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THEORETICAL REVIEW

White dreams are made of colours: What studying contentless dreams can teach about the neural basis of dreaming and conscious experiences

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SUMMARY

Reports of white dreams, the feeling of having had a dream experience without being able to specify this experience any further, make up almost one third of all dream reports, yet this phenomenon—until very recently—had not yet been in the focus of targeted investigations. White dreams are typically interpreted as forgotten dreams, and are sidelined as not being particularly informative with regard to the nature of dreaming. In this review article, we propose a paradigm shift with respect to the status of white dreams arguing that focusing on this phenomenon can reveal fundamental insights about the neural processes that occur in the dreaming brain. As part of this paradigm shift, we propose a novel interpretation of what white dreams are. This new interpretation is made possible by recent advancements in three different though interrelated fields focusing on dreaming, mental imagery, and wakeful perception. In this paper, we bring these different threads together to show how the latest findings from these fields fit together and point towards a general framework regarding the neural underpinnings of conscious experiences that might turn out to be highly relevant not just for dream research but for all aspects of studying consciousness.

Introduction

Theorising about dreaming necessarily relies on two sets of data that ought to be collected in parallel: objective measures of brain processes occurring in the dreaming brain, and subjective reports of the contents of dreams. In a significant proportion of all cases, however, subjective reports are not available—subjects, although certain that they had dream experiences, cannot recall any specific content. Our paper focuses on this phenomenon, called white dreaming.

Until very recently, no targeted endeavour ventured to explore the characteristics of white dreams. This changed when a study provided white dream specific electroencephalography (EEG) data for the first time [1]. Nevertheless, since in evaluating its findings the original study did not directly focus on white dreams, this corpus of data has not been fully analysed, and conclusions about the nature of white dreaming have not been discussed in detail. The findings, however, are worth analysing: as we shall argue, they fundamentally reshape how to think about white dreams and the process of dreaming in general.

This paper has three parts. In the first, introductory part, we discuss the phenomenon of white dreaming, and the two main existing strategies that attempt to interpret it. In the second part, we overview recently published findings about the EEG correlates of white dreams, and argue that they suggest a third, novel kind of interpretation that offers a distinctive picture with regard to the nature of white dreams. Finally, in the third part, we provide a review of the literature arguing that our new interpretation is also supported by the body of evidence that has been accumulated in the relevant sub-fields of dreaming, mental imagery and wakeful perception.

Abbreviations: PAS, perceptual awareness scale.

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White dreams and their interpretations

Subjects waking from sleep sometimes report having specific dream experiences (sleep mentations) which they can describe in detail (*contentful dreams*). Other times subjects deny having any kind of pre-awakening experience whatsoever (*no dream experience*). Interestingly, a significant portion of post-awakening reports describe a distinct feeling of having been dreaming prior to awakening, yet subjects are unable to recall any details about these dream experiences. Such instances of dream experiences without reportable content are called *white dreams* [2–5] or contentless dreams [6].

Early studies utilising dream diaries to record dream reports found that approximately 30% (varying between 11% and 45% in different studies) of post-awakening reports described white dreams (approx. 50% contentful dreams and 20% no dream experience; all sleep stages combined) [6]. This general distribution has been confirmed by recent studies relying on a serial awakening paradigm performed in a laboratory environment finding that 33% of total post-awakening reports described white dreams (45% contentful dreams, 22% no dream experiences) [7]. The specific proportion of white dreams, however, widely varies in different stages of sleep: it is around 15% in rapid eye movement (REM) sleep [7], and around 40% in non-rapid eye movement (NREM) sleep (Noreika and colleagues reported an overall 39% from NREM [8]; Siclari and colleagues found approx. 20% in N1, almost 40% in N2, and almost 40% in N3 [7]).

In experimental paradigms aiming to study factors underlying differences in dream recall, both reports of no dream experience and reports about white dreams sometimes count as instances of 'non-recall', i.e., a failure to report dream content [9,10]. Moreover, studies focusing on the content of dream recalls typically sideline white dreams as particularly uninformative [11–14]. On the other hand, when the ability to recall any dream experience is in the centre of interest, white dreams are sometimes lumped together with contentful dreams [15].

However, reports of contentful dreams, white dreams, and no dream experience presumably describe different phenomena. Early studies already established that the phenomena characterised by contentless and dreamless reports were qualitatively distinct, as the proportion of their occurrence was differently affected by factors like the actual stage of the menstrual cycle or the length of total sleep time [6]. A more recent study concluded that all three phenomena have unique EEG signatures [1].

White dreams as forgotten dreams

To be able to report any kind of dream content upon awakening requires many conditions to be met. First, a dream experience needs to occur during sleeping (*dream generation*), second, the content of the experience needs to be stored (*encoding*), and third, the subject needs to have access to this stored information after awakening (*retrieval*) [16,17].

In the case of white dreams, taking subjects' reports that they did undergo dream experiences but don't have access to the details at face value implies a problem either with dream encoding or with retrieval. From the perspective of this 'forgotten dreams' interpretation, then, white dreams are full-fledged (contentful) dream experiences, the content of which nevertheless cannot be recalled either due to failures of storing these experiences in memory or due to failures of accessing such memory traces after awakening.

Traditionally, white dreams are accounted for in terms of problems with retrieval. Cohen [18] summarises three different explanations of reporting white dreams: the content of white dreams might be repressed by defence mechanisms; they might be lost due to interference with unrelated tasks after awakening; or they might be lost due to the dramatic state change that occurs during the transition from sleeping to waking (see also Ref. [19]).

White dreams as imageless dreams

According to an alternative interpretation, at least a proportion of the reports describing white dreams might not result from forgetting the content of the dream, but might rather faithfully characterise the actual dream experience itself. That is, some dream experiences underlying reports of white dreams might be 'contentless' or '*imageless*' in the sense that subjects experience only a minimal form of conscious presence with no narrative structure, and no specific percepts, bodily sensations or thoughts occurring during such experiences [20,21].

The guiding analogy of this interpretation of white dreams is the experience that expert meditators describe as a bare form of consciousness that involves only a basic form of subjective temporality (experiencing a phenomenal 'now') with a sense of duration [20], or a basic form of subjective existence (experiencing being alive) [22,23] that might even be deprived of the spatial aspects of self-location and self-identification [21].

