

REVIEW ARTICLES

The vision of dreams: from ontogeny to dream engineering in blindness

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The mechanisms involved in the origin of dreams remain one of the great unknowns in science. In the 21st century, studies in the field have focused on 3 main topics: functional networks that underlie dreaming, neural correlates of dream contents, and signal propagation. We review neuroscientific studies about dreaming processes, focusing on their cortical correlations. The involvement of frontoparietal regions in the dream-retrieval process allows us to discuss it in light of the Global Workspace theory of consciousness. However, dreaming in distinct sleep stages maintains relevant differences, suggesting that multiple generators are implicated. Then, given the strong influence of light perception on sleep regulation and the mostly visual content of dreams, we investigate the effect of blindness on the organization of dreams. Blind individuals represent a worthwhile population to clarify the role of perceptual systems in dream generation, and to make inferences about their top-down and/or bottom-up origin. Indeed, congenitally blind people maintain the ability to produce visual dreams, suggesting that bottom-up mechanisms could be associated with innate body schemes or multisensory integration processes. Finally, we propose the new dream-engineering technique as a tool to clarify the mechanisms of multisensory integration during sleep and related mental activity, presenting possible implications for rehabilitation in sensory-impaired individuals. The Theory of Proto-consciousness suggests that the interaction of brain states underlying waking and dreaming ensures the optimal functioning of both. Therefore, understanding the origin of dreams and capabilities of our brain during a dreamlike state, we could introduce it as a rehabilitative tool.

Keywords: sleeping brain, dream engineering, dream development, blindness

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INTRODUCTION

In the 21st century, studies on dreams have focused on 3 main topics: functional networks that underlie dreaming, neural correlates of dream contents, and signal propagation in dreams.¹ To date, some findings have identified cortical correlates and anatomical structure and physiological processes of dreams involved in the generation of this mental event.^{2–4} Nonetheless, more data are necessary to understand the neural basis of dreams. Indeed, the mechanisms involved in dream activity during different sleep phases and their nature (eg, more linked to perception or imagination) remain unclear.

To better comprehend the ontogenesis of dreams, blind individuals may prove a worthwhile population to investigate the involvement of perceptual systems, particularly visual systems, considering the primarily visual nature of dreams. Literature suggests that congenitally blind people maintain the ability to produce visual content in their dreams, although the underlying mechanism remains unknown. Could it be related to the imaginative origin of the dream or the input's integration from other sensory modalities, as has been proposed?⁵ It is less clear if blind people also maintain a solid spatial conception in their dreams while other sensory components increase. Thus, 1 possibility is that dream representation shifts from the spatial domain, more typically associated with the visual system,⁶ to the temporal domain, more typically associated with the auditory system. Indeed, the auditory sensory modality is the

primary channel used by blind people to represent reality.⁷ A better understating of the relationship between sensory perception, multisensory integration, and imagination could help elucidate the origin of dreams. Also, understanding the sensory brain during dreams and how it is modified by blindness could clarify the process of neural plasticity, potentially generating significant improvements in rehabilitation strategies, with repercussions on the quality of life.

This review provides the general scientific community updates on findings regarding the mechanisms involved in dreaming. We present the most recent findings/issues about cortical correlates of dreams during rapid eye movement (REM) and non-REM (NREM) stages and the related neural process models. Second, given the primarily visual representation of dreams, we explore how blind participants' dreams are reorganized.^{5,8,9} Third, we consider the development of oneiric activity in sighted and blind children. Finally, in the general discussion, we propose the following: (1) the use of dream engineering to better understand multisensory integration during different phases of sleep and its relationship with sleep mentation and (2) implications for rehabilitation in those with sensory deficits.

DREAMS

Dreaming is typically considered a subjective experience generated by the mind and brain while cut off from the body and the

external environment.¹⁰ Although the neural basis and the cortical mechanisms underlying dreams are still being investigated, some consistent findings emerge from recalled dreams. Traditionally, dreaming was identified with REM sleep^{11–13}; however, it is now known to occur in NREM sleep, albeit with some differences. First, the recall rates of dreams after REM awakenings are considerably higher than after NREM awakenings.^{11,13–15} Moreover, NREM recall rates depend on the sleep stage.¹⁴ The second difference involves total recall count—that is, the number of unique words present in a dream report: based on total recall count, REM reports are more extended than NREM ones.^{15–18} Third, REM reports are generally more intense, bizarre, perceptually vivid, emotional, with greater connectedness, and story-like.^{15,16,18–20} Conversely, NREM reports are typically more thought-like and conceptual with a more random-like report structure.²¹

Although there is a consensus that dreaming may occur in both REM and NREM sleep and that distinct sleep stages seem featured by different dream parameters, disagreement persists over whether dreaming in REM or NREM sleep can be qualitatively different. This point has critical implications for understanding the ongoing neural mechanisms responsible for mental sleep experience. Therefore, this section describes physical and electrophysiological correlates of oneiric experience and content dreams during REM and NREM sleep. Specifically, the first part reports electrophysiological correlates of REM dream retrieval, while the second part reports on physiological correlates of REM dream content. Then, recent findings of NREM dreams are presented. Finally, neural process models are discussed.

