Research Article

An Explanation for Dreaming Based on Neuronal Maintenance

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Nighttime dreams are an interesting phenomenon. Investigations have moved from attempts to interpret their content to seeking a biological function. In both cases, it has proven difficult to obtain convincing answers. I shall argue that dreams are the consequence of a requirement for sustained activity in nervous systems. That is, regular firing of signals is necessary for neuronal development and maintenance. Dreams result from this principle being applied to circuits involved in generating conscious experiences. The brain is prone to create a form of sense out of neurological activity; I hypothesize that this mechanism contributes to the story-like quality of dreams. The lack of cognitive (or top-down) control explains their bizarreness. The activity would be expected to be partly arbitrary and partly converge on prominent circuits such as those commonly or recently used. Circuits are strengthened by activation, dreams can therefore contribute to memory consolidation and learning.

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Introduction

Dreaming is a strange phenomenon that has eluded a natural account and has consequently led to a variety of proposals. Ancient attempts considered dreams to reflect contact with spiritual entities. Late in the 19th century, the focus shifted to regard dreams as a means to expose and manage the unconscious mind, exemplified by the psychoanalytical approach of Freud and Jung. Jung considered dreams to be fragments of involuntary psychic activity that are sufficiently conscious to be recalled in the waking state [1]. Most people still believe that dreams reveal meaningful, hidden truths [2]; however, as a guide to the unconscious, they are at best bewildering. In recent times, the focus has shifted toward biological function and neurological correlates.

Dreams can be described as a succession of spontaneously generated images, ideas, feelings, and sensations that occur during sleep. Each dream may last from a few seconds to several minutes; combined, they occupy a substantial fraction of the night [3]. Dreams are primarily associated with REM (rapid eye movement) sleep; the brain's activity during this stage is remarkably similar to that of the awake state. They also occur frequently in non-REM (NREM) sleep, but these dreams are less vivid and less storylike. Most dreams are probably not recognized by the dreamer [4]. It helps if the person is woken up at the right moment, but even then, the dream may not be recalled.

The scientific approach to understanding the function of dreams, oneirology, has suggested several explanations, but none of them are entirely convincing. For example, one suggestion is that dreams can boost creativity and help us solve problems [5]. The unconscious brain sometimes comes up with solutions where the conscious mind struggles; when awake, we call it intuition; at night, a similar process may lead to inspiring dreams. But dreams are evanescent [3]; thus, most of the energy used for dreaming would be wasted. Moreover, the awake form of intuition is likely more to the point. Others have suggested that dreams help with emotional regulation and mental housekeeping [6], but it is not apparent how that works.

The bizarre and hallucinatory quality of dreams does not align with any well-defined function. If they were to serve these purposes, at best, they would represent an awkward design.

One of the functions proposed stands out as more substantiated. Sleep is important for memory consolidation and learning [7][8]; dreams may serve the same purpose [9]. According to the hypothesis I present below, dreams did not evolve for a particular purpose but are primarily a byproduct of neuronal development and maintenance (the two are combined under the term *maintenance*). An effect on memory and learning would then be a secondary outcome.

A craving for explanations is part of human nature. The feature presumably evolved to enhance our understanding of the environment as that would improve the chances of survival. When there is no obvious explanation to be found, the urge may lead to myths, religious constructs, or pet ideas. The human tendency to desire and seek explanations provides a clue as to why REM dreams typically expand in the direction of stories.

The neuronal maintenance hypothesis is based on an evolutionary perspective. I will begin by providing some background on this approach. One should keep in mind that evolution does not produce optimally designed organisms; sometimes its products are strange and imperfect.

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The evolutionary perspective

Brain modules and brain exercise

The brain can be described as a set of functions, here referred to as *modules*, that were added and continuously adapted by evolution, starting with the early nervous system some 600 million years ago (Mya) [10]. Each module consists of neuronal circuits that may include millions or billions of neurons [11]. The concept of modules helps us understand the brain, even though they are not neatly organized, but rather a mesh of activity.