According to this interpretation, then, (at least a portion of) white dreams would be somewhere in between dreams with reportable content and dreamless sleep with no experiences whatsoever forming a transitional state in which subjects are not yet totally unconscious but already lack content-specific experiences [20,21].

Neural correlates of white dreaming

In a recent study that is groundbreaking in many respects, Siclari and colleagues presented, for the first time, EEG data comparing white dreams (in their terminology: DEWR standing for 'dream experiences without recall of content') with no dream experiences (in their terminology: NE standing for 'no experiences') and with contentful dreams (in their terminology: DE standing for 'dream experiences') [1]. Focusing on an uncommented aspect of the original findings sheds new light on the neural underpinnings of white dreaming, and allows for a reevaluation of existing accounts of white dreams.

The original findings

In their study, Siclari and colleagues relied on a serial awakening paradigm where subjects were awakened in 15–30 min intervals [7]. Using high-density EEG recordings they contrasted both high- (20–50 Hz) and low-frequency (1–4 Hz) components of the EEG signals from the last 20 s preceding awakenings that were followed by reports of no dream experiences, white dreams, or contentful dreams.

Comparing white dreaming to no dream experiences in NREM sleep, the findings showed decreased low-frequency component over posterior regions labelled *posterior hot zone* (low- and high-level sensory areas, precuneus, posterior cingulate, retrosplenial cortex—Fig. 1(a)), whereas there was no significant difference in the high-frequency component (Fig. 1(b)).

Comparing contentful dreams to white dreams in NREM sleep no significant differences could be detected in the low-frequency component, however, in the high-frequency range there was an increase over medial and lateral frontal areas (Fig. 1(d)).

Comparing contentful dreams to no dream experiences in both REM and NREM sleep showed decreased low-frequency component over the posterior hot zone, and an increase in high-frequency activity over the posterior hot zone that also extended to parts of the lateral frontal cortex and temporal lobes (Fig. 1(c)).

Finally, in cases in which subjects reported contentful dreams with specific content-types occurring in them (e.g., dreams with

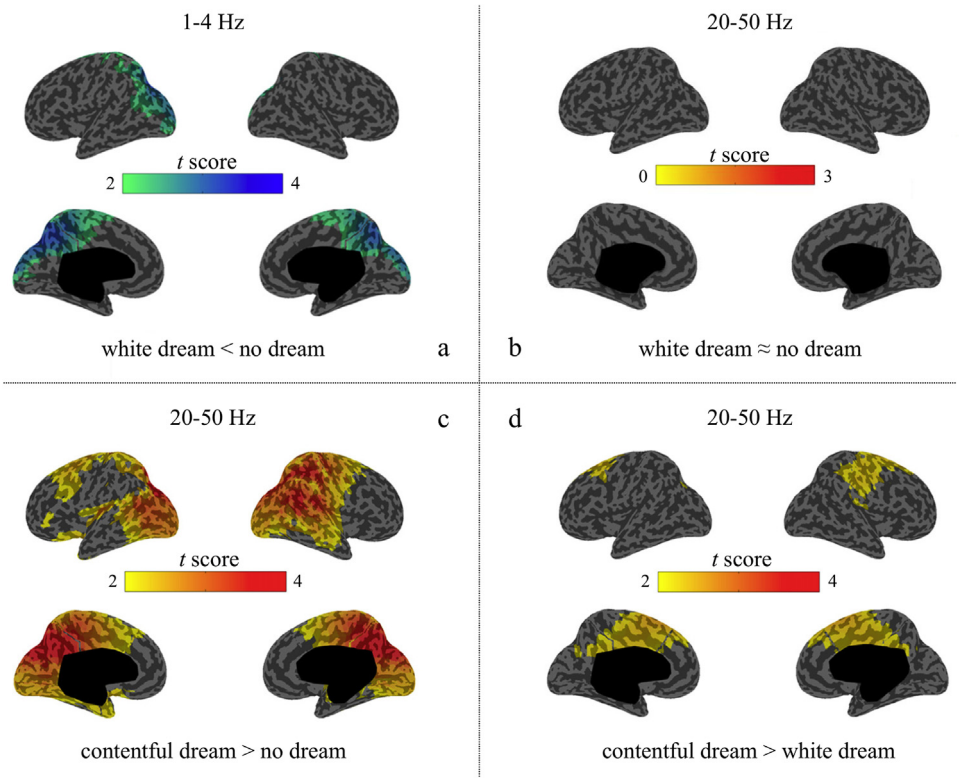

Fig. 1. Comparisons of local changes in low- and high-frequency electroencephalography (EEG) components in non-rapid eye movement (NREM) sleep [1]. **(a)** Comparison of 1–4 Hz component in subjects reporting white dreams compared to subjects reporting no dream experience. Low-frequency component decreases in the posterior hot zone, when subjects report dream experience (Fig. 1b in Ref. [1]). **(b)** Comparison of 20–50 Hz component in subjects reporting white dreams compared to subjects reporting no dream experience. No significant difference in high-frequency component is detected in the posterior hot zone (Supplementary Fig. 4a in Ref. [1]). **(c)** Comparison of 20–50 Hz component in subjects reporting contentful dreams compared to subjects reporting no dream experience. High-frequency component increases in the posterior hot zone and lateral posterior and temporal regions when subjects report contentful dreams (Fig. 3a in Ref. [1]). **(d)** Comparison of 20–50 Hz component in subjects reporting contentful dreams compared to subjects reporting white dreams. Significant difference in high-frequency component is detected only in medial and lateral frontal areas, *but not in the posterior hot zone* (Fig. 3b in Ref. [1]). Reproduced with permission.

faces) the EEG signal (obtained during REM sleep) showed increased activity in the high-frequency component compared to contentful dreams without the specific content-type (e.g., dreams with reportable content but no faces occurring in them) in the particular brain area that processes the specific content-type in question during normal perception (e.g., in fusiform face area in the case of dream experiences containing faces).

The original interpretation

White dreams, according to Siclari and colleagues, are forgotten dreams, i.e., subjects reporting white dreams had contentful dreams but they have forgotten the content of these dreams. Contrary to the traditional retrieval-centred explanation of the inability to recall relevant dream content [18], Siclari et al. shift the focus to problems with encoding as their findings indicate that the most consistent difference between being versus not being able to report dream content lies in increased high-frequency activity (correlating with contentful dreams) in fronto-central areas that are typically associated with memory encoding (Fig. 1(d)).