Electrophysiological correlates of REM dream retrieval

Different attempts have been made to find electrophysiological correlates of oneiric experience. Some studies have focused on the cortical mechanisms linked to retrieval of a dream from REM sleep but results vary.^{3,22–27} For example, Marzano et al,²² in agreement with others,²³ found that participants could recall dreams when the immediately preceding sleep interval was characterized by higher frontal theta activity. Other studies have reported a relationship between high-frequency activity (18–50 Hz) and dream recall,^{24–26} combined with a decrease in delta waves in posterior regions.^{3,24,27,28} Possible involvement of alpha and beta frequencies has also been reported²⁹; dream recall during REM sleep was associated with low frontal alpha activity and high alpha and beta activity in occipital derivations.

As with electroencephalogram (EEG) bands, conflicting data also exist regarding the brain areas related to dream experience. Some studies support the hypothesis that dreaming and especially visual imagery of dreaming is a right hemisphere function,^{5,30,31} but this hypothesis is not universally accepted.^{32,33} It is also possible the 2 hemispheres have different roles during dreaming. For example, Doricchi and Violani³⁴ proposed that the right hemisphere provides the core material for dreams and the left hemisphere provides the means of decoding it.

Electrophysiological correlates of dream content

Research on dreams has also focused on the electrophysiological activity underlying the encoding and retrieval of the content from REM dreams. Most studies have tried to identify objective measures of visual content, given the typically visual nature of dreams. Physiological measures correlated with visual information during dream experience are eye movements (EMs); sawtooth waves, which is the human equivalent of ponto-geniculo-occipital (PGO) waves³⁵; and occipital alpha activity. The most popular theory regarding the functional role of EMs in dream imagery and visual content is the “scanning hypothesis,”^{36,37} which posits that rapid EMs reflect the orientation of an individual’s gaze during their oneiric experience. Rapid EMs have also been correlated with PGO waves,³⁸ particularly the presence of PGO waves preceding the rapid EM onset.^{39,40} Andrillon et al³⁹ suggested that activation of the visual cortex through PGO waves could be the underlying source of visual dream content during REM sleep and the precursor of EMs during this sleep stage. Both rapid EMs and PGO imply visual cortex activation during REM dreams with visual content, consistently with increased metabolic activity during this stage¹⁹ in the brain and specifically in the visual cortex.^{40–42} Visual cortex activation in the absence of visual stimuli while asleep supports the similarity of dream experience with visual perception and imagery exercises.^{1,43,44} Moreover, occipital alpha activity is linked with visual^{5,45} and emotional^{46,47} dream content. A recent study showed that frontal alpha asymmetry might be a neural correlate of affect regulation in waking and dreaming states.⁴⁶ Earlier evidence suggested a possible correlation between alpha oscillations and lucid dreaming,⁴⁸ although more recent discoveries link lucid dreaming with gamma frequencies.^{25,49,50}

High frequencies have been associated with different dream content. For example, 1 study found increased high-frequency activity (20–50 Hz) within the specific regions correlated with certain dream contents, such as thoughts, perceptions, faces, spatial setting, movement, and speech.³

Cortical correlates of NREM dreams

In the last decade, several studies have looked for electrophysiological correlates with the retrieval of dreams from NREM sleep^{3,22,28,29,51–54} to broaden our view of the conscious experience of this mental sleep activity. As with neural correlates of REM sleep, literature data report multiple conclusions.

Siclari and colleagues³ showed that reports of dream retrieval were associated with a local decrease in low-frequency activity (1–4 Hz) in the posterior cortical regions during NREM sleep. This decrease mostly involved a bilateral parieto-occipital region, including the medial and lateral occipital lobe, and extended superiorly to the precuneus and posterior cingulate gyrus. Increased high activity (20–40 Hz) has also been found in the same areas. Monitoring this posterior “hot zone,” they could predict whether an individual would report oneiric experiences during NREM sleep in real time. These data support the activation model, suggesting that a certain activation level is necessary to retrieve dream material.⁵⁵ This posterior “hot zone” of EEG activity may correspond to the temporo-parietal junction associated with the dreaming process.^{2,56} Siclari et al’s

results partially agree with some previous and later studies^{24,29,53} but contrast with others.^{22,57} Notably, a reduction in alpha activity in the temporo-parietal area could have a role in the retrieval of dreams from NREM sleep.^{22,57} A more recent study supported the role of delta activity in this process and added important temporal dynamic information on brain states using the EEG microstate approach.⁵¹ Bréchet and colleagues⁵¹ associated NREM dreaming with 2 distinct EEG microstates: one whose sources involved the medial frontal lobe, observed more during periods that preceded dream recall, and the other, whose sources involved the occipital cortex, thalamic, and brainstem structures, which decreased during the same period. These data have been interpreted as deactivation of the frontal brain region, possibly preventing the brain from waking up and activating structures involved in perceptual experiences.

Conclusions on cortical correlates of dreams

To summarize, both frontal and posterior areas seem to be involved in the dream-retrieval process during REM and NREM sleep, with some differences. An activation of posterior regions, with an increase in high-frequency beta/gamma activity and a decrease in delta activity, seems to be a common feature of both NREM and REM dream retrieval. However, during REM sleep, there is greater involvement of the occipital cortex, with increased metabolic activity, alpha oscillations, and PGO wave formation. This could explain the more visually complex and perceptually vivid dreams in this stage. Moreover, during NREM sleep, frontal activity decreases, while during REM sleep, alpha-theta activity increases, possibly clarifying the more emotional, connected, and story-like dreams. These findings are compatible with the Global Workspace theory of consciousness.⁵⁸ Global Workspace architecture allows a specific input (eg, sensory content) to be broadly distributed. In this way, particular programs can answer with solutions to centrally posed problems. Neuroscientific results about consciousness showed a link with a widespread cortical activity, highlighting frontoparietal regions. Compatible with these results, a decreased gamma and an increased low-frequency activity were found during the loss of consciousness. A lower involvement of frontal activity during NREM sleep could explain the observed greater difficulty in dream retrieval characterizing this sleep stage.

