distortions.

Dream reporting is the externalizing of internally retrieved dream content, typically conveyed with words. As with dream retrieval, this step is influenced by cognitive deficits associated with sleep inertia which can hamper accurate translation even when events might be accurately retrieved internally. The level of detail in reports varies between individuals, and emotions are often under-identified [114,115]. The process of reporting is not instantaneous. As a dream is reported, the recall can shift, leading to either forgetting of specific details or surfacing of additional elements of the dream. Furthermore, dreams might contain ineffable features, making an accurate translation of dreaming difficult even after successful retrieval.

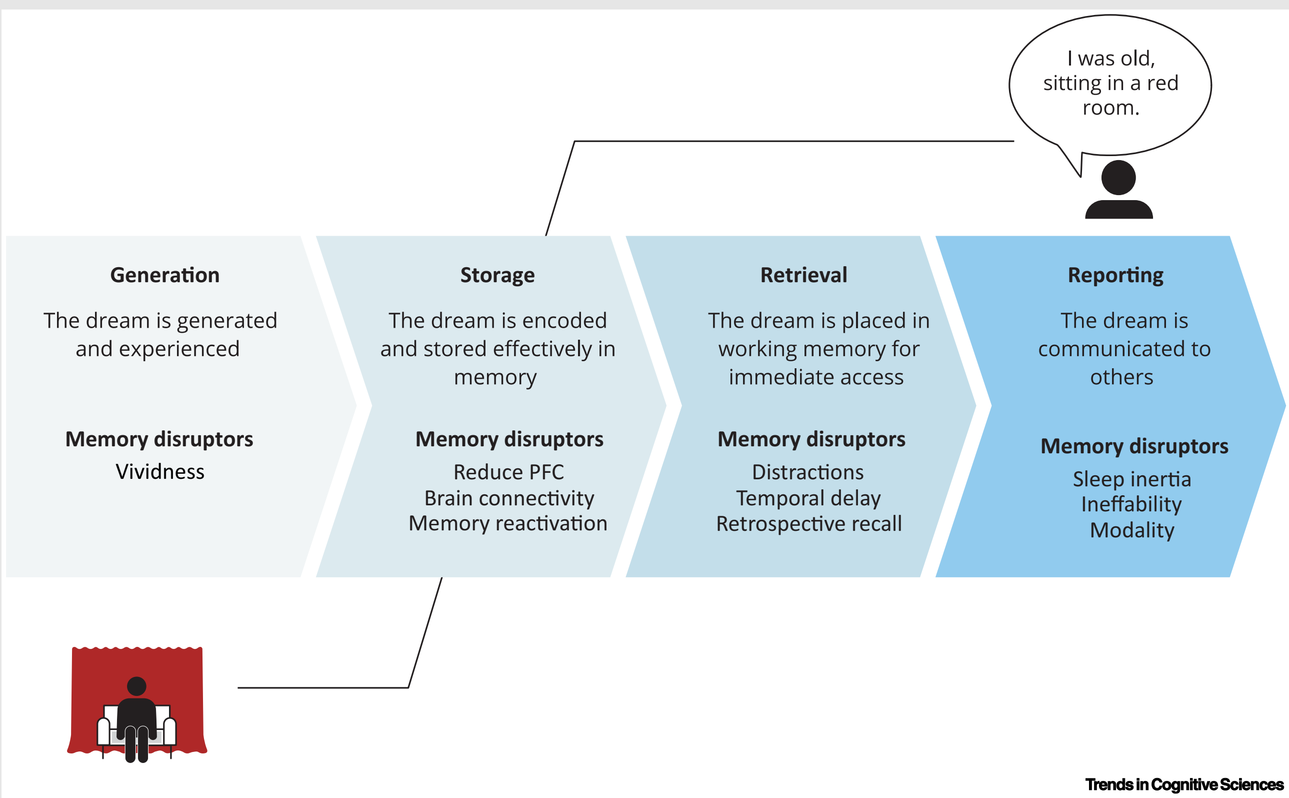

Figure I. The dream recall process. The complex process of recalling a dream involves multiple cognitive steps, each of which has the potential to reduce the reliability of the final dream report by adding to accumulated information loss.