Siclari and colleagues emphasise the importance of *local changes* over specific brain regions in high- and low-frequency activity as the correlate of the presence or absence of different dream experiences irrespective of global EEG characteristics and overall sleep stages. Motivated by the findings regarding increased high-frequency EEG activity over content-specific regions, Siclari and colleagues conclude that the local increase in high-frequency activity is the neural correlate of specific dream contents. On the other hand, since a local decrease in low-frequency (slow wave) activity over the posterior hot zone was observed both during white dreams and contentful dreams, Siclari and colleagues suggest that the localised reduction of low-frequency activity over the posterior hot zone is a necessary condition for conscious experiences to occur [24,25].

Weak content-codes in white dreaming

However, importantly from our present perspective, with regard to the EEG correlates of white dreaming some results may suggest an alternative interpretation.

First, the interpretation that white dreams are contentful dreams which, then, are forgotten is not consistent with the finding that there is no difference in high-frequency activity when white dreaming is compared to no dream experiences (Fig. 1(b)). According to the forgotten dream interpretation white dreamers have contentful dreams but after awakening this content cannot be recalled. Siclari and colleagues propose that a difference in high-frequency activity over fronto-central areas (Fig. 1(d)) is related to this difference in the ability to recall. However, if this interpretation was true, then during white dreams the high-frequency component should have shown the same kind of elevated activity over the posterior hot zone than during contentful dreams, since increased activity in these content specific regions are supposed to be the neural correlates of specific dream contents [1,26]. But when compared to no dream experiences, white dreams show no such elevated activity (Fig. 1(b)).

Even more interestingly, note a discrepancy in the data-set itself. The comparison between contentful dreams and no dream experiences (Fig. 1(c)) tells us that the high-frequency activity in the

posterior hot zone in contentful dreams is significantly higher than during no dream experiences. The comparison between contentful dreams and white dreams (Fig. 1(d)) adds that the high-frequency activity in white dreams *in the posterior hot zone* is also higher than during no dream experiences, since it is not significantly different from the similar activity in contentful dreams. (Note that Fig. 1(d) shows a difference between contentful dreams and white dreams *only* in medial and lateral frontal areas). But, as we have seen, according to the comparison between white dreams and no dream experiences (Fig. 1(b)), activity in the high-frequency range in the posterior hot zone during white dreams is not significantly higher than during no dream experiences.

How can high-frequency activity during white dreams appear to be significantly higher than baseline (i.e., during no dream experiences) when compared to contentful dreams but appear to be around baseline when compared directly to no dream experiences? A plausible answer seems to be that high-frequency activity in the posterior hot zone shows a small amount of increase during white dreams as well—which could then have been concealed by thresholding in the original study. This hypothesis is supported by the unthresholded map on Fig. 4b in the supplementary material of Siclari et al. [1] that shows slight but non-significant increase in high-frequency activity in contentful dreams with respect to white dreams. That is, high-frequency activity in the posterior hot zone during white dreams is somewhere between baseline, i.e., the level of activity characteristic of no dream experiences, and the level of activity characteristic of contentful dreams (such that the differences neither between contentful dreams and white dreams, nor between white dreams and no dream experiences are statistically significant, whereas the difference between contentful dreams and no dream experiences is statistically significant). This would, then, mean that white dreams correlate with a low but existing increase in high-frequency activity over the posterior hot zone. (Note that high variability in this activity could also account for the results — for more details see the section "Quality of experiences and dream recall" below.)

White dreams are low quality experiences

The finding that high frequency activity during white dreams is increased compared to no dream experiences but weaker than during contentful dreams seems to be incompatible with existing accounts of white dreaming and points towards a new interpretation.

Quality of neural representations and quality of experiences

Increased high-frequency EEG activity indicates higher neural firing rates, and thus higher intensity population codes [1,27–29] representing specific contents of dreams. The intensity of population codes (i.e., the amplitude of the neural response function) is a determinant of the *quality of neural representation*: more intense population codes are more robust, produce stronger signals and allow for better read out [30,31]. Other determinants of the quality of neural representations are the precision of the neural response (i.e., the inverse variance of the population response function) as more precise population codes provide more unique representations, and the length of active maintenance [32,33].

Changes in the quality of underlying neural representations are reflected in the perceived *quality of* corresponding *conscious experiences*. For instance, attention induced increase in the intensity of population codes [34] representing e.g., stimulus contrast or saturation results in higher apparent contrast [35] or increased level of perceived saturation [36], respectively.

In general, the quality of conscious experiences is a feature-family of experiences determining how specific content-elements (visual, like e.g., spatial setting, faces, movement; auditory, like e.g., speech; and also thoughts; emotions, etc.) appear in an experience. The quality of an experience can be characterised along dimensions like vividness (how noticeable a specific content-element is), ambiguity (how distinguishable a content-element is from other content-elements), and stability (how long a content-element is present in the experience) [37,38].

The quality of conscious experiences can be reduced along all these dimensions. The different ways of having degraded conscious experiences are underlain by neural representations, which are reduced in quality along corresponding dimensions (less vivid – lower intensity; more ambiguous – lower precision; less stable – shorter maintenance). This correspondence between the quality of neural representation and the quality of conscious experiences accounts for a multitude of findings reporting reduced awareness [38–43].

Weak content-codes in white dreams implicate low quality experiences

According to the alternative interpretation provided by our proposal, the weak (i.e., low intensity) content-codes indicated by the Siclari et al. study [1] as the correlate of white dreaming imply that subjects having white dreams undergo reduced quality dream experiences.

White dreams (at least a significant portion of them, see below), therefore, are not forgotten dreams, as suggested by the standard interpretation [1,20,21]—not at least in the sense of having clear and vivid content that cannot be recalled, as the content of white dreams, according to our interpretation, is neither clear nor vivid, but reduced in quality. The pre-awakening EEG differences between white dreams and contentful dreams in posterior regions implicated by our analysis suggest that a full explanation requires more than reference to failure of retrieval (since that would imply only a post-awakening difference) or of encoding (since that is typically associated with activity in fronto-central areas).