Consciousness is a feature, or module, of certain advanced nervous systems. It enables individuals to experience select aspects of life [10][12]. The nonconscious brain typically turns it on in the morning and off again at night, but it may also linger in an in-between state. Your experiences are based on a process referred to as broadcasting, which takes some 300 ms [13]. Several modules produce information to be included in each moment of experience (Figure 1). The broadcasting implies that the information fuses to form 'one frame in the film of life'.

The neurological signature of daytime experiences resembles the activity seen during REM sleep, which suggests that the relevant neurology can be activated in the absence of actually experiencing anything [14]. The observation that dreams sometimes reach your awareness implies that a form of broadcasting takes place while asleep, but that you may or may not be 'turned sufficiently on' to register the content. I consider REM sleep and the accompanying dreams to reflect a state different from consciousness. One key difference is that you are not in a position to impact dreams even if you become aware of them. Lucid dreaming is a state between dream sleep and regular consciousness [14].

The brain is programmed to develop by a combination of innate directives and environmental influences, the latter of which can be roughly equated with experience. Regular activation of a module tends to strengthen the responsible neuronal circuits, primarily by refining the synaptic wiring diagrams, while circuits that are not used tend to degenerate [15][16][17]. In extreme cases, as with people kept alive in a vegetative state, the whole brain can shrink to a fraction of its volume. I expect the 'exercise' effect obtained by activating circuits to occur whether the subject is awake or asleep.

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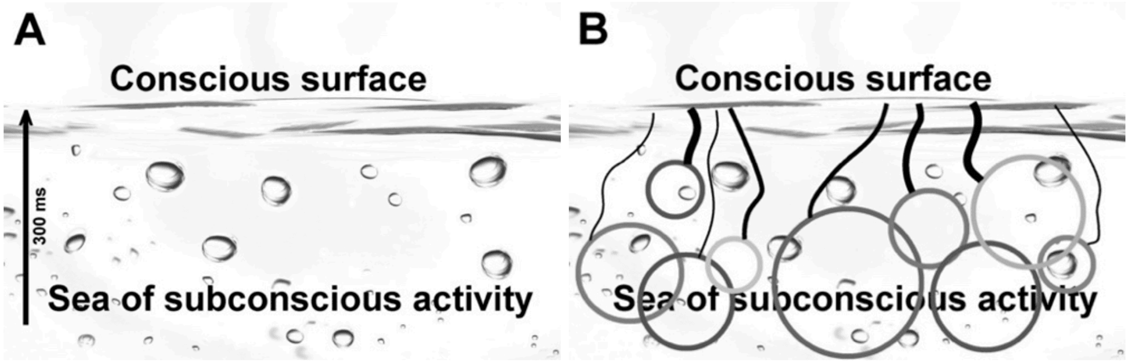

Figure 1. Modules and consciousness. Consciousness can be construed as the surface of the 'sea of brain activity' (A). Conscious content starts as neurological activity in the nonconscious or subconscious depths; the product of this activity is 'packed in bubbles'. It takes some 300 milliseconds for the bubbles to reach the surface, a process referred to as broadcasting. Some bubbles may disappear in transit, but those that go all the way fuse to form the surface layer, which is your moment of conscious experience. The various modules (circles in B) are responsible for creating the bubbles, but belong primarily to the nonconscious brain. The curvy lines indicate that there are 'paths' that lead from your conscious life to several of these modules; consequently, you can impact (more or less decisively) on the sort of experiences you have. Modules that are regularly engaged will expand and tend to produce more bubbles. (Adapted from [18])

Energetic considerations

The brain is an expensive organ to operate, requiring 20% of the energy while constituting only 2% of the body's mass. A substantial part of the energy is used by the ionic pumps that maintain the electrical potential across the (axonal and dendritic) membranes [19]. Each time a neuron fires, considerable activity is required in these pumps.

The brain needs an equal amount of energy when in REM sleep as when awake, while expenditure is reduced to 80% during NREM sleep. During anesthesia, consumption may be reduced to 60-70%, suggesting that even in NREM stages, the brain is more active than what is required to sustain life. Evolution is assumed to be prudent regarding the use of energy; thus, the high level of night-time activity is a surprising observation for which there ought to be a rational explanation.