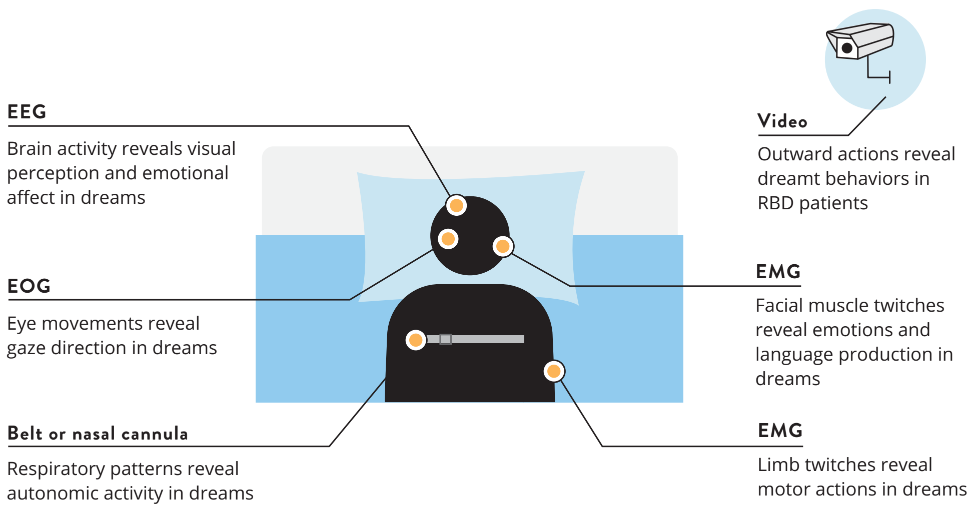

Figure 2. Polysomnography (PSG) and objective views into dreaming. As the primary measure of sleep, PSG also serves as the primary tool for observing dreams. Different aspects of dream content can be observed through the unique lens of each PSG component. Many of these components, such as EOG, have been used for both content decoding and real-time reporting. Abbreviations: EEG, electroencephalography; EMG, electromyography; EOG, electrooculography; RBD, rapid eye movement (REM) sleep behavior disorder.

for model validation. Enhancing data quality, such as incorporating phenomenological report training to obtain more detailed and precise accounts, may mitigate this limitation [35]. However, the inherent reliance on retrospective recall continues to be a major obstacle, thereby preventing the distinction between recalled content and dreams that remain unrecalled.

Observing dreams with real-time reporting

A complementary approach to directly observing dreaming is for the dream to be reported as it is occurring as opposed to upon awakening. Whereas the aforementioned approaches aim to decode the spontaneous content of dreams, real-time reporting uses the same suite of electrophysiological PSG measures to decode deliberate messages from the dreamer, thus conserving the first-person perspective and avoiding fallacies inherent to retrospective recall. This approach typically capitalizes on the unique state of **lucid dreaming**, a state where the dreamer is aware of the dream as it occurs and is often able to perform predetermined actions within the dream [36]. In a typical real-time dream reporting study, participants are, before sleep, instructed that a particular sequence of eye movements or facial expressions should be performed while dreaming [37]. When performing these actions from within the dream, electrooculography (EOG) and EMG channels capture these signals with as much clarity as when performed when awake, and standard PSG patterns are used to verify that the signal occurred during sleep (Figure 3).

This approach allows event-based neural analyses of dreaming. With retrospective dream reports, it is difficult to pinpoint the time of a dreamt behavior or event, making it implausible to study the neural correlates of specific dream events. By sending a signal immediately before performing a complex behavior in the dream (e.g., jumping jacks), the signal serves as a timestamp for later event-based analyses (Figure 3). This approach has helped to reveal neural correlates of lucidity, the similar recruitment of the nervous system during dreaming and while awake [38,39], and estimations of time perception while dreaming and when awake [40].