White dreams are not imageless dreams, as suggested by Windt and colleagues [20,21] either, as they do have content, although this content is not clear, not vivid enough. Content-specific brain areas that underly having conscious experiences with specific contents are activated during white dreams—only to a lesser degree than during dreams with reportable content.

Put another way, in accordance with our hypothesis, both the 'forgotten dreams' and the 'imageless dreams' interpretations capture something correctly about white dreams: the former is right that white dreams have some content that cannot be recalled after awakening; and the latter is right that white dreams are somewhere in between contentful dreams and no dream experiences in the sense that subjects undergo a reduced kind of experience.

Low quality experiences in dreaming, mental imagery and wakeful perception

In this section, we argue that by focusing on the quality of conscious experiences, various threads in the literature can be brought together providing further support for the interpretation that white dreams are low quality experiences.

Quality of experiences in REM dreams and NREM mentations

To determine the visual qualities of dream experiences (and to circumvent the problem of describing often vague dream experiences verbally [19]), several studies developed different varieties of visual scales based on variations of a single photograph, where each variation was reduced along one or more dimensions like colour saturation, brightness, figure clarity, background clarity, overall hue, etc. [44–50]. These studies uncovered that, in general, REM

dreams are better quality (i.e., more vivid, clear, etc.) than NREM mentations [46,47,51], and that awakenings from phasic periods of REM are followed by reports of better quality dream experiences than awakenings from tonic periods [46,52–55]. It has also been implicated that enhanced quality dream experiences are underlain by increased neural activity [46,48,56].

Our proposal extends this picture with the suggestion that individual dream experiences reported from the same state (REM or NREM sleep; phasic or tonic period) as well can and typically do differ in quality (vividness or clarity), just as individual vividness changes in mental imagery on a trial-by-trial basis [57,58].

Quality of experiences in mental imagery

In line with a recent shift from a bottom-up framework [59,60] to a top-down framework [61,62] regarding how to think about dream experiences, various lines of evidence suggest that mental imagery is closely related to dreaming [19]. Damage in or near the temporo-parieto-occipital junction is followed by both a cessation of dreaming [63,64] and problems with mental imagery in wakefulness [65–67]. In children, the ability to recall dreams correlate with the development of mental imagery and visual-spatial skills [19,68,69]. Dream recall frequency in adults also correlates with a greater waking capacity for visualisation [70–72]. Most interestingly from our present perspective, the strength (vividness) of mental imagery correlates with the quality of dream experiences [72].

This association between mental imagery vividness and dream vividness is especially informative as a correlation between mental imagery vividness and brain activity in relevant content-specific regions [1] has recently been reported by a series of studies both at a trait level [73,74], and at the level of trial-by-trial variations [57,58]. Trial-by-trial subjective mental imagery vividness also correlates with 'imagery strength', i.e., the priming effect of mental imagery on the dominant stimulus in a succeeding binocular rivalry presentation [75–77], which can be seen as an indicator of the quality of the neural code underlying the imagined content [78–81].

More specifically, Dijkstra and colleagues [57] found that experienced imagery vividness correlated with increased activity in posterior regions like early visual cortex, precuneus and right parietal cortex (and also in the medial frontal cortex) on a trial-by-trial basis. Similarly, Fulford and colleagues [58] reported that subjective imagery vividness judged image by image correlated positively with activations of a series of posterior brain regions including the precuneus, posterior cingulate, and higher order visual association cortex. The posterior regions implicated in these studies are all parts of the posterior hot zone in which the findings of Siclari et al. [1] indicate slightly increased activity during white dreams (compared to no dream experiences).

Quality of experiences in wakeful perception

In masking paradigms, it has been demonstrated that there is a continuous transition between clearly seen and not seen stimuli, such that in intermediate cases subjects, although report having experiences but only in a dim or unclear form, and are less certain about or even have no knowledge of the identity of the stimuli [82–88]. As one moves along this continuum from clearly seen stimuli towards not seen stimuli, the experiences subjects report get more and more degraded, their content becomes less vivid and more generic up until a point where subjects, although still confident that they are perceiving something, are not able to discern any kind of detail in their experience. These are the kind of experiences that are reported as a 'weak glimpse' on the perceptual awareness scale (PAS) [83,86,88]. PAS offers four categories that had been constructed to reflect and generalise subjects' own descriptions of how to differentiate between degrees of awareness of a stimulus [83]. These categories are: 'no experience', when subjects have no impression of the stimulus; 'weak glimpse', when subjects have a feeling that something has been shown but cannot specify any features of the stimulus; 'almost clear experiences', when subjects have an ambiguous experience of the stimulus with more vivid impressions of some stimulus aspects and less vivid impression of others; and 'clear experience', when subjects have a clear, unambiguous experience of the stimulus. The 'weak glimpse' rating captures the case when subjects are almost certain that they have experienced something but cannot recall any detail about the stimulus—which is strikingly similar to the descriptions subjects typically give about white dreams.

Over and above these phenomenological similarities, recent findings regarding the neural underpinnings of degraded wakeful experiences also support the new interpretation proposed here that white dreams are low quality experiences, as degraded experiences are found to be underlain by reduced neural activity [84,89–91] such that the level of the neural activity correlates with the quality of the experience.

Conclusion: a continuum of reduced quality experiences

The results reviewed so far support the claim that individual conscious experiences in general, and dream experiences in particular can be of different quality, and this difference in perceived quality correlates with local changes in neural activity over content-related brain regions. We propose that the Siclari et al. study [1] uncovered a manifestation of this phenomenon in the varied increase of high-frequency EEG component in contentful dreams and in white dreams.

Quality of experiences and dream recall

'Weak glimpse' type of experiences in wakefulness are at the low quality end of the spectrum of degraded conscious experiences, where the experience is so unclear and generic that no detail can be discerned, and the corresponding neural activity is also very weak. However, the high-frequency EEG activity found during white dreams over the posterior hot zone had intermediate values relative to values characteristic of no dreams and contentful dreams [1]. This means, that not all white dreams are of the lowest quality, rather, the reported intermediate values might have resulted from averaging over a continuum of different dreams with vividness (and corresponding intensity of underlying neural activity) ranging from very low to relatively high.