Clarifying the neural process models

Some doubts remain about the neuronal processes underpinning dream activity from the above-reported data. A debate continues regarding whether a 1-generator model can explain dream activity from REM and NREM stages or if a 2-generators model is required. The 1-generator, or activation, model stems from a general perspective whereby dream activity is linked to cortical activation related to the dream report's length or complexity.^{55,61,62} The 2-generators, or state-like, model assumes that dream activity is a direct function of different physiological profiles characterizing REM and NREM sleep.¹⁹ It has been proposed that taking electrophysiological correlates of the dream as a reflection of specific anatomical pathways could help underpin this ongoing cognitive process.²⁹ However,

results are controversial. Some studies showed different electrophysiological correlations for retrieving dreams from REM and NREM sleep^{22,29}; other studies indicated a unique correlate in all sleep stages.^{3,57}

One result that seems consistent among studies is the association between specific cortical activations and the dream-retrieval ability.^{3,22,27,52,53} Furthermore, awakening during NREM sleep may have particular importance for dream recall frequency.⁵⁴ High-frequency-recall dreamers showed significantly more awakenings across the night.^{2,54} More information about the nature of arousal could be provided by analyzing the cycling alternating pattern (CAP).

Currently, the only study investigating the relationship between CAP and dreams⁶³ found that the NREM sleep of participants with frequent nightmares had reduced amounts of CAP subtype A1, increased CAP subtypes A2 and A3, and longer durations of CAP phases compared with controls. An attenuated amount of A1 is in line with the well-known reduced slow-wave sleep in those who experience frequent nightmares, while the increase in A2 and A3 is linked to increased fast EEG activity, confirming that greater cortical arousal occurs in individuals with frequent nightmares.

This typical pattern between REM and NREM dream retrieval is compatible with the activation-synthesis hypothesis of the dream process theorized by Hobson and McCarley,⁶² affirming that the periodic activation state of the brainstem represents the background neuronal substrate for the synthesis of dream.

Even if arousals have a crucial role in dream recall, the influence of chronobiologic and sleep-dependent factors on dream production should not be underestimated. Although the activation mechanism could be shared among sleep stages, the underlying subcortical activity during NREM and REM sleep is distinct, consequently differently influencing the dream-retrieval process. Thus, it is essential not to disregard homeostatic, ultradian, and circadian cycles when studies on dream recall are considered.^{4,64} Some of these time-dependent effects seem familiar to all sleep stages. For example, both REM and NREM dream reports become longer, more dream-like, hallucinatory, and bizarre during the night.^{16,17,21} However, other features appear to be stage-specific. For example, a selective increase in emotionality and narrative complexity characterizes REM dreaming,^{16,65} while a selective decrease in directed thought characterizes NREM dreaming.²¹ Moreover, considering the variable stages' distribution during the night, dream content also changes during the night.⁶⁶ Dreams during the early night, which show a prevalence of NREM stages, are more continuous with waking life, while dreams later in the night, characterized by REM stage, are more emotional and hyper-associative.

Similarly, trait-like interindividual differences should be examined. As suggested by Scarpelli et al,²³ to reach a complete knowledge about sleep mentation, it is necessary to disentangle the trait-like differences linked to dream recall (ie, specific stable differences characterizing each individual) from the state-like discrepancies (ie, specific brain activity strictly related to the physiological sleep scenario).

Finally, both activation model and circadian/ultradian processes influence dream recall, as proposed by the covert-REM

model¹⁴ or dual rhythm model.¹⁶ Therefore, to investigate mental sleep activity in a specific population, it is essential to consider all sleep processes. For example, light perception sets the internal circadian clock. However, what happens to this clock when light perception is missing, as in blind individuals? Also, dreams are mostly visual representations, so how is this representation built when vision is absent?

SLEEP, DREAMS, AND BLINDNESS

Given the mainly visual nature of dreams, blind individuals with a peripheral visual system impairment are a worthwhile population to understand whether dreams have a top-down or a bottom-up origin.

Both early- and late-blind (ie, with the onset of blindness before or after the age of 5–7 years) individuals could provide important information about sleep mentation and the role of sight in sleep regulation mechanisms. Conversely, individuals with Charles Bonnet syndrome could offer new insights about visual representation in dreams.

Moreover, sleep and dreams seem to be altered differently when blindness occurs at different ages. It is unclear how sleep mechanisms and dreams are affected in late-blind individuals after many years of blindness. Further clarification can be provided by distinguishing the cause of blindness, the visual acuity, and the submission to the enucleation procedure. Not all types of blindness equally affect mechanisms involved in sleep regulation. Since these mechanisms could also be engaged in the dreaming process, we consider how sleep processes may differ for this population before exploring mental sleep activity in blind participants.