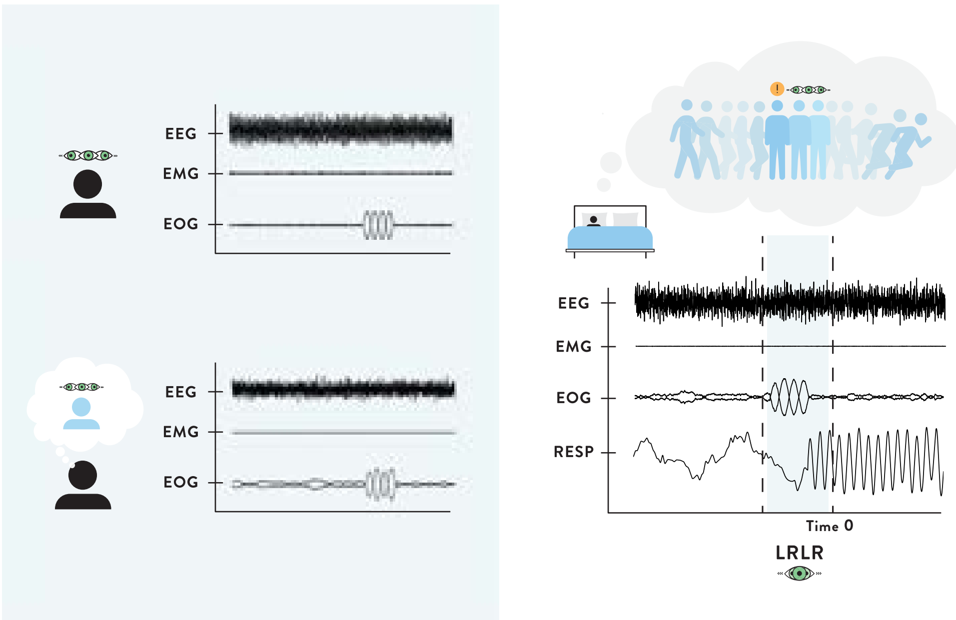

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Figure 3. Real-time dream reporting and time-locked dreaming for event-based electroencephalography (EEG) analysis. (Left) Electrooculography (EOG) signals captured during dreaming reflect the gaze direction of the dreamer. Moving the eyes horizontally in a repeated fashion (left–right–left–right, LRLR) while dreaming shows an EOG trace that mimics the same movements performed while awake. (Right) Real-time dream reporting is used to indicate the onset/offset of dreamt events. In this example the participant experiences a non-lucid dream of walking. After the moment of lucidity (exclamation), the dreamer begins to perform the assigned sequence of events. First, they indicate the onset of performing the action (here, moving eyes LRLR). Second, they perform the primary action of interest (here, running). During later analysis, the researcher is able to use the end of the LRLR sequence to know precisely when the participant started to dream of running. Abbreviations: EMG, electromyography; RESP, respiratory airflow.

A recent extension of real-time dream reporting, termed **interactive dreaming**, highlights the ability of lucid dreamers to not only send but also receive messages while remaining asleep [41,42]. After participants signaled to indicate that they were lucid, researchers presented simple mathematical problems and yes–no questions through verbal, tactile, and Morse-coded means [41]. In multiple instances, participants heard the questions, performed computations in the case of mathematical problems, and responded with correct answers using horizontal eye movements or muscle twitches, all while remaining asleep and dreaming. In a follow-up study, accurate responses from dreamers without post-sleep recall were observed, raising the intriguing question of whether their responses were automatic and without conscious dream experience or were indeed experienced in the dream but forgotten at the time of the report [42].

Real-time reporting of dream content is a promising technique but is currently hindered by low success rates and biased population samples. The rarity of naturally occurring lucid dreams [43] and the difficulty in inducing them [44] forces these studies to often rely on specific inclusion criteria, such as participants who are narcoleptics or frequent lucid dreamers. This restricts sample sizes and reduces the power and generalizability of such studies.