Nonetheless, reports of white dreams are uniform in that subjects cannot recall any content. This raises the question why the contents of the higher quality experiences of the continuum leading to reports of white dreams are not reflected in dream recalls. A possible answer might be a consequence of the fact that contrary to the 'online' reports of the typical mental imagery and wakeful perception paradigms, studying dreams characteristically relies on 'offline' reports that depend on encoding in and retrieval from long-term memory. As the quality of neural representations determines how robust they are and how efficient read out they make possible at later stages of processing [30,31], successful memory encoding might require a certain minimal quality, i.e., there might be a threshold such that dream experiences with below-threshold quality cannot efficiently be encoded in memory. This might also account for the weaker high-frequency medial and lateral frontal activity during white dreams compared to contentful dreams

uncovered by Siclari et al. [1] (see Fig. 1(d)), which is associated with reduced memory encoding.

Having said all this, it needs to be acknowledged that the findings available so far are compatible with the possibility that a smaller proportion of white dreams are better quality and are above the threshold of encoding, but nevertheless, due to some encoding failures, they do not get encoded properly. That is, the category of white dreams might not be a uniform category, it might be a mixture of low-quality and forgotten dreams. Note, however, that high quality but forgotten dreams cannot form a significant proportion of white dreams, as that would be incompatible with the intermediate values of high-frequency EEG activity over the posterior hot zone detected during white dreams (compared to no dreams and contentful dreams).

Cases in which subjects reporting white dreams upon awakening become able to recall details about their dreams later during the day might indicate a third subtype of white dreams that are initially forgotten due to a failure of retrieval. This subtype, however, must, at best, forms only a minority of all white dreams as a more significant proportion would be incompatible with not just the intermediate values of high-frequency EEG activity in the posterior hot zone, but also with the decreased high-frequency activity over medial and lateral frontal areas, as these cases would require properly encoded dream experiences.

These considerations reinforce the old idea emphasised by Goodenough [16] that thinking about dream recall as an "all-or-nothing affair" is a mistake. Dream experiences vastly vary with regard to their content and formal characteristics (length, complexity, bizarreness, etc.), and also their quality (vividness, ambiguity, stability). At least three stages lead to successful dream recall from dream generation, through memory encoding to retrieval. The standard account interpreted white dreams as results of problems either with encoding or with retrieval. Our goal in this paper was to highlight the importance of the first stage. The process of dream generation, especially the quality of the generated dream experiences (and the corresponding neural representations)—in line with the salience hypothesis that (besides other factors) also emphasised the importance of the vividness of dream contents [10,18,92]—does affect whether the content of dreams can be recalled or not. Very low quality contents are not clear, not vivid enough even for online recognition. Better but still low quality experiences might not be robust enough to be properly encoded. And even if encoded, low quality dream contents might be more difficult to retrieve [46,93,94] (see also in the case of mental imagery [95]) explaining why cued or prompted recall is more effective than free recall [17]. This continuum in the quality of dream experiences is further reflected (above the threshold of encoding and in the case of successful retrieval) in the reports that sometimes describe highly vivid complex dream scenery with a lot of details, but other times only a clear central image in front of an unspecific background, or great uncertainty even with regard to the foreground as well [46].

Quality of experiences and different stages of sleep

REM dreams and NREM mentations in general differ in length, complexity, and also in their perceptual quality [19,96]. It is known that slow waves, characteristic features of NREM sleep, reflect an oscillation between neuronal up- and down-states, which disrupts stable causal interactions between, and interferes with the normal functioning of, affected cortical areas [25,97,98]. Nir and Tononi [19] suggest that the shortness and lower complexity of NREM mentations might be due to the quick disruptions caused by occurring down-states. Longer, complex dreams might require long up-states, which is normally the case in REM sleep. Similarly, the occurrence of slow waves (and the neurochemical milieu in general) might also constrain the stability and intensity of possible neural representations, and thus the quality of conscious experiences as well. For example, local slow waves can occur during wakefulness [99], and REM sleep as well [100], while slow wave activity can locally decrease during NREM sleep [1].

These considerations, together with the framework proposed here reframes the classical debate about the role of REM and NREM sleep in dreaming, and instead of a dichotomous view that emphasises the differences in the number, length, complexity and perceptual quality of dreams recalled from REM and NREM stages of sleep [62,96], it advocates a more continuous, more graded picture. According to this graded view, the actual physiological characteristics of the brain impose local constraints [25] on the stability and intensity of relevant neural activity patterns, and thus influence the qualities of conscious experiences. In NREM sleep the overall conditions are in general unfavourable for the occurrence of higher quality experiences, but local changes could nevertheless subserve them and could give rise to NREM dream experiences that are similar to REM dreams. This could then reconcile the conflict between the two strands of findings that, on the one hand, highlight the lower number and lower quality of contentful dreams and the higher number of white dreams reported from NREM sleep, whereas on the other hand, stress the similarities between some REM and NREM dream experiences [62,96].

Practice points

1. Recent white dream specific EEG data indicates a weak but higher than baseline neural activity (i.e., weak but existing content-specific population codes) in posterior areas during white dreams.
2. Characteristics of the underlying neural representations (intensity, precision) are associated with corresponding characteristics of conscious experiences (vividness, clarity), which, we argue, implies that during white dreaming subjects undergo low quality dream experiences.
3. Studies focusing on the visual appearance of dreams already established differences between the vividness of dreams in REM and NREM and during tonic and phasic periods. We extend this picture by emphasising similar difference between individual dream experiences.
4. Recent findings regarding wakeful mental imagery vividness—which is associated with the vividness of dreams—demonstrated that changes in mental imagery vividness correlated with changes in cortical activity in the same posterior regions that were implicated by white dream specific EEG data.
5. Experimental paradigms focusing on wakeful perception also demonstrated that consciousness was graded, and found a correlation between the quality of experiences and the intensity of brain activity.
6. We emphasise that recall failures might occur not just due to problems with encoding or retrieval, but also because dream generation itself produces experiences with different quality.
7. Features of dreams are determined by local fluctuations of the physiological characteristics of brain activity. The global neurochemical milieu in different stages of sleep only constrains these fluctuations. This shifts the emphasis from a traditionally dichotomous REM/NREM view of dream generation to a more continuous picture.