Sleep mechanism in absence of vision

The main mechanism affected by lack of vision is the circadian process, which is normally entrained to the light-dark cycle. The loss of light perception shifts sleep-wake patterns due to an incorrect suppression of melatonin.^{67,68} The common rhythm in early-blind people without light perception is a free-running circadian rhythm that is the dominant factor for the sleep disturbances experienced in blindness⁶⁹ and affects approximately 72.2% of them.⁷⁰ Not all types of blindness compromise the retinal-suprachiasmatic nuclei pathway since the retinal mechanisms needed for sight are not entirely the same as those required to control circadian rhythms. Melanopsin contained in intrinsically photosensitive retinal ganglion cells needed for entrainment of circadian rhythms may be preserved in blind individuals with light perception. Specifically, a correlation was found between a greater impairment of circadian rhythm and an individual's degree of vision loss.⁷¹ Despite these apparent effects on the circadian cycle, data on the impact of blindness on sleep architecture are conflicting.^{8,72–75} It is unclear whether the plastic changes of the cortical and subcortical structures induced by visual deprivation also affect structures involved in sleep architecture or whether the alterations observed in some cases are only a consequence of the desynchronization of the circadian rhythm. Considering the effect of Circadian

Process on dream retrieval and dream contents, an incorrect entrainment of the circadian process could have a considerable influence on mechanisms that arise during sleep mentation. Moreover, understanding the real effect of blindness on sleep structure is also crucial to investigate cortical correlates of dreams in blind participants.

Dreams and blindness

Whether dreams are generated from activity in low-level sensory areas and then integrated into higher-order areas, similar to perception, or are generated from abstract thoughts, more similar to the imagination, is a longstanding question. Historically, 2 different philosophies of thought have been put forward: (1) followers of Freud ascribe a privileged top-down direction of dream generation¹ and (2) those who support sensory experience as the source of dreams.^{76,77} However, no specific experiments revealed which is the predominant pathway or if dreams emerge from an interaction of both systems. This section summarizes the data available on blind participants' dreams and considers some dream reports of other sensory- or motor-deprived participants.

Sensory and thematic reorganization of dreams in blind individuals

The debate on the presence of visual content in the dreams of congenitally blind individuals is still open. Indeed, even while it is currently claimed that those who are congenitally blind do not have visual imagery and are therefore unable to have visual content in their dreams, some data in the literature refute this belief.

It is now accepted that the dreams of blind people are vivid and self-engaging. However, visual deprivation leads to a reorganization of the sensory composition of dreams. Visual content is generally absent in early-blind individuals^{8,9,78} as spatial context. Yet, some cases of visual imagery in the dreams of congenitally blind individuals have been reported.^{5,8} Typically, their dreams contain sounds, touch sensations, or emotional experiences.^{5,9} In a 4-week experiment in which participants filled in a questionnaire every morning related to their dreams' sensory construction and thematic contents, congenitally blind participants reported more auditory, tactile, gustatory, and olfactory dream components than control participants.⁹

The situation differs for late-blind individuals who had visual experience in the first part of their lives. Their brains can still draw on visual memories and related brain circuits. Although they reported higher visual dream content, they had fewer visual dream impressions (ie, impressions of perceiving visual stimuli). An inverse relationship exists between the onset of blindness and the presence of visual content.^{8,9} The frequency of visual dream elements (duration, clarity, and color) decreases as the duration of blindness increases.⁸ Moreover, in late-blind people, the frequency of visual dream elements is proportional to their visual imagery capabilities, as measured by the Vividness of Visual Imagery Questionnaire.⁹ Unlike those who are congenitally blind, late-blind people show a slight sensory reorganization reporting only more elements linked to haptic or tactile systems

in their dreams. However, blind and sighted participants did not differ in emotional and thematic contents.

Electrophysiological parameters of visual images in blind people's dreams

Different electrophysiological parameters have been investigated to better clarify the presence of visual images in blind people. Rapid EMs during REM sleep typically indicate the presence of visual imagery in dreams (scanning hypothesis). However, congenitally and late-blind participants did not show EMs during the REM period, even those late-blind individuals who reported visual elements in their dreams.⁸ Thus, in blind individuals, the dream experience and the generation of nocturnal EMs seem to be disassociated. Two interpretations were proposed for this finding. The first suggested a cortical reorganization such that PGO waves correlated with EMs might produce phasic activity related to other sensory regions (eg, auditory activity). The second interpretation was that late loss of vision causes an uncoupling between the activity of the visual cortex and the production of EMs.

The existence of visual imagery in the dreams of congenitally blind people was also evaluated and correlated with attenuation/blocking of EEG alpha activity (considered an indicator of visual imagery), a graphical analysis of drawings of their dream images, and a content analysis to calculate the Visual Activity Index.⁵ Congenitally blind individuals and sighted controls had a similar Visual Activity Index and produced equally complex drawings. The only group difference was the vertical placement of the drawing on the page. Moreover, both groups had a negative correlation between alpha power in the central and occipital derivations and Visual Activity Index. However, alpha power was lower in the blind group in the central derivation.

According to Lopes da Silva,⁷⁹ Bértolo and colleagues supported these results that congenitally blind participants can also have visual content in their dreams, but they cannot describe them verbally. Instead, they can provide a graphical representation of the visual and visuospatial contents. Specifically, they hypothesized that blind people could produce virtual images from other sensory modalities, as De Volder et al⁸⁰ found. They argued that visual imagery is independent of visual perception because the visual system mediates the integration of other senses to produce concepts capable of graphical representation. It is still unknown how these reported images in dreams by blind people were constructed in their brains and whether these images were based on truly visual experiences or learned behavioral reports.