Testing causality with dream engineering

A fundamental challenge for dream researchers has been the inability to reliably control and manipulate dream content, a constraint that has often limited experimental designs and causal inferences [45]. Mental activity, even when awake, is cumulative in that current content is partially influenced by previous content [46]. This is also true of the continuity between wake and sleep because pre-sleep cognition will influence dream content [47], but with limited impact. Pre-sleep exposure to stimuli such as reading material [48], films, video games [49], and virtual reality [50] partially influences dreaming, and adding depth of processing to stimulus exposure with **dream incubation** can enhance this influence [48]. However, the reliability of pre-sleep exposure and the limitations it places on the ability to conduct blind studies have been areas of concern. Traditional approaches, where all participants are exposed to the stimuli and outcomes are analyzed based on those who incorporate them into their dreams, have been criticized for potential confounding variables [51]. Such experiments often suffer from baseline performance variations and uncontrolled variables that overshadow the ability to decipher the direct causal impacts of dreams [52]. Direct testing of hypothesized dream functions, such as benefits to learning, requires precise experimental control of content. **Dream engineering** via systematic stimulation and lucidity aims to overcome this barrier by increasing manipulation frequency and specificity [53]. Reliably engineering dreams can enable properly controlled experiments to elucidate the causal roles of dream content, and has already begun to reveal valuable clinical applications (Box 2).

Engineering dreams with systematic stimulation

Sensory processing continues during sleep [54], allowing the presentation of visual, auditory, olfactory, or tactile cues to influence ongoing mental content. Dream-engineering approaches administer such sensory stimulation to manipulate dream content in a highly targeted fashion. An increasingly popular approach is the **targeted memory reactivation (TMR)** method that was developed to study the causal role of sleep in memory processing [55,56]. With this method, stimuli with common-knowledge or arbitrary associations formed before sleep can be presented during sleep to influence dream content. The desired effects range from contextual to targeted modifications.

Box 2. Clinical applications of dream engineering

The inability to choose and control one's own dream content can be immensely problematic for frequent nightmare sufferers. Extremely negative dreams disrupt sleep and can instill a fear of returning to sleep. Frequent nightmares are associated with a host of psychiatric disorders and are increasingly recognized as a crucial marker of post-traumatic stress disorder (PTSD) severity and recovery. In the same way that dream engineering can be used to further our scientific understanding of dreaming, it can be used in therapeutic settings to reduce the frequency of nightmares and address other challenges in sleep medicine.

Imagery rehearsal therapy (IRT) is an effective nightmare treatment that aims to alleviate the negative emotions associated with nightmares through dream rescripting [116]. IRT uses cognitive-behavioral techniques while awake to influence nightmare content. Patients recall, document, and then rewrite a recurring nightmare with preferred changes for their dream. Despite being a leading therapy, ~30% of patients do not respond to IRT, highlighting a significant unmet need that newer dream-engineering methods could address. These methods seek to enhance the effectiveness of IRT and append it with real-time dream manipulation.

A recent study found that reactivating the awake practice of IRT during sleep with targeted memory reactivation (TMR) offered health benefits to a group of participants with nightmare disorder by increasing positive dream content and reducing nightmare frequency [117]. Participants mentally rehearsed a new ending for one of their nightmares while listening to a piano chord. When the chord was presented again during sleep, participants had fewer nightmares and more joyful dreams. Although combining IRT and TMR could be beneficial, it may face the same low adherence issues as IRT alone, particularly because individuals with PTSD might hesitate to engage in mental exercises that involve revisiting traumatic nightmares during wakefulness.

Lucid dreaming therapy (LDT), another extension of IRT, maintains a similar structure but focuses on achieving lucidity within the dream rather than on rescripting specific dream narratives. LDT empowers patients to become aware during their dreams, enabling them to modify dream content at will rather than focusing on pre-sleep modifications. This approach is particularly promising for treating nightmares because it involves training patients to become lucid, control their dream environments, and interact therapeutically with the negative elements of their dreams. A recent systematic review of case studies provides early support for this approach [118], but further work will be necessary to determine its therapeutic effectiveness and appropriate application, particularly among populations prone to psychosis or sleep loss [119].

An early test of the effects of sensory stimulation on dreaming showed higher positive and negative emotions in dreams recalled from participants exposed during sleep to pleasant and unpleasant odors, respectively [57]. A follow-up study revealed that forming specific associations before sleep between odors and stimuli allowed more targeted reactivation of dream content – pairing an odor with a cityscape induced more city-related dreams when the odor was presented again during sleep [58]. TMR cues can also impact higher-order cognition during dreaming; light and sound cues that are associated pre-sleep with a self-reflective mind state enabled subsequent lucid dreams [59]. Regarding the engineering of more complex behaviors, an immersive pre-sleep virtual reality flying task not only stimulated flying dreams in a laboratory nap [49] (Figure 4) but TMR of the same task also boosted task-related dream content in accordance with the **dream-lag effect** [60]. A major benefit of manipulating dream content is in testing its impact on subsequent awake behavior. For instance, increasing the amount of tree-related sleep-onset dreams using **targeted dream incubation (TDI)** [61] improved performance on tree-related creativity tasks during a subsequent wake period [62]. A variety of other sensory modalities, including tactile stimulation, have been used to influence dream content [53], although more research will be necessary to determine the pros and cons of using each modality (see Outstanding questions).