One key difference between sleep and anesthesia is that sensory processing is shut down in the latter. You wake up if sensory input indicates danger while you are asleep, but not when you are anesthetized.

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Yet, the apparent activation of consciousness-like activity in REM sleep should not be required to maintain vigilance.

The sleep-wake cycle of mammals evolved from the inactive-active transition in nonconscious animals. It has been assumed that a key role of the inactive stage is to conserve energy [20]. In the case of mammals, there is a reduced use of muscles, resulting in some energy savings; however, the expenditure of the brain is noteworthy.

Neurology of dreams

According to Vitali et al. [21], periods associated with dreaming typically correlate with changes in the activity of the posterior regions of the cortex. Here, there is an increase in high-frequency (beta/gamma) activity, and a simultaneous decrease in slower (delta) activity. This is the case for both REM and NREM stages, but REM dreams also engage the occipital cortex. The authors suggest that the occipital activity explains the more perceptually complex and vivid dreams. They find a similar distinction in the frontal cortex; in NREM sleep, the activity decreases here, while particularly alpha-theta activity increases in REM sleep. The frontal cortex difference could be related to the addition of the emotional and story-like qualities of REM dreams.

The above observations align with current ideas regarding the brain correlates of consciousness; the frontal part is more engaged in cognitive and emotional functions, while the posterior part is more vital for the actual broadcasting. Other observations corroborate the idea that REM dreams utilize the same brain resources as awake experiences [14][22]; for example, half of the dreams include faces and consequently activate cortical areas associated with face recognition.

In NREM sleep, there are subtle differences in brain activity, as measured by EEG, between periods with dream content and those without [23], perhaps reflecting whether the dream touches the broadcasting circuitry. REM sleep appears more homogeneous in terms of EEG, which may indicate that dreams are the norm (in healthy adults), regardless of whether the person can recall them or not.

Neuronal maintenance hypothesis

Why REM sleep?

All active (non-dormant) cells require maintenance to remain healthy; that is, to preserve cellular integrity, repair damage, and sustain essential functions. Organic molecules are unstable in an oxygenrich environment, which means that damaged components need to be removed and replaced. This is particularly relevant for proteins and other macromolecules, as these are intended to function for an extended period. Autophagy is a key pathway for cellular maintenance [24]; if ablated in neurons, it leads to neurodegeneration [25].

It seems likely that cells need to engage in tasks for which they are designed to detect malfunctioning components. The primary function of neurons is to generate and transmit signals. To maintain performance, there should be regular firing. Moreover, these cells are meant to last a lifetime and may therefore require more maintenance compared to renewable cells [24].

At night, many circuits are free from other tasks, making it a suitable time for maintenance. The drainage of cerebrospinal fluid by the glymphatic and lymphatic systems is associated with waste clearance [26]; as expected, the flux is higher during the night [27]. The process of aging is considered to reflect a balance between allocating resources to either maintenance or reproduction [28]. In long-lived species such as mammals, more resources are earmarked for preservation. In short, the brain's consumption of energy at night is consistent with a requirement for extensive care.

The periodic alternation between REM and NREM sleep suggests that different parts of the brain take turns in being the focus of maintenance. NREM is 20% cheaper to operate; thus, there is also an economic incentive for not spending the entire night in REM. The REM periods presumably mean maintenance of circuits involved in conscious processing, and are therefore more likely to produce 'experiences', while the NREM periods target other circuits. If the purpose is maintenance, the 'experiences' do not need to be brought to awareness.

True dreams with story and vitality may not occur until age six or older [29], and even in adults, most dreams are not consciously recognized [4][14]. These observations imply that whatever function dreams have, it does not require awareness of content. The purpose seems to be the activation of circuits involved in consciousness rather than the generation of dreams. The point is corroborated by a study on focal lesions in the forebrain that incapacitate dreaming in adults (at least the ability to recall content) even though REM sleep is retained, and the individuals do not seem to otherwise suffer from the lesions [30].

