Do all animals sleep?

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Some animals never exhibit a state that meets the behavioral definition of sleep. Others suspend or greatly reduce 'sleep' behavior for many weeks during the postpartum period or during seasonal migrations without any consequent 'sleep debt.' Rats die from one form of sleep deprivation, but sleep loss has not been shown to cause death in well-controlled studies in other vertebrate species. Some marine mammal species do not show evidence for REM sleep, and convincing evidence for this state in reptiles, fish and insects is lacking. The enormous variation in the nature of rest and sleep states across the animal kingdom and within the mammalian class has important implications for understanding the evolution and functions of sleep.

Introduction

An assumption made by many is that all animals sleep or that all animals with nervous systems sleep. A Google search for the phrase 'all animals sleep' brings up 3090 hits. A Google search for the phrase 'do all animals sleep' brings up only 327 hits, and many of these answer the question in the affirmative. Many neuroscientists and sleep researchers [1] have assumed (without, I would contend, good evidence) that all animals sleep. A further assumption is that sleep deprivation is lethal. Together, these two assumptions suggest that a universal, vital function is accomplished in sleep.

Defining sleep

We all understand what it means to be asleep, but it is not always obvious whether observed animals are experiencing the same state. Sleep must be distinguished from circadian changes in alertness controlled by the suprachiasmatic nucleus and other body clocks. Most animals need to adjust their activity to optimal conditions of prey availability, predator threat, sexual opportunities, temperature and other variables affecting survival that vary with time of day. Hence, even when completely sleep deprived, most animals exhibit a marked circadian rhythm of alertness and activity, and reduced responsiveness and inactivity. The presence of such periods of reduced activity and alertness cannot be assumed to be sleep. Sleep persists in animals in which circadian rhythms have been eliminated [2]. It is the summation of the circadian and homeostatically regulated sleep processes that determines our alertness [3]. Sleep must be distinguished from hibernation and torpor, states that have distinct physiological correlates. It is also very important to distinguish sleep from rest, a state of reduced activity without loss of consciousness or greatly reduced responsiveness.

Sleep is generally defined as a rapidly reversible state of immobility and greatly reduced sensory responsiveness. An important further criterion is that sleep is homeostatically regulated, namely that lost sleep is made up with an increased drive for sleep and a consequent 'sleep rebound.'

It would appear to be highly maladaptive for animals to be driven to make up for lost sleep at a time of danger and stress unless some vital function was being subserved. Indeed, it has often been asked why some animals have not evolved a quiet waking state as a substitute for sleep. Surely it would be more adaptive to reduce activity and maintain vigilance. As we shall see, a survey of the literature reveals that evolution might well have produced species that have states that can be better described as quiet waking than as sleep.

Two types of sleep have been identified in mammals, non-REM sleep (slow-wave sleep) and REM sleep. At the neuronal level, non-REM sleep is characterized by greatly reduced activity in brainstem systems [4,5]. Forebrain neuronal activity rates are reduced below those of quiet waking, although the predominant change is from irregular discharge patterns to a rhythmic pattern of discharge. Reflecting this, high-voltage slow waves and spindles are present in the neocortex [6]. Cortical release of acetylcholine is minimal during non-REM sleep [7].

The human brain consumes more than 20% of the body's energy usage in quiet waking, ten times the amount that would be predicted by its relative weight and not substantially less than it consumes while engaged in difficult cognitive tasks [8]. During non-REM sleep, forebrain metabolic activity is reduced far below the level in quiet waking [9]. This reduction in brain metabolic rate can make a significant contribution to reduction in the body's overall energy consumption.

In contrast to non-REM sleep, REM sleep is characterized by a pattern of discharge that closely resembles that of waking in most brain regions. Brainstem neurons are highly active at rates often equal to or exceeding rates in active waking [5]. Cortical neurons also show a waking pattern of activity, with the electroencephalogram (EEG) in many species being indistinguishable from that of waking [4].

Therefore, mammalian sleep can be accompanied by either high- or low-voltage cortical activity. Conversely, although waking is usually characterized by low-voltage cortical activity, it can be accompanied by a high-voltage EEG similar to that seen in non-REM sleep [10]. Despite the similarity of REM sleep brain activity to the waking pattern, the loss of environmental awareness that characterizes

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non-REM sleep is also present in REM sleep. Although most neurons behave similarly in REM sleep and waking, noradrenergic, serotonergic and histaminergic neurons, which are tonically active throughout waking states, are silent in REM sleep. These cell groups also greatly reduce activity in non-REM sleep. The reduction in activity of the noradrenergic neurons has been linked to the reduction in muscle tone that occurs in REM sleep, whereas the reduction in activity of the histaminergic neurons has been related to the loss of consciousness occurring in sleep [11].