Dreams of sensory- and motor-deprived individuals and the perception–imagination relationship

Results similar to those in the Bértolo et al⁵ study were also found in congenital deaf-mute and paraplegic people.⁸¹ Indeed, a content analysis of deaf-mute participants' dreams revealed that about 50% of them reported sound and speech in their dreams. Similarly, the dream reports of paraplegic people do not differ from controls regarding the overall movement rate reported or the instances in which they self-moved in the dream. As with blind individuals, it is unknown how these reported

sounds/speech in dreams by deaf-mute participants were constructed and whether they relied on authentic auditory experiences. Voss et al⁸¹ discussed their results based on the theory of REM sleep as a state of proto-consciousness, assuming that dream content feeds itself from an innate body scheme. Following this theory,⁷⁶ REM sleep is a virtual reality template driving development and maintaining complex functional abilities, such as perception and motility. Understating the relationship between sensory perception, multisensory integration, and imagery during wakefulness may help to know the origin of dreams. Sensory-deprived individuals could clarify how a person missing a perceptive sensorial experience can have a sensory feel. A subsequent step could be to evaluate whether implementing these sensory feels, trying to access this “epigenetic substrate,” could be helpful in rehabilitation to strengthen the secondary limitation given by sensory deprivation, such as the development of spatial abilities in blind individuals.

DREAMING DURING DEVELOPMENT

Sleep deeply impacts early brain development and undergoes essential changes in the first decade of life. At birth, infants spend more hours sleeping than awake, and sleep time decreases with age. This pattern reflects the crucial role of sleep, especially the REM stage, for optimal brain development.⁸² REM sleep trajectory during development corresponds to the critical periods of brain maturation.^{83,84} Whether dreams contribute to this process, as well as when dreams arise during development, is unclear. Investigating these aspects could better illuminate their origin and qualitative nature.

Finally, additional consideration could be made to understand when the differences between sighted and blind children emerge in dream regulation and modulation of dream content.

Ontogeny of dreaming

Although REM sleep appears early in infancy, it remains unclear whether infants dream or when during development dreams arise. REM sleep in early life has led scientists to conclude that dreaming occurs in these stages and has an essential role in development. However, the REM stage of infants differs from that of adults, with the elements of infant REM sleep only gradually acquiring the distinct features of adult REM sleep. It has been proposed that dreaming moves through a maturation process similar to REM sleep.⁸⁵

Literature supports this gradual acquisition of adult REM and dream characteristics. Young children may have less vivid and intense dreams than older children because REM sleep in young children is associated with relatively low EM activity.⁸⁶ Dream narratives in younger children are often shorter and simpler than those reported by older children. Moreover, preschoolers often communicate only 1 relevant aspect of the dream when reporting their dreams and typically have difficulties distinguishing between internal and external events.⁸⁵ However, the idea that preschoolers' dreams depict static images about mostly animals and body states of themselves and that they lack active representation of the self, social

interactions, emotions, and motion imagery has been refuted.⁸⁷ This discrepancy appears to be correlated with the experimental method used to collect data. In an attempt to associate dreaming with brain maturation, cognitive performance was correlated with dream reports in children from 4 to 8 years old. Dream bizarreness and recall frequency were not related to cognitive indicators, but the dreamer's presence in their own dreams and the quality of their interactions were correlated with the children's abilities of emotional processing.⁸⁸ Emotional content affects the dreams of school-aged children, usually characterized by nightmares. The highest prevalence of nightmares is between ages 6 and 10 years, and they are often associated with emotional regulation difficulties and anxiety.^{89–91} During the preadolescent period, the frequency of recalled dreams is similar to that in adults. However, around 13–15 years of age, the dream report rate decreases and REM dream reports seem to lose some of their vividness, cinematic features, and narrative complexity, becoming more like NREM dreams. This may be connected to ongoing neural changes (synaptic pruning) in the adolescent.⁹²

The birth of dreams

Although the development of mental activity during the lifespan exists, it is uncertain when this capability emerges. Few observational investigations of preverbal children's dreams exist.⁸⁵ Nevertheless, previous research has found close connections between nighttime behavior and everyday life. This led the authors to assume that mental imagery similar to dreaming occurs in the first year of life.⁹³ However, dream recall does not develop until 3 years of age because children cannot organize and retrieve mnemonic traces below that age.^{94,95} In addition, children start to discern dreams from reality at 4 years old, but they can completely distinguish them only at 9 years old.^{96,97}

The absence of objective and quantitative data prevents us from identifying the exact developmental moment when dreams begin. Collecting data on how the main feature of dreams and dream recall during development are related to cortical activity changes could be a starting point to obtaining objective data. Children's dream studies are primarily based on self-reported information and limited to cognitive abilities, such as memory and verbal skills. A correlation between long-term memory and the bizarreness of dreams has been found in groups of 3-year-old compared with 5-year-old children.⁹⁸ Verbal abilities and sociability also play a role in dream report frequency⁹⁹ and bizarreness.⁹⁸ However, Foulkes considered the dream reports from children under 5 years old unreliable because they are more influenced by gregariousness than the expected cognitive skills. He also confirmed that the maturation of visuospatial skills is necessary for dream production. This would suggest that children younger than 3 years of age cannot dream.⁹⁹ Several studies have shown a strong link between organizational abilities and visuospatial skills with dream recall¹⁰⁰ and dream bizarreness.⁹⁸

These data could suggest that dream activity emerges early in infancy due to a bottom-up mechanism. However, a real awareness of dreaming ability occurs later, after acquiring cognitive skills. To more deeply investigate this aspect, it would be interesting to compare the development of dreams to perceptual

spatial skills of blind and sighted children. It is known that blind individuals have impaired skills during complex spatial tasks and develop some spatial skills later. Therefore, the development of perceptual systems on spatial skills and the relationship with dreams may elucidate their origin and qualitative nature.