In addition to sensory stimulation approaches, more recent studies have shown that specific dream content can be engineered using other forms of noninvasive electrical brain stimulation. Just as transcranial direct current stimulation (tDCS) applied over the sensorimotor cortex has an influence on motor actions and imagery, the same application during dreaming influences the amount of motor activity reported in dreams [63,64]. tDCS might also impact the visual content of dreams when applied over parietal areas [65], and on levels of lucidity while dreaming when applied over the prefrontal cortex [66]. Levels of self-awareness were also increased using a complementary method – transcranial alternating current stimulation (tACS) ([67], *cf* [68]).

Although recent studies indicate that dreams can be influenced by external stimulation, the reliability and consistency of this method remain debated [69]. There is considerable variability in success rates both across and within studies. Several factors likely affect the reliability of influencing dreams, including the timing of stimulation relative to **dream incorporation**, the modality of stimulation, prior stimulus associations, and the integration of the stimulus into the dream content. In addition,

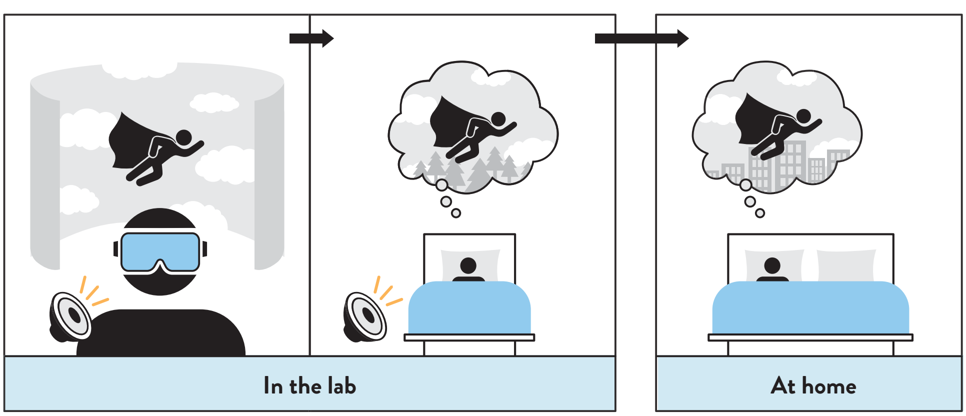

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Figure 4. Engineering flying dreams with sensory stimulation. During a laboratory visit, the participant plays a virtual reality (VR) game that involves flying. During a subsequent nap in the same laboratory visit, the experimenter plays the sounds from the VR game to induce dreams about flying. For the next week, the participant keeps a dream diary and records more flying dreams than usual.

accurate identification of any systematic relationship between a stimulus and its presence in dream content depends on a thorough understanding of dream norms, an accurate observation of dream content, and accounting for potentially distant semantic relationships.

Engineering dreams with lucidity

External stimulation during sleep is not the only way to engineer dream content. Recruiting frequent lucid dreamers [43] and inducing lucid dreams in naive participants [44] are common methods to induce specific dream content in research settings. When a dreamer becomes lucid, they can remember highly complex tasks that were assigned to them before sleep and carry them out in detail. For instance, when researchers wanted to better understand the differences between perception in wake and dreaming, they asked participants to move their hand in a circle and track the motion with their eyes [70]. Crucially, they asked participants to do this thrice; once while awake with eyes open, once while awake with eyes closed, and again while (lucid) dreaming. When dreamers visually tracked a moving target during dreams they had smooth pursuit eye movements that were reminiscent of tracking motion during perception, not imagination. Similar wake versus dream comparisons have been done for counting (to test differences in time perception), jumping jacks (to test autonomic responses of dreamt behaviors) [38,71], and fist clenching (to test neural control of dreamt behaviors). Studies like these can also be used to test the behavioral outcomes of performing motor actions in dreams, such as practicing darts [72] or throwing coins into a cup [73]. Such studies have revealed learning benefits of dreamt practice.

