Title: HOW THE MAMMALIAN SLEEP WAS BORN

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SHORT SUMMARY

Around early Jurassic some small-sized diurnal reptiles increased the endothermic metabolism and extended their activity to dark time, to fill the void nocturnal niche. Their excellent visual capabilities, acuity, spatial resolution and chromatic discrimination were traded-off for increased sensitivity, useful for the nocturnal dim lit, but they turned defenseless against the dangerous daylight. To avoid blindness -and extinction- they rested in lightproof burrows with closed eyes during daytime. For further security, they developed a bi-stable switch separating nocturnal activity and diurnal rest. This was how the mammalian sleep was born. The development of the cortex, with improved audition and olfaction, compensated the visual impairments.

The K-Pg event extinguished the dinosaurs softening the evolutionary pressure for maintaining nocturnal life. The variability in mammalian chronotypes and sleeping patterns increased greatly, but most of the newly developed variations lacked adaptive significance and only quiescence remained invariable. Therefore, quiescence must be the single vital trait of sleep.

The Wilson's Principle of Stringency: "Time-energy budgets evolve to fit to the times of greatest stringency", explains why wildly gluttonous foraging and ceaseless reproductive activity is non-adaptive. Furtherly, the victims of predation aren't the sleeping animals, but the immature, sick and senescent ones. Therefore, contrary to current opinion, excessive foraging and reproductive activity is non-adaptive and the claimed disadvantages of sleep are uncertain. Oppositely, quiescence, either resulting from sleep or laziness, is adaptive. We conclude that the vital function of sleep consists in enforcing quiescence in both nocturnal and diurnal mammals.

244 words

Keywords: Evolutionary bottleneck, Evolution of sleep, Sleep variability, Function of sleep, Principle of Stringency, Laziness.

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1. Introduction

The mysterious nature of sleep has been repeatedly affirmed. Indeed, we ignore the answer to many important sleep-related questions. Among others, why we sleep, why sleep is an active process, why two sleep phases exist and why wake-sleep transitions are discontinuous.

It is generally recognized, however, that the answer to these questions would be immediately understood if we would know, with precise details, how sleep evolved. Many reports attempted disclosing the evolution of sleep but, for the time being, all were incomplete and leaved many important facts unexplained.

We present solid evidence showing that the mammalian sleep appeared because of an evolutionary bottleneck that forced, in the reptilian ancestors of mammals, a change in the chronotype, from diurnal, to nocturnal. This change facilitated the loss of the mechanisms protecting the eye against the dangers of diurnal bright light. This, in turn, provoked, the apparition of active sleep during light time.

2. Phylogeny of mammals

Mammals, comprising Prototheria (monotremes) Metatheria (marsupials) and Eutheria (placental), constitute a monophyletic group that arose in or before the Early Jurassic, about ~200 Million Years Ago (Ma) (1). Mammals evolved from small sized reptiles that were strictly dependent on solar heat to warm their body. However, some descendants of the primitive reptilian stock began developing endothermic metabolism to extend their activity, first to crepuscular hours and then to the entire night. Simultaneously, their sensory equipment, their behavior and the corresponding neural controlling networks were adapted to nocturnal life.

These changes are currently attributed to “The Nocturnal Evolutionary Bottleneck” (NEB), that was first proposed by Walls in 1942 (2). This author observed numerous adaptations to nocturnal vision in the eyes of modern mammals, irrespective of their current chronotype. He concluded that mammals evolved from reptiles as the result of a prolonged nocturnal phase (over 100 million years) that was facilitated by the absence of small sized competitors during night time and was forced by the competition with the big sized ectothermic dinosaurs that occupied the diurnal niche. After Walls, many authors provided confirmatory evidence for the NEB hypothesis (3-6) and, to our knowledge, it remains undisputed. Furtherly, it is believed that only after the Cretaceous–Palaeogene (K–Pg) mass extinction event (about 66 Ma), the mammalian radiation was possible (7-9) and some mammalian orders (e.g., primates) began the quest for diurnal lifestyle.

3. How reptiles developed endothermic metabolism

It is believed that basal reptiles possess the basic cardiovascular and metabolic mechanisms for endothermic generation of heat (10). They possess subcutaneous lipid layers providing thermal isolation (11, 12) that was furtherly improved after developing the hairy epithelial tegument (13) concomitantly with sweating and milk secreting glands (14). Reptiles also possess heat saving countercurrent vasculature in the limbs (15) and may use the muscular activity to increase the production of endogenous heat (16, 17). It has been thus affirmed that the thermoregulatory difference between reptiles and mammals is only quantitative and not qualitative (18). In fact, some extant turtles maintain a high Body Temperature (BT) while submerged in cool water (11, 12) and tegu lizards may increase their BT during the reproductive season to extend the activity to crepuscular and dark time (10). Most likely, these animals use the same physiological adaptations that allowed early mammals to substitute the original diurnal chronotype for nocturnal life.