Sleepwalking and related pathological 'dissociated states' seen in humans are neither normal sleep nor normal waking [12]. They regularly lead to severe injuries if there is no intervention and would exert a substantial negative selection pressure in the wild.

The elevation of sensory thresholds that we use to define our sleep is not absolute. When we sleep, we are not aroused by household noises, tactile stimulation and smells that we would attend to during the day. However, we can often hear our baby cry, the opening of the front door and other significant sensory stimuli. Sensory response thresholds also vary within waking. We can be inattentive or immobile for long periods without being asleep. Vigorous exercise will tend to produce a 'rebound' of inactivity without being perceived by the subject or observers as sleep. Although eye closure is correlated with sleep, individuals can close their eyes for long periods of time with completely unimpaired consciousness. These phenomena must be kept in mind in evaluating evidence for sleep in animals.

Sleep deprivation

In a classic series of studies, Rechtschaffen and colleagues demonstrated that sleep deprivation in rats produces a consistent behavioral and physiological syndrome leading to death within 2–3 weeks [13]. The deprivation procedure did not completely eliminate sleep, but rather interrupted and reduced it by 70%–90% compared to controls who lost 30%–40% of their baseline sleep [14,15]. Deprivation greatly increased body temperature and food intake, but weight fell rapidly. A stereotyped pattern of fur discoloration and skin lesions occurred. Finally, body temperature fell and death followed. No similar syndrome has been described in mice or other mammals commonly observed in laboratories, or in rats' sleep deprived by other means. Sleep deprivation in pigeons by the same technique used in rats is not lethal and produces none of the metabolic and thermoregulatory changes observed in rats [16]. Human sleep deprivation for as long as 11 days and chronic sleep restriction does not produce even the earliest signs of the autonomic changes seen in rats undergoing sleep deprivation by the 'disk-over-water' technique. Body temperature tends to fall in sleepy humans, rather than rising as it does in the initial stages of sleep deprivation in rats [17,18]. Humans whose sleep is reduced for long time periods tend to gain weight, rather than lose weight as rats do under 70%–90% sleep deprivation conditions [19]. Fatal familial insomnia, a rare genetic condition reported in humans, is not analogous to the disk-over-water method of sleep deprivation [13] because it is characterized by massive brain degeneration and autonomic dysregulation [20].

Sleep rebound

If we reduce our sleep for 1 or 2 h, we will be sleepy the next day and when allowed to sleep will repay this 'sleep debt' by significantly increasing sleep time. Most studies of human sleep deprivation have reported that this 'rebound' sleep is disproportionately made up by increased amounts of slow waves during sleep [21]. However, in rats and pigeons, the effects of long-term sleep deprivation can be completely reversed by a rebound made up almost entirely of REM sleep [13,16]. There appears to be some common function served by these two very different patterns of brain activity.

Sleep in simple organisms

To my knowledge, there has been no claim of sleep occurrence in unicellular organisms. However, there is ample evidence that some cyanobacteria, protists, euglenozoa and dinoflagellates show circadian rhythms of activity [22]. There are more than 400 000 unicellular species [23].

Sleep in insects

It has been shown that cockroaches, bees and scorpions have quiescent behaviors with elevated arousal thresholds (reviewed in Refs. [24,25]). Rest deprivation, studied in cockroaches, did not produce a significant or consistent increase in rest time during the recovery period [25], although it did produce increases in metabolic rate, with all effects being critically dependent on the exact parameters of the stimulation used to arouse them [26]. Circadian changes in sensory response thresholds have been documented in bees [27,28]. Changes in certain movement parameters were reported after disturbance of the quiescent state in bees, although no increase in rest duration was noted [28]. *Drosophila* appear to show a behavioral state which satisfies all the behavioral criteria of sleep [29,30]. In this case, as in the other non-mammalian species, it is unclear whether the *Drosophila* state that meets criteria for sleep is homologous or analogous to the sleep state experienced by humans. Clearly the anatomical and some of the neurochemical properties of sleep cannot exist in insects, because of the differences in the structure of their nervous systems. No claims of insect REM sleep have been made. There are more than 700 000 insect species [23].

Sleep in fish

There are more than 30 000 species of fish [23]. They vary in size, diet and ecological specialization. Fewer than 10 fish species have been examined for rest or sleep behavior in laboratory studies.

In studies of rest/sleep-like activity of the zebrafish (*Danio rerio*), circadian variations in responsiveness and activity and decreased response to stimuli were seen after rest deprivation, leading the authors to conclude it was a 'sleep-like' state [31,32]. The state characterized as 'sleep' could be completely blocked for long periods by light, with no evidence of subsequent rebound [31]. Zebrafish with a null mutation of the receptor for the peptide hypocretin