Like most other research on lucid dreaming, current studies on engineering dreams with lucidity suffer from limitations of small and biased samples that limit the generalizability of the results. Successful manipulation of lucid dream content is generally higher among frequent or experienced lucid dreamers. The variability in study outcomes likely stems from these limited sample sizes. Future research could potentially address these issues if a reliable method for inducing lucid dreams becomes available that would allow the recruitment of a broader population.

Identifying content patterns with computational dream analysis

The narrative structure of dreaming shows more variability and less constraint than that of awake mind-wandering [74], making it particularly difficult to elucidate any underlying systematic structure to dream content. To date, most descriptions of dream content are derived from dream reports collected in laboratory and survey settings, both of which suffer from limitations of sample size and ecological validity. The large influence of laboratory settings on dreams makes dreams collected therein less representative of natural dreaming [75], and survey studies are further susceptible to response bias and demand characteristics. Deriving meaning from written dream reports has traditionally been done using manual human scoring, which also lacks scalability and is susceptible to experimenter bias. Thus, studying dreams in the laboratory and with human scorers offers a limited understanding of dreaming. **Computational dream analysis** complements these approaches by merging big data and scalable computational approaches (e.g., natural language processing) to study dreaming. These approaches have begun to shed new light on dreaming and carve out clear directions for additional fruitful research.

Analyzing dreams with big data

Big data approaches provide new opportunities to overcome the limitations of traditional dream research. By analyzing large collections of naturalistic dream reports shared publicly online or in existing dream databases [76,77], researchers can identify patterns and insights that are not detectable in smaller laboratory samples. For example, comparison of word frequencies and other language properties of these dream reports against wake control texts (e.g., news articles) reveals unique linguistic signatures of dream reports [78–82]. Studying the dream reports of an individual over months or years also becomes possible, thus enabling direct tests of how awake experiences are incorporated into dreams over time [83,84]. Digital trace data [85] from public dream-sharing websites and forums offer further advantages such as ecological validity, population diversity, and temporal precision. For example, public dream archives have been mined to observe the influence of cultural events on population dreaming [86] and to compare dream reports with psychedelic experience reports to infer brain mechanisms of dream generation [87].

Big dream-report databases, although valuable, still face significant limitations that prevent them from providing a representative and comprehensive view of all dreams. For example, digital trace datasets collected from a single social media site will contain dreams of a specific userbase. In addition, dream reports shared on public platforms might be biased towards more socially acceptable or shareable dreams and exclude private details (e.g., sexual content). There is also the potential for reports to be fabricated or embellished for social validation by presenting more stereotypical or humorous dreams. Such large databases are also likely to be biased towards REM dreams recalled naturally when waking from a full night of sleep. By contrast, serial awakening studies conducted in laboratory settings reveal a broader spectrum of dreams, particularly from non-REM stages that were obtained through direct awakenings. Although large datasets can propel dream science forward, their flaws must be acknowledged and supplemented with other approaches.

Analyzing dreams with natural language processing

Researchers have adapted computational language tools from other fields to analyze big dream datasets [88]. The longstanding Hall and Van de Castle system involved manually coding dream reports into quantitative variables [89,90], but this laborious process lacks scalability. Recent methods have automated this coding using word searches [76,83,91–94] and custom language analysis pipelines [84,93,95] that provide practical solutions for the analysis of big dream data. Quantifying the language structure of dreams is beginning to offer clinical insights, where the language used in **dream rescripting** (Box 2) predicts remission [96–99]. An important advance is the use of novel computational language tools that go beyond applying word-search approaches to dream reports, such as measuring levels of creativity in recalled dreams [62] or extracting key people and places referenced [84,100,101].

Another fruitful approach has been the application of structural graph analysis, or the examination of network patterns in textual data, to transcribed dream reports from clinical samples. This technique quantifies structural properties such as word recurrence and lexical diversity. Graph metrics have been used to differentiate dreams from various sleep stages [102], thereby offering insight into the neural correlates of mental experience. These measures also predict future psychiatric diagnosis [103–105], and even offer additional predictive power beyond awake reports in the diagnosis of schizophrenia [106], bipolar disorder [107], and obsessive-compulsive disorder [108].