Sleep and dreams in blind children: a poorly investigated issue

The dreaming process and dream content in blind children are still mostly unclear, although it is interesting to evaluate their origin. Furthermore, sleep research in blind children is lacking and primarily involves the sleep-wake cycle. Unlike adults, circadian disorders seem to be rare in children and adolescents who are born completely blind.¹⁰¹ One possibility is that alternative synchronizers are being brought into play, such as regular meals, work patterns, and physical activity.¹⁰² However, a study revealed that a higher percentage of blind children (compared with controls) had sleep complaints,^{103–105} suggesting that a larger percentage of blind than sighted children have problems related to sleep regulation. The time at which strong circadian desynchronization, as well as possible changes in the NREM-REM cycle and dream reports, appear during the lifespan is not clear. Given the role of sleep in the plastic reorganization of the visual cortex during development in cats,¹⁰⁶ future research should study the relationship between sleep and dream activity and the reorganization of visual areas in blind children.

GENERAL DISCUSSION ON NEUROSCIENTIFIC FINDINGS

Sleep and associated mental activity have a fundamental role in life. Although dreams have been studied for more than a century, much is still unknown. The main open issues proposed in recent decades on dreams¹ are the related functional networks, neural correlates, and signal propagation. Here, we discuss these open issues and present some possible pathways for future research and implications for the motor and psychological skills training programs of blind individuals.

Functional networks underlying dreaming

In the last decade there have been discoveries regarding cortical mechanisms of dream retrieval. Globally, studies on cortical correlates of dreams reveal that both frontal and posterior areas (which included the temporo-parietal junction) are involved in the retrieval process of dreams. These findings are coherent with clinical, neuroimaging, and transcranial magnetic stimulation studies of dreaming (see reviews^{56,107}). Also, these areas are those typically implied in conscious cognition, as theorized by the Global Workspace theory of consciousness.⁵⁸ The gamma frequency is a particularly relevant rhythm, as shown in cortical and intracranial EEG, transcranial magnetic stimulation, and lucid dream studies.^{25,108,109} Evidence from neuroimaging studies is not restricted to cortical regions but also extends to subcortical areas. Notably, a complementary role in dream generation and retrieval of the hippocampus and amygdala was suggested.^{56,110}

However, the objective difficulties in obtaining reproducible results and the limitations of the experimental paradigms leave the cortical mechanisms underlying conscious dream experiences a largely unresolved issue.⁵⁹ Furthermore, none of the most critical studies passed the “dream catcher test.”⁶⁰ This test defines the criterion for the genuine discovery of neural constituents of phenomenal consciousness: the ability to predict dreaming consciousness based purely on brain-based (EEG) data. Additional studies using standardized experimental procedures or asking the same question using different approaches are needed to establish the robustness of these findings. New paradigms that could provide data on dream retrieval and physiological mechanisms have been proposed or utilized, including studies on lucid dreaming,^{25,56,111} nonhuman mammal dreams,¹¹² and white dreams.¹¹³ A white dream is the feeling of having had a dream experience without recalling any detail about an oneiric activity. White dreams are linked to dream encoding or retrieval problems, allowing to focus on the dream-generation process. Dream researchers are interested in lucid dreams (LDs).^{114–117} An LD is a specific state of dream consciousness that mainly occurs during REM sleep where people are aware that they are dreaming and can control the oneiric content while remaining asleep.¹¹⁷ This is considered an intermediate level between dream experience and wakefulness, and thus an intermediate state of consciousness. From this point of view, an LD is an interesting state from which to best understand the underlying neural mechanisms of the dream experience, thanks to the possibility of controlling the dream’s content. The approach may also allow us to infer the neural basis of consciousness. For this purpose, epileptic patients, regardless of whether they lose their consciousness during seizures or not, might confirm EEG correlates of consciousness with a different approach.³

A still debated issue is the generic model of the dream experience. Literature reveals that activation models, circadian processes, and ultradian influences play a role in dream retrieval. Thus, all sleep cycles should be studied, focusing on creating a universal model of dreams that considers the impact of chronobiologic and sleep-dependent factors on dream production. Another new aspect is how these cortical mechanisms change during development. Early studies found that children report dreams in the early years of life^{118,119} and that dream content undergoes a maturational process, suggesting the development of brain mechanisms and generator models of dreams.

Neural correlates of dream contents

Full discovery of the neural and physiological correlates of dream content is still far away. Information about a dream’s content is reported during wakefulness and thus is both separate from when the dream experience is lived and in a different state of consciousness. Moreover, the report of sleep mentation at awaking impacts the same oneiric content. Without triggers specifically identifying the exact moment when an image was elaborated or an emotion felt, it is difficult to determine the brain’s correlates related to that event. Some objective measures (eg, EMs) and some hypotheses (eg, the scanning hypothesis) exist, but they are insufficient to achieve the final aim of dream

reconstruction. Only 1 study successfully tried to decode visual imagery during the sleep-onset period using machine-learning models. The authors predicted the visual contents given functional magnetic resonance imaging (fMRI) patterns, associating brain activity, and verbal reports.¹²⁰ This “brain reading” approach uses noninvasive techniques¹²¹ to decode perceptual or mental conscious states from brain activity (currently, primarily fMRI patterns). Furthermore, no findings on brain correlates with sensorial content other than visual exist. From this point of view, the dreams of blind people could be helpful since they have a higher frequency of auditory, tactile, gustatory, and olfactory dream components.⁹ However, even if their dreams could be informative, all the problems of indirect access to dreams remain. Studies on patients with REM behavior disorder⁵⁶ and sleep-talking individuals¹²² have been proposed to overcome this problem. Although these approaches can give us essential information about oneiric experience, they limit the possibility of studying dream contents to a reduced population.