Research agenda

1. New investigations should focus on how local changes in brain activity are related to trial-by-trial changes in the vividness of dreams, the vividness of mental imagery, and the degree of awareness of rapidly presented or masked stimuli.
2. Multivariate pattern analyses techniques should be combined with the serial awakening paradigm to confirm the hypothesis that white dreams are underlain by higher than baseline but weak cortical activity in posterior brain areas.
3. Such techniques might also be used to test whether the features (e.g., intensity) of cortical activity correlating with conscious experiences are able to predict the quality (e.g., vividness) of dream experiences or mental imagery.
4. The link between trait-like characteristics (like high/low level of dream recall, proclivity for daydreaming, vividness of mental imagery) and the intensity of underlying brain activity should also be systematically explored both within and across individuals.
5. Investigations need to be extended to the relation between other features of relevant neural representations and corresponding dream experiences as well. For example, bizarreness is a prominent characteristic of dream experiences, and uncertainty in dreams is one of the important factors that determines dream bizarreness. Reported uncertainty, however, might result from the perceptual ambiguity of certain elements of the dream, i.e., the decreased quality in the sense of too generic nature of particular contents of dream experiences, which in turn could arise from low precision neural representations.

Conflicts of interest

The authors do not have any conflicts of interest to disclose.

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References

*[1] Siclari F, Baird B, Perogamvros L, Bernardi G, LaRocque JJ, Riedner B, et al. The neural correlates of dreaming. Nat Neurosci 2017;24(6):171–878.
[2] Montplaisir J, Cote J, Laverdiere M, St-Hilaire J. Dream recall before and after partial commissurotomy. In: Koella W, Ruther E, Schulz H, editors. Sleep '84. Stuttgart: Gustav Fischer Verlag; 1985. p. 346–8.
[3] Monday J, Montplaisir J, Malo J-L. Dream process in asthmatic subjects with nocturnal attacks. Am J Psychiatry 1987;144:638–40.
[4] De Gennaro L, Violani C. White dreams: the relationship between the failure in dream recall and degree of hemispheric lateralization. Assoc Study Dreams Newsl 1990;7:7.
[5] Strauch I, Meier B. In search of dreams: results of experimental dream research. Albany: State University of New York Press; 1996.
[6] Cohen DB. Failure to recall dream content: contentless vs dreamless reports. Percept Mot Skills 1972;34:1000–2.
[7] Siclari F, LaRocque J, Postle B, Tononi G. Assessing sleep consciousness within subjects using a serial awakening paradigm. Front Psychol 2013;4(542).
[8] Noreika V, Valli K, Lahtela H, Revonsuo A. Early-night serial awakenings as a new paradigm for studies on NREM dreaming. Int J Psychophysiol 2009;74(1):14–8.
[9] Lewis HB, Goodenough DR, Shapiro A, Sleser I. Individual differences in dream recall. J Abnorm Psychol 1966;71(1):52–9.
[10] Schredl M. Dream recall: models and empirical data. In: Barrett D, McNamara P, editors. The new science of dreaming, vol. 2. Westport: Praeger; 2007. p. 79–115.
[11] Cipolli C, Bonanni E, Maestri M, Mazzetti M, Murri L. Dream experience during REM and NREM sleep of patients with complex partial seizures. Brain Res Bull 2004;63(5):407–13.
[12] Mazzetti M, Bellucci C, Mattarozzi K, Plazzi G, Tuozzi G, Cipolli C. REM-dreams recall in patients with narcolepsy-cataplexy. Brain Res Bull 2010;81(1):133–40.
[13] Zadra A, Robert G. Dream recall frequency: impact of prospective measures and motivational factors. Conscious Cognit 2012;21(4):1695–702.
[14] Sikka P, Valli K, Virta T, Revonsuo A. I know how you felt last night, or do I? Self- and external ratings of emotions in REM sleep dreams. Conscious Cognit 2014;25:51–66.
[15] Herlin B, Leu-Semenescu S, Chaumereuil C, Arnulf I. Evidence that non-dreamers do dream: a REM sleep behaviour disorder model. J Sleep Res 2015;24(6):602–9.
[16] Goodenough DR. Dream recall: history and current status of the field. In: Ellman SJ, Antrobus J, editors. The mind in sleep: psychology and psychophysiology. 2nd ed. New York: John Wiley; 1991. p. 143–71.
*[17] Cipolli C, Ferrara M, De Gennaro L, Plazzi G. Beyond the neuropsychology of dreaming: insights into the neural basis of dreaming with new techniques of sleep recording and analysis. Sleep Med Rev 2017;35:8–20.
[18] Cohen DB. Toward a theory of dream recall. Psychol Bull 1974;81(2):138–54.
*[19] Nir Y, Tononi G. Dreaming and the brain: from phenomenology to neurophysiology. Trends Cognit Sci 2010;14(2):88–100.
[20] Windt JM. Just in time—dreamless sleep experience as pure subjective temporality – a commentary on Evan Thompson. In: Metzinger T, Windt J, editors. Open MIND, vol. 37C. Frankfurt am Main: MIND Group; 2015.
[21] Windt JM, Nielsen T, Thompson E. Does consciousness disappear in dreamless sleep? Trends Cognit Sci 2016;20(12):871–82.
[22] Thompson E. Waking, dreaming, being: self and consciousness in neuroscience, meditation, and philosophy. New York: Columbia University Press; 2015.
[23] Thompson E. Dreamless sleep, the embodied mind, and consciousness. In: Metzinger T, Windt J, editors. Open MIND, philosophy and the mind sciences in the 21st century, vol. 2. New York: MIT Press; 2015. p. 1551–69.
[24] Siclari F, Tononi G. Sleep and dreaming. In: Laureys S, Gosseries O, Tononi G, editors. The neurology of consciousness. 2nd ed. San Diego: Academic Press; 2016. p. 107–28.
*[25] Siclari F, Tononi G. Local aspects of sleep and wakefulness. Curr Opin Neurobiol 2017;44:222–7.
[26] Boly M, Massimini M, Tsuchiya N, Postle B, Koch C, Tononi G. Are the neural correlates of consciousness in the front or in the back of the cerebral cortex? Clinical and neuroimaging evidence. J Neurosci 2017;37(40):9603–13.
[27] Masuda N, Doiron B. Gamma oscillations of spiking neural populations enhance signal discrimination. PLoS Comput Biol 2007;3(11):2348–55.
[28] Le Van Quyen M, Staba R, Bragin A, Dickson C, Valderrama M, Fried I, et al. Large-scale microelectrode recordings of high-frequency gamma oscillations in human cortex during sleep. J Neurosci 2010;30(23):7770.
[29] Panzeri S, Macke JH, Gross J, Kayser C. Neural population coding: combining insights from microscopic and mass signals. Trends Cognit Sci 2015;19(3):162–72.
[30] Farah MJ. Neuropsychological inference with an interactive brain: a critique of the "locality" assumption. Behav Brain Sci 1994;17(1):43–104.
[31] Cleeremans A. The radical plasticity thesis: how the brain learns to be conscious. Front Psychol 2011;2:1–12.
[32] Martinez-Trujillo JC, Treue S. Feature-based attention increases the selectivity of population responses in primate visual cortex. Curr Biol 2004;14(9):744–51.
[33] Maunsell JHR, Treue S. Feature-based attention in visual cortex. Trends Neurosci 2006;29(6):317–22.
[34] Carrasco M. Visual attention: the past 25 years. Vis Res 2011;51:1484–525.
[35] Carrasco M, Ling S, Read S. Attention alters appearance. Nat Neurosci 2004;7(3):308–13.
[36] Fuller S, Carrasco M. Exogenous attention and color perception: performance and appearance of saturation and hue. Vis Res 2006;46(23):4032–47.
[37] Fazekas P, Overgaard M. Multidimensional models of degrees and levels of consciousness. Trends Cognit Sci 2016;20(10):715–6.
[38] Fazekas P, Overgaard M. A multi-factor account of degrees of awareness. Cognit Sci 2018;42(6):1833–59.
[39] Lavie N. The role of perceptual load in visual awareness. Brain Res 2006;1080(1):91–100.