Neuronal activity is expected to be required not only for maintenance but also for development. Sleep, and particularly the REM stage, serves a crucial role in brain maturation [21], which explains why the fetus has the highest level and children have more REM sleep than adults. Presumably, they need to

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develop the neuronal machinery for consciousness. The notion is supported by the observation that the trajectory of REM activity reflects critical periods of brain maturation [31].

Development and maintenance are related processes. The brain needs to adapt constantly, so maintenance does not simply imply retaining the status quo. The focus likely shifts from development to maintenance as we grow up, but the need for nighttime activity remains. The shift is accompanied by a decrease in the time spent sleeping.

A steady level of activity appears to be the norm for the brain. Whereas muscles can be left inactive for relatively long periods without harm, it seems that nervous systems cannot. The general principle that organs strengthen upon use and degenerate in its absence applies to both, but the brain is likely more vulnerable to periods of inactivity. It is well known that prolonged general anesthesia can have adverse effects, particularly in the young and the elderly. These effects are typically ascribed to factors such as hypoxia, inflammation, and toxicity, but they could also reflect the suppression of activity.

Other observations are compatible with the idea that neurons need to fire regularly. Even in a resting, awake brain, neurons exhibit spontaneous activity in the form of globally coordinated firing [32]. Consciousness is associated with an additional, less synchronized, and higher frequency firing. Meditators attempt to restrict the generation of conscious content to enter a more relaxed state; however, achieving this 'minimal' consciousness is challenging. The brain is prone to generate conscious content in the form of insignificant thoughts or percepts that distract the meditator. In other words, what appears to be superfluous commotions take place both day and night. This is expected if maintenance cannot be limited to specific periods. The brain pushes all sorts of 'unrequested' thoughts during the daytime, but these are partly under conscious control and therefore less bizarre. Nighttime maintenance is not necessarily more important than what goes on during the day; it suffices to postulate that daytime maintenance is insufficient.

Why dreams?

Even if nighttime brain activity reflects maintenance, it is not obvious why it should result in dreams. The expected outcome from targeting circuits involved in broadcasting would be random percepts. NREM dreams are more like that, but REM dreams typically include stories that last several minutes.

One explanation could be that maintenance requires the generation of stories; there needs to be a consecutive activation of related circuits, as this is typical for how the neuronal circuits function. A perhaps more plausible explanation rests on the human propensity to find explanations, as mentioned in

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the Introduction. There appears to be a mechanism associated with broadcasting that tries to generate sense out of sparse and incoherent information. The same feature may be at work when dreaming; the brain spins a story based on the signaling taking place. In short, an 'internal interpreter' forms dreams because it tries to find meaning in the commotion of signals. One scene may give rise to the next because the interpreter sets up expectations for what is to come. The lack of vivid dreams in children may be because their internal interpreter is still developing.

The brain's interpreter is not just about explanations; when awake, it deciphers sensory information to form a coherent picture of the world. Part of the job is pattern recognition, how objects are understood based on limited input; for example, a circle with two dots is enough to 'see' a face. The interpreter is part of the nonconscious brain and should operate while asleep for vigilance; that is, sensory information is constantly processed and evaluated for potential danger.

The mesh of connectivity in the brain suggests that activity in one part can lead to neuronal firing in other parts, including the extensive circuits of the forebrain engaged in consciousness. In NREM sleep, the circuitry involved in broadcasting may be activated to a lesser extent and the interpreter not engaged.

Dreams use the same circuitry as when awake [14], which helps explain why they can be experienced and recalled upon waking up as long as the sleep is sufficiently 'shallow'. Recall is more likely if the dreams are salient, as when they involve strong feelings [33]. The capacity to recall could depend on how 'shallow' the sleep is, on the capacity for short-term memory, or on the ability to direct attention to something that has already occurred (this ability is discussed in [34]).