A recent study demonstrated the possibility of doing real-time communication with lucid dreamers during REM sleep.¹¹⁵ This finding provides a potential opportunity to obtain real-time information about the dream’s content. However, the neural processes underpinning LDs, being 2 different states of consciousness, could be different from those of a typical dream. The emerging method of dream engineering that we discuss in the “The Frontiers of Dreaming” section may offer a solution.

Signal propagation in dreams

The final unresolved issue is the nature of the dream’s origin. A dichotomy exists between the perception-like origin, thus from activity in low-level sensory areas that are then integrated into higher-order areas, or an imagination-like origin, thus generated from abstract thoughts. The scientific community is divided into who argue for a privileged top-down direction of dream generation^{1,123} and those who argue that sensory experience is the source of dreams.^{77,78}

Several pieces of evidence support a top-down origin. First, a strict correlation between visual imagery and dreams has been demonstrated in adults¹²³ and children.¹ Participants experiencing aphantasia, a condition in which the individual cannot generate visual imagery, report a significant decrease in frequency and vividness during dreams.¹²³ Some evidence exists for the presence of visual imagination in congenitally blind individuals’ dreams.^{5,8}

Different studies support the idea that visual experiences in dreaming are linked to a bottom-up model.^{39,120,124,125} Consistent with this, LaBerge and collaborators¹²⁴ demonstrated that similar smooth pursuit eye movements characterize waking perception and lucid dreaming during tracking. In contrast, they observed a characteristic saccadic tracking during visuomotor imagination. The “brain reading” approach used by Horikawa et al¹²⁰ revealed that specific visual contents during sleep could be predicted by the same brain patterns of stimulus perception. Other studies in congenitally blind participants have found no visual content in their dreams.^{9,78} A strong link between organizational abilities and visuospatial skills and dreams has also been

demonstrated both in adults¹²⁶ and in children.^{98,100} The spatial skills are not compromised in participants with aphantasia,¹²³ although some findings reveal a spatial impairment in blind individuals.¹²⁷ Evidence on brain lesions cannot help clarify dream mechanisms (see reviews^{56,107}).

Finally, dream studies in congenitally blind individuals suggest the presence of visual awareness independent of visual perception but do not exclude a bottom-up origin. As indicated, dreams could arise from an innate body scheme or be linked to a multisensory integration mechanism.

Future investigations on blind participants and the relationship between spatial skills and dreams in adults and during development can provide new information about the origin of dreams. Interestingly, recent evidence suggests that early-blind individuals use the temporal domain to represent reality.⁷ Indeed, where the visual system is more associated with the spatial domain, the acoustic system is more associated with the temporal domain. Hearing is the primary sense used by blind people and the increase in the other sensory components in blind peoples' dreams, so there may be a shift from the spatial to the temporal domain in their oneiric context. Further, the temporal response of blind individuals during a spatial task is associated with an early cortical response in the occipital area,¹²⁸ and we can hypothesize that this shift has a perceptive nature.

Nonetheless, excluding a more complex interaction between perceptual and imaginative sources in dream origin is impossible. This interaction could also change during the lifespan and during the same night. Therefore, defining objective measures is fundamental to obtaining reliable and reproducible data. As for dream content investigation, applying new technologies that allow interfacing with the sleeping mind could solve this challenge.

THE FRONTIERS OF DREAMING: APPLICATIONS AND REHABILITATION

Dream engineering

Dream engineering emphasizes the causal role of the body in dream generation and describes a circuitry between the sleeping body and the dreaming mind.¹²⁹ Thus, it assumes that nearly any sensory stimulus has the potential to modulate experiences in sleep. It further suggests that different physiological and electrophysiological sensors can capture the dream experience.

The attempt to influence dream contents using different stimuli (ie, visual, auditory, somatosensory, or olfactory cues) has a long history. Dement and Wolpert¹³⁰ defined the beginning of studies on dream manipulation in 1958. Subsequently, research has been conducted both during presleep^{131,132} and sleep.^{133,134} More recently, stimuli were presented in different sleep stages¹³⁵ and LDs elicited.¹¹⁴ Although most stimuli tested have been visual or auditory,^{131,133–135} some studies have applied other sensory stimuli during sleep, such as thermal,¹³⁴ tactile,¹³⁶ or olfactory stimulation.^{114,137} Results of these experiments are mixed and not comparable because of the absence of a systematic methodology.¹⁰⁷ Moreover, little information is available

about cortical correlates associated with these types of stimuli and the ongoing neural processes.