* The most important references are denoted by an asterisk.

[40] Overgaard M, Fehl K, Mouridsen K, Bergholt B, Cleeremans A. Seeing without seeing? Degraded conscious vision in a blindsight patient. PLoS One 2008;3(8):e3028.
[41] Windey B, Gevers W, Cleeremans A. Subjective visibility depends on level of processing. Cognition 2013;129(2):404–9.
[42] Asplund CL, Fougnie D, Zughni S, Martin JW, Marois R. The attentional blink reveals the probabilistic nature of discrete conscious perception. Psychol Sci 2014;25(3):824–31.
[43] Lavie N, Beck DM, Konstantinou N. Blinded by the load: attention, awareness and the role of perceptual load. Phil Trans Biol Sci 2014;369(1641), 20130205.
[44] Rechtschaffen A, Buchignani C. Visual dimensions and correlates of dream images. Sleep Res 1983;12:189.
[45] Antrobus J, Hartwig P, Rosa D, Reinsel R, Fein G. Brightness and clarity of REM and NREM imagery: photo response scale. Sleep Res 1987;16:240.
[46] Rechtschaffen A, Buchignani C. The visual appearance of dreams. In: Antrobus J, Bertini M, editors. The neuropsychology of sleep and dreaming. Hillside, NJ: Lawrence Erlbaum; 1992. p. 143–56.
[47] Kerr N. Mental imagery, dreams and perception. In: Cavallero C, Foulkes D, editors. Dreaming as cognition. Prentice-Hall; 1993. p. 18–37.
[48] Antrobus J, Kondo T, Reinsel R, Fein G. Dreaming in the late morning: summation of REM and diurnal cortical activation. Conscious Cognit 1995;4:275–99.
[49] Fosse R. REM mentation in narcoleptics and normals: an empirical test of two neurocognitive theories. Conscious Cognit 2000;9(4):488–509.
[50] Antrobus JS, Wamsley EJ. REM/NREM differences in dream content. In: Stickgold R, Walker MP, editors. The neuroscience of sleep. Academic Press; 2009. p. 310–5.
[51] Antrobus J. Dreaming: cognitive processes during cortical activation and high afferent thresholds. Psychol Rev 1991.
[52] Molinari S, Foulkes D. Tonic and phasic events during sleep: psychological correlates and implications. Percept Mot Skills 1969;29(2):343–68.
[53] Foulkes D, Pope R. Primary visual experience and secondary cognitive elaboration: a modest confirmation and an extension. Percept Mot Skills 1973;37:107–18.
[54] Pivik RT. Tonic states and phasic events in relation to sleep mentation. In: Ellman SJ, Antrobus J, editors. The mind in sleep: psychology and physiology. New York: Wiley; 1991. p. 214–47.
[55] Kahn D, Pace-Schott EF, Hobson A. Consciousness in waking and dreaming: the roles of neuronal oscillation and neuromodulation in determining similarities and differences. Neuroscience 1997;78(1):13–38.
[56] Nielsen T. Microdream neurophenomenology. Neurosci Conscious 2017;2017(1):nix001.
*[57] Dijkstra N, Bosch SE, van Gerven MAJ. Vividness of visual imagery depends on the neural overlap with perception in visual areas. J Neurosci 2017;37(5):1367–73.
*[58] Fulford J, Milton F, Salas D, Smith A, Simler A, Winlove C, et al. The neural correlates of visual imagery vividness – an fMRI study and literature review. Cortex 2017.
[59] Hobson A, Pace-Schott EF, Stickgold R. Dreaming and the brain: toward a cognitive neuroscience of conscious states. Behav Brain Sci 2000;23(6):793–842.
[60] Hobson JA, Pace-Schott EF. The cognitive neuroscience of sleep: neuronal systems, consciousness and learning. Nat Rev Neurosci 2002;3:679–93.
[61] Foulkes D, Domhoff GW. Bottom-up or top-down in dream neuroscience? A top-down critique of two bottom-up studies. Conscious Cognit 2014;27:168–71.
[62] Domhoff GW. The emergence of dreaming: mind-wandering, embodied simulation, and the default network. New York: Oxford University Press; 2018.
[63] Murri L, Massetani R, Siciliano G, Giovanditti L, Arena R. Dream recall after sleep interruption in brain-injured patients. Sleep 1985;8(4):356–62.
[64] Solms M. Dreaming and REM sleep are controlled by different brain mechanisms. Behav Brain Sci 2000;23(6):843–50.
[65] Kerr NH, Foulkes D. Right hemispheric mediation of dream visualization: a case study. Cortex 1981;17(4):603–9.
[66] Kosslyn S. Image and brain. Cambridge: MIT Press; 1994.
[67] Kosslyn SM, Ganis G, Thompson WL. Neural foundations of imagery. Nat Rev Neurosci 2001;2(9):635–42.
[68] Piaget J, Barbel I. Mental imagery in the child. Basic Books; 1966.
[69] Casey BJ, Tottenham N, Liston C, Durston S. Imaging the developing brain: what have we learned about cognitive development? Trends Cognit Sci 2005;9(3):104–10.
[70] Hiscock M, Cohen DB. Visual imagery and dream recall. J Res Pers 1973;7:179–88.
[71] Okada H, Matsuoka K, Hatakeyama T. Dream-recall frequency and waking imagery. Percept Mot Skills 2000;91(3):759–66.
[72] Watson D. To dream, perchance to remember: individual differences in dream recall. Pers Indiv Differ 2003;34(7):1271–86.