Unsupervised analyses are particularly beneficial for exploring the multifaceted nature of dreams where traditional *a priori* hypotheses can be limiting. Data-driven methods allow researchers to delve into large datasets with an open-ended approach, revealing patterns and insights that are not immediately apparent. For example, instead of searching for specific dream themes based on prior literature, recent work has applied computational methods to dreams from social media to observe common content and temporal changes in relation to global events [86]. Reddit posts surrounding the onset of the Russo-Ukrainian war were filtered to include only dream reports, and topic modeling revealed an increase in war-related dream topics. These novel insights reveal crucial advances in our understanding of what dreams consist of and also how they relate to awake events and behaviors.

Like other areas within the psychology of language, the computational analysis of dream reports is constrained by the limitations of natural language processing tools. Dream reports are often succinct, and these tools are only capable of extracting accurate emotional measures if emotional content is included in the text. Moreover, the accuracy of detecting complex cognitive phenomena in text remains a contentious issue. Furthermore, typical dream reports seldom provide a complete depiction of the dream scene, and usually offer only a short excerpt when collected outside the laboratory. As language processing tools advance, so will our ability to quantify and understand dream content. Recent progress in objectively identifying features from other media, such as images and audio, suggests the possibility of applying similar methods to dream reports collected through these mediums, and could potentially capture elements of dreams that are otherwise difficult to express.

Concluding remarks

The scientific study of dreams, that is notoriously fraught with methodological challenges, is now poised for future success thanks to a set of groundbreaking interdisciplinary innovations. These breakthroughs each address distinct challenges in dream science but hold potential for synergistic application. For instance, although a study might engineer dream content through sensory stimulation, it may fall short if solely based on retrospective dream reports and manual ratings. The additional inclusion of methods from observable dreaming and computational dream analysis would produce an even more powerful approach.

Dreaming is no longer a black box. The latest advances highlight how our increased understanding of the neuroscience and psychology of sleep allows us to measure and manipulate more parameters. Historically, most scientists held serious reservations about the feasibility of rigorously studying dreams. Although this skepticism was once defendable, contemporary methodologies challenge that notion. We are optimistic that cognitive scientists from all corners of the field can fruitfully contribute to future advances in dream science, and that such efforts will help to illuminate one of the most enigmatic puzzles at the core of the human condition. For any scientist captivated by the allure of dreams, now is the time to chase them.

Outstanding questions

Is there a neural transformation between awake and dreamt representations? Current methods for decoding dreams rely on models trained on awake behavior to decode dream behavior.

How much precision can be achieved using TMR to influence dreaming? Instead of influencing the affect or context of a dream, can sounds played in sleep induce participants to dream of exactly the same object, location, or complex behavior?

How reliably can lucid dreams be induced in naïve participants? The immense potential of lucid dreaming for discovery and application hinges on the development of more reliable methods of inducing lucid dreams.

Can a multimodal dream report provide access to a more detailed dream phenomenology? Dream science has been focused on text reports of dreaming, but the ineffable qualities of dreaming might be captured with a non-verbal modality such as drawing.

Does dream engineering influence forgotten dreams? The influence of dream engineering on unrecalled dreams and their cognitive and emotional implications remain an unexplored domain.

How should dream incorporation be assessed? Currently, the degree to which a reported dream includes specific content has not been clearly defined.

Do findings from lucid dream research generalize to non-lucid dreams? Lucid dreaming is an effective way to manipulate dream content, but the degree to which these study designs generalize to non-lucid dreams is not clear.

How long are dreams influenced after a single laboratory session?

Does EEG have the precision for item-level dream-content decoding? This possibility might hinge on the development of neurocomputational vision modeling with EEG data, which is rapidly increasing in sophistication.

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Declaration of interests

K.A.P. is a consultant for NextSense, Inc. The other authors declare no competing interests.

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How can large language models be used to spur discovery in dream science? As with other fields, dream science awaits an outpour of new discoveries and methods based on the opportunities afforded by artificial intelligence.

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