Dream engineering attempts to standardize this approach by adapting human–computer interaction approaches to dream studies and collecting all possible information on dream experiences using numerous sensors. Data collection starts with the recording of EEG cortical activity, while other sensors capture different bodily sources of dream events. These include sensory incorporation, muscular twitches, and isomorphisms between EMs, respiration, motor circuitry, and heart rate.¹²⁹

The application of sensory stimulations within the context of dream engineering presents some limitations: first, gating and arousal mechanisms (with possible induced shifts in sleep stages); then, the fragility of the sleep state; and finally, the poor control of the oneiric experiences. Nonetheless, dream engineering has the potential to strengthen dream and sleep studies. While some technological devices have been developed,¹²⁹ further experimental research to create new devices and find new stimuli that cross the threshold of sleep is fundamental for discovering how such stimuli interact and are eventually integrated into dream content. This approach can provide the basis for investigating multisensory integration during the sleep period. It can also investigate time and space perception to study how different stimuli become elaborated during sleep periods and capture dream events' cortical and bodily sources. Previous studies on time perception during sleep used electrical stimulation to influence dream content and quantify time perception during the oneiric experience.¹³⁸ The first experiments of Dement and Kleitman showed a relationship between REM-dream time and real time.¹¹ A more recent study shows varying time perception and speed alterations of the internal clock after different states of EEG vigilance using an auditory rhythmic stimulus.¹³⁹ Their study does not provide the data necessary to elaborate a model of time perception during the dream, but it provides a hint regarding sensory stimulation and time perception. Different physiological and psychological factors influence time perception, including age, sex, body temperature, mental concentration, exercise intensity, and emotional state.¹⁴⁰ Some of these factors must be considered to understand time and space perception during sleep.

This information may help design a rehabilitative program for sensory-impaired individuals that incorporates this critical period of our daily life.

Continuity hypothesis and rehabilitative approach

The continuity hypothesis states that continuity exists between daily experience and dream content.¹⁴¹ Studies based on this hypothesis investigate dream recall as a direct psychological correlate of personality and emotional features of daily mental activity. This hypothesis has been generalized to consider a continuum also for what concerns the underlying neurobiological, perceptual, and cognitive mechanisms.^{107,120} Although some studies on dreams of sensory- and motor-deprived participants did not support the existence of this continuum, most studies show a connection between waking life and sleep mentation. For example, the most emotionally intense waking events can be incorporated into dreams,¹⁴² learning-related

dream production is related to trait-like cognitive abilities,¹⁴³ and dreaming about a specific learning task is associated with enhancing sleep-dependent memory consolidation.¹⁴⁴

Most research related to the continuity between sleep and waking states focuses on how the waking experience can influence dreams. However, is the reverse true? As the waking experience can influence dreams, can sleep mentation activity influence waking life? Some studies have investigated this aspect. For example, in an oddball novelty paradigm, Eichenlaub and colleagues¹⁴⁵ reported that being called with the first name induced a greater alpha activity decrease in high-dream-recall than in low-dream-recall individuals during wakefulness.¹⁴⁶ They interpreted the more sustained alpha decrease in high-dream-recall as deeper processing of complex sounds compared with low-dream-recall during wakefulness. Accordingly, a previous study showed more complex processing of stimuli in high-dream-recall than in low-dream-recall individuals.¹⁴⁷ In addition, it has been observed that participants who dreamt about a learning experience performed during the previous waking state showed improved spatial performance compared with participants who did not dream about it.^{144,148} More generally, the idea that REM sleep has an active role in development was proposed several decades ago⁸² and the concept was further developed in the theory of proto-consciousness.⁷⁶ Proto-consciousness suggests the interaction of brain states underlying waking and dreaming, ensuring the optimal functioning of both. This theory emphasizes the primary aspects of consciousness that include perception and emotion. Subsequently, Voss et al⁸¹ discussed their results on the dreams of sensory- and motor-deprived participants in the context of this theory. They assumed that dream content feeds itself from an innate body scheme allowing sensory- and motor-deprived individuals to experience sensations that they cannot feel while awake. In contrast, Lopes da Silva⁷⁹ interprets the Bértolo et al⁵ study in terms of multisensory integration, hypothesizing that blind people can produce virtual images starting from other sensory modalities that integrate the inputs via the visual system to produce concepts that can be graphically represented, as found by De Volder et al.⁸⁰

These hypotheses can be further developed by introducing the dreamlike state as a rehabilitative tool. For example, suppose waking and dreaming cooperate for the optimal functioning of both, and during the dream, state is possible to access an experience that cannot be lived while awake. In that case, it might be possible to use this “virtual reality” to strengthen some abilities. Indeed, even if the experienced dreams themselves could not perform a function, as proposed by Hobson and McCarley,⁶² since dreams are simply a reflection of the underlying spontaneously generated brain activity, this highlights that brain activity itself seems to be a relevant role in our life. In addition, some experiments have succeeded in enhancing sleep NREM patterns and generating correlated memory improvement using sensory stimuli during sleep.^{149,150} Therefore, it is fundamental to understand better how sensory perception, multisensory integration, and imagination are related during sleep and dream-like states to consider new rehabilitative programs for those with sensory deficits.

CONCLUSIONS

Dreams have fascinated scientists, doctors, psychologists, and philosophers for centuries. Nevertheless, the function of dreaming remains one of the great mysteries of science. Like a stereogram, the dream remains something perceptible but not palpable, almost unattainable. However, thanks to the progress of science and technology, this status might change. Studies on the development and emergence of this mental activity and the link between nocturnal and diurnal activity can clarify the relationship between dreaming and waking mentation. Furthermore, studies in sensory-deprived individuals, studies on complex perceptual functions, and studies that exploit advanced technologies to obtain real-time information might tell us more about the nature of dreams and the underlying neural processes. Perhaps in this way we might reach the long-sought answer to the question, “Why do we dream?”

ABBREVIATIONS

CAP, cycling alternating pattern
 EEG, electroencephalogram
 EM, eye movement
 LD, lucid dream
 NREM, non-rapid eye movement
 PGO, ponto-geniculo-occipital
 REM, rapid eye movement

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