[73] Amedi A, Malach R, Pascual-Leone A. Negative BOLD differentiates visual imagery and perception. Neuron 2005;48(5):859–72.
[74] Cui X, Jeter CB, Yang D, Montague PR, Eagleman DM. Vividness of mental imagery: individual variability can be measured objectively. Vis Res 2007;47(4):474–8.
[75] Pearson J, Rademaker RL, Tong F. Evaluating the mind's eye: the metacognition of visual imagery. Psychol Sci 2011;22(12):1535–42.
[76] Rademaker R, Pearson J. Training visual imagery: improvements of metacognition, but not imagery strength. Front Psychol 2012;3(224).
[77] Bergmann J, Genç E, Kohler A, Singer W, Pearson J. Smaller primary visual cortex is associated with stronger, but less precise mental imagery. Cerebr Cortex 2016;26(9):3838–50.
[78] Wiggs CL, Martin A. Properties and mechanisms of perceptual priming. Curr Opin Neurobiol 1998;8(2):227–33.
[79] James TW, Humphrey GK, Gati JS, Menon RS, Goodale MA. The effects of visual object priming on brain activation before and after recognition. Curr Biol 2000;10(17):1017–24.
[80] Pearson J, Brascamp J. Sensory memory for ambiguous vision. Trends Cognit Sci 2008;12(9):334–41.
[81] Pearson J, Clifford CWG, Tong F. The functional impact of mental imagery on conscious perception. Curr Biol 2008;18(13):982–6.
[82] Overgaard M, Feldbæk Nielsen J, Fuglsang-Frederiksen A. A TMS study of the ventral projections from V1 with implications for the finding of neural correlates of consciousness. Brain Cognit 2004;54(1):58–64.
[83] Ramsøy T, Overgaard M. Introspection and subliminal perception. Phenomenol Cognitive Sci 2004;3(1):1–23.
*[84] Christensen MS, Ramsøy TZ, Lund TE, Madsen KH, Rowe JB. An fMRI study of the neural correlates of graded visual perception. NeuroImage 2006;31(4):1711–25.
[85] Overgaard M, Rote J, Mouridsen K, Ramsøy T. Is conscious perception gradual or dichotomous? A comparison of report methodologies during a visual task. Conscious Cognit 2006;15(4):700–8.
[86] Sandberg K, Timmermans B, Overgaard M, Cleeremans A. Measuring consciousness: is one measure better than the other? Conscious Cognit 2010;19(4):1069–78.
[87] Sandberg K, Bibby BM, Timmermans B, Cleeremans A, Overgaard M. Measuring consciousness: task accuracy and awareness as sigmoid functions of stimulus duration. Conscious Cognit 2011;20(4):1659–75.
[88] Sandberg K, Overgaard M. Using the perceptual awareness scale (PAS). In: Overgaard M, editor. Behavioural methods in consciousness research. Oxford: Oxford University Press; 2015. p. 181–96.
*[89] Andersen LM, Pedesen M, Sandberg K, Overgaard M. Occipital MEG activity in the early time range (<300 ms) predicts graded changes in perceptual consciousness. Cerebr Cortex 2016;26:2677–88.
*[90] King J-R, Pescetelli N, Dehaene S. Brain mechanisms underlying the brief maintenance of seen and unseen sensory information. Neuron 2016;92(5):1122–34.
[91] Tagliabue CF, Mazzi C, Bagattini C, Savazzi S. Early local activity in temporal areas reflects graded content of visual perception. Front Psychol 2016;7:572.
[92] Cohen DB. Sleep and dreaming: origins, nature and functions. Oxford: Pergamon Press; 1979.
[93] Cohen DB, MacNeilage PF. A test of the salience hypothesis of dream recall. J Consult Clin Psychol 1974;42:699–703.
[94] De Gennaro L, Ferrara M. Brain correlates of successful dream recall. In: Kryger MH, Roth T, Dement WC, editors. Principles and practices of sleep medicine. 6th ed. Philadelphia, PA: Elsevier; 2017. p. 523–8.
[95] D'Angiulli A, Runge M, Faulkner A, Zakizadeh J, Chan A, Morcos S. Vividness of visual imagery and incidental recall of verbal cues, when phenomenological availability reflects long-term memory accessibility. Front Psychol 2013;4(1):1–18.
[96] Nielsen TA. A review of mentation in REM and NREM sleep: “covert” REM sleep as a possible reconciliation of two opposing models. Behav Brain Sci 2000;23(6):851–66.
[97] Pigorini A, Sarasso S, Proserpio P, Szymanski C, Arnulfo G, Casarotto S, et al. Bistability breaks-off deterministic responses to intracortical stimulation during non-REM sleep. NeuroImage 2015;112:105–13.
[98] D'Andola M, Rebollo B, Casali AG, Weinert JF, Pigorini A, Villa R, et al. Bistability, causality, and complexity in cortical networks: an in vitro perturbational study. Cerebr Cortex 2017:1–10.
[99] Bernardi G, Siclari F, Yu X, Zennig C, Bellesi M, Ricciardi E, et al. Neural and behavioral correlates of extended training during sleep deprivation in humans: evidence for local, task-specific effects. J Neurosci 2015;35(11):4487–500.
[100] Funk Chadd M, Honjoh S, Rodriguez Alexander V, Cirelli C, Tononi G. Local slow waves in superficial layers of primary cortical areas during REM sleep. Curr Biol 2016;26(3):396–403.