Dream content

If the starting point for dreams is random activity in consciousness-generating circuits, one would expect the content to be arbitrary. This is not entirely the case; dreams are biased in three ways [4][14][21]: They tend to reflect, for one, daytime activity; two, critical circuitry; and three, sensory input while dreaming. For example, sex is highly important for genes and a common topic of dreams [35]. The three biases could signify circuits that are more easily activated, but there could also be a priority in the direction of maintaining salient circuits. Beyond these biases, there does not seem to be a plan behind a dream. The point is substantiated by the observation that, rather than acting out a dream, sleepwalkers appear to adapt to sensory input as the dream unfolds [29].

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Response to external stimuli during sleep may be expected as the brain is processing (and potentially responding to) information – particularly sounds, touch, and smell – regardless of sleep state. For example, touching the leg can induce a dream about running [36]. Visual content tends to dominate in dreams (except for people with congenital blindness) due to the importance of vision [37], but perhaps also because the circuits involved in visual processing are otherwise idle as a consequence of closed eyes. Maintenance does not interrupt anything of importance when focusing on circuitry in the visual cortex.

Dreams reflect what is referred to as primary consciousness; they are about perceptions and feelings, while they have limited access to secondary consciousness, which includes self-awareness and metacognition [14]. This is to be expected as they are initiated and driven by the nonconscious. It seems likely that secondary functions require 'real' consciousness, while primary functions can be engaged without. Even when awake, the response to sensory input and feelings does not require awareness (see [10] for a discussion). If the higher cognitive functions were deemed necessary by the nonconscious during sleep, you would presumably wake up.

Both recent notable events and long-standing mental issues can influence dream content. We live in a world with a high level of anxiety, as witnessed by the prevalence of anxiety disorders [38]; unsurprisingly, anxiety seems to be the most common feeling experienced in dreams [39]. Fear in dreams activates the same brain resources as when awake [40]. If hyperactivated at night, they result in nightmares, which are common for people with posttraumatic stress disorder or other forms of stress and anxiety [4][21].

Dreams as memory consolidation and learning

As pointed out above, activity in a circuit tends to strengthen that circuit, which means it is possible to 'exercise' circuits by activating them regularly. Evolution has installed features that urge the individual to do so for the sake of learning. Play behavior is one example; another is the 'learning window' for language acquisition. Dreams could fit a similar purpose.

There are several indications suggesting that sleep helps with memory and learning (or that lack of sleep is bad for these functions) [7][8]. The exercise effect is expected to take place regardless of whether one is conscious or not – a night with a high level of activity should leave an impact. For example, hippocampal sharp-wave ripples during deep (NREM) sleep in rats most likely imply a 'replay' for the purpose of memory consolidation [41][42]. In this case, the activated circuits are related to spatial memory, which

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means the replay helps the animals find their way. This form of memory is probably nonconscious, which fits with the idea that deep sleep is used for exercising nonconscious circuits.

The observation that dreams are influenced by activity before falling asleep and sensory input during sleep means it is possible to sway the content in a desired direction [4][36]. For example, a pleasant odor causes people to report happier dreams, and recurring nightmares can be alleviated by repeatedly thinking through alternative endings before going to bed.

It has been suggested that the activation of fear in dreams (and the resulting nightmares) serves to simulate threats [43]. The idea is that in a safe environment, the simulation could help the person prepare for real-life dangers. Based on the maintenance model of dreaming, this seems unlikely. The activation of fear is expected to strengthen the responsible circuits, thus the result should be more anxiety problems rather than improved coping [44]. If so, nightmares are not biologically adaptive but a consequence of a less-than-ideal evolutionary design combined with the present prevalence of anxiety.

Although dreams may have a positive impact on the mind, it does not mean that this is their primary function. The bizarre and unpredictable nature of dreams does not quite fit that notion. The limited positive effect and the indications that the effect may be harmful, as in the case of nightmares, further contradict the idea that dreams evolved to serve memory and learning. It seems more likely that the initial rationale was maintenance, but that the activity either simply happened to help in certain ways or evolved in a direction that enhanced positive outcomes. If so, a positive effect on memory and learning can be described as an exaptation [45].

Comparison with other species

I have previously argued that some form of consciousness is present in amniotes (reptiles, birds, and mammals), but not in other animals [10][12]. I expect dreams to be restricted to conscious animals. REM-type activity is evident in mammals and birds [46], and there are signs of similar EEG patterns in reptiles [47]. The point that REM activity often employs salient circuits is observed in both mammals and birds; for example, pigeons activate neurology associated with the control of flying [46].

The activation of circuits associated with daytime pursuits does not necessarily imply experiencing – or mentating in any other form – the activity. As pointed out above, fetuses and infants exhibit REM sleep, but at least fetuses may not have true dreams or experiences. Yet, it seems likely that most adult mammals have some form of dreams [48]. Aquatic species such as cetaceans could be an exception. They

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typically sleep with one half of the brain at a time, and it seems difficult to imagine how they can have an awake experience based on the active half and a simultaneous dream experience based on the other. That is to say, it seems unlikely that REM activity leads to mentation.

As expected, neuronal activity is present in invertebrates when dormant, and has, in some cases, been considered a sign of consciousness. For example, octopuses have 'active' and less active stages of sleep, somewhat similar to REM and NREM [49][50]. In the active stage, they sometimes appear to act out a dream, displaying behavior such as changes in skin patterning and defense reactions reminiscent of sleepwalking in humans. The behavior is based on the activation of neuronal circuits used for similar daytime pursuits.

Octopuses split with mammals while nervous systems were still rudimentary [51]. The resemblance of advanced functions in these two lineages should therefore be based on convergent evolution. Convergent evolution of consciousness and dreams seems unlikely [10][12], but the shared characteristics of neurons [51][52] suggest that all animals require related activity for development and maintenance. In the more advanced nervous systems, such as those of octopuses and mammals, nighttime maintenance could have converged on engaging alternating parts of the brain. In both cases, one would expect the maintenance to focus on critical neuronal circuits; in the case of the octopus, this would include skin patterning and defense reactions. The observed behavior does not require any form of mentation.

Conclusions

It has proven difficult to find a reasonable function for dreams. One problem is that their bizarre and haphazard nature does not fit – if they evolved for a particular purpose, one would expect a better design. The idea that they are accidental byproducts of neuronal maintenance seems to harmonize with the available data. The extent to which an activity is mentated in the form of dreaming may differ between species. One might expect that at least other mammals can experience dreams, but perhaps less vivid and narrative. Storylike dreams presumably require a sophisticated 'internal interpreter'.

NREM dreaming can be explained by postulating that brain activity tends to 'leak' in the direction of circuits involved in broadcasting. The observation that these dreams are less elaborate could reflect that the broadcasting circuits are only activated indirectly and thus do not engage the interpreter.

It would be expected that the maintenance, and consequently the dreams formed, focus on salient circuits. Dreams may therefore both improve memory and reflect personality. Thus, even if these are not their primary functions, they can be used for learning and (to a limited extent) probing the subconscious mind. As to the latter, frequent nightmares, for example, suggest an anxiety-prone personality.

To maintain a functional brain, neurological circuits must adapt, develop, and sustain structural and functional health. These processes presumably require neuronal firing and include the formation and pruning of neuronal connections [11]. Although the processes are active during the day, they also need nighttime commitment. The nightly activity can lead to dreams when circuits involved in consciousness are engaged. The dream percepts form stories because an 'internal interpreter' seizes the ongoing action and directs it toward something 'sensible'.

Even in the healthy brain of an adult, there is likely a significant amount of redundant firing both during the day and at night; however, the brain still serves enough functional activity to keep the individual alive. Sometimes, the more chaotic form of commotion may start to dominate – a situation that might help explain conditions such as psychosis. As pointed out by Limosani et al. [53], dreams resemble psychosis in that both are driven by haphazard firing. The bizarreness in both cases may be due to deregulation or skewing of the process responsible for generating (broadcasting) conscious experiences. In dreaming, the process is *not* meant to be 'on track'; while in psychosis, something, perhaps the top-down cognitive control, is flawed.

More information is needed to test if the present hypothesis is correct. Further research on neuronal maintenance might be helpful. It should also be possible to block nighttime activity by various anesthetic agents in mammalian model animals and determine the effect on neuronal health.

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