4. Adapting the sensory systems to nigh time

The mammalian ancestors were sight-oriented reptiles, with well-developed eyes, sophisticated tetrachromatic color vision and capacity for fine visual analysis (19, 20). However, the light of high intensity is harmful, even in the wavelengths of maximal absorption of the retinal pigments (21-24). For instance, despite being well protected against high light intensities, actinic keratosis, cataracts and retinal degenerations are common conditions in humans (25, 27). So, pursuing the highest visual sensitivity, early mammals abandoned the mechanisms that protected, from photo oxidation, their eyes and retina (28-30). As the chromatic discrimination is unnecessary in dark environments, it was also abandoned. In consequence, most extant mammals were and still are nocturnal, dichromatic (27) and even monochromatic (31). Summarizing, the full set of protective mechanisms present in the eyes of diurnal reptiles, as well as their high visual acuity, spatial resolution and chromatic capabilities, were traded-off by increased sensitivity. They incurred, however, in high susceptibility to the dangerous diurnal light (3, 4).

The reductions in visual performance were compensated by developing alternatives for orientation in the dark. The auditory sensitivity was greatly increased after modifying the reptilian articulation of the jaw, relocating the residual bones, malleus, incus and staples, in the middle ear. This also extended the audition to high frequency ranges (32, 33). The development of the ear pinnae, with its motor control, allowed locating the precise origin of sounds and the capacity to follow the movement of the sound sources (34, 35). Furtherly, the development of the mystacial vibrissae allowed the “face touch”, enhancing the exploration in the dark (36).

The skull endocasts of successive pre-mammals show continuous size increase in olfactory bulbs (37), which was correlated with increased telencephalic and cerebellar size (38, 39). The improvement of olfaction, needed for orientation in the dark, imposed high demands in computational power for creating and memorizing precise navigational maps to find foods, recognizing dangers, friends and relatives and is currently considered capital for the development of the distinctive mammalian isocortex (40, 41).

5. How the mammalian sleep was born

As a result of the changes in the visual system, and to avoid blindness, early mammals were highly pressed to remain immobile with closed eyes in light-proof burrows during the entire illuminated period (~12 h daily). An on-off switch exists in the reptilian hypothalamus, with warm- and cool-sensitive neurons forcing the immobility before the advent of the first lights of dawn, (42-45). The quiescence was furtherly facilitated after developing a bi-stable switch marking a discontinuity between nocturnal activity and diurnal rest, so avoiding an environment full of powerful competitors and illuminated by dangerous bright light. A Flip-Flop switch served as fail-safe guarantying the impossibility of coming out of the burrow with the risk of accidental exposure to diurnal light.

This was how the mammalian sleep was born, as an active state, dependent on the presence of a flip-flop (46) with two neuronal networks: a set of sleep motor neurons and another set of wakefulness promoting neurons, interconnected through mutually inhibitory fibers (47).

6. The variability in sleep signs as indicative of low adaptive value

After the K-Pg extinction event, the environmental pressure to sleep during light time was softened and the current variety of mammalian chronotypes was possible, with the current inter- and intra-specific variation of sleep in duration, timing, deepness, architecture, etc. (48-54). Sleep was certainly vital for the first mammals during millions of years but, despite the huge variety of sleep patterns appearing after the K-Pc extinction, mammals were still able to survive. In other words, the importance of those highly variable traits was low. Indeed, sleep may be a paradigmatic example of an old, well-known principle of evolutionary biology: the genetic and phenotypic variability is inversely related to the intensity of stabilizing selection (55). As an easy example, the color variability of modern cars is infinite, but no car exists without wheels. No one could thus discuss the importance of wheels vs color. Thus, to apply this principle to sleep, we should search, among the phenotypic traits of sleep, those that, without exception, can be always observed in sleeping animals. Only after finding such trait(s) the evidence for its/their vital function would be convincing.

Of course, the benefits of this eventual, but universal trait, must be higher than the costs. It is currently affirmed, for instance, that sleep detracts time from feeding and reproduction and that sleeping animals are exposed to higher predatory risks. Therefore, although the balance was highly positive for early nocturnal mammals -avoiding blindness- the costs seemed too high for modern diurnal mammals that support high light levels without harm. Thus, sleep should have been disposed by natural selection. The immediate answer to this question consists in observing that animals always reduce the costs of sleep by minimizing the traits that, according to their ecological niche, were less needed for survival. For instance, altricial and prey animals reduce the daily quota of sleep, contrasting with predators that show almost unlimited amounts of sleeping time. Therefore, the importance of predation largely surpasses that of sleep and the same can be said for every trait showing high variability. This answer is, however, insufficient. Despite predation, lambs still dare to sleep.

7. Why diurnal and prey animals do sleep?

To explain why sleep so obstinately persists in preys and in diurnal mammals, we will begin looking at the definition of sleep. Then, we will continue analyzing the most conspicuous trait of sleep: the motor rest.

7.1. Sleep is a state showing circadian control, motor quiescence, raised sensory thresholds and homeostatic regulation, the last one being responsible of the rebounds observed after deprivation. Regarding to the circadian regulation and the reduced sensory acuity, both appear not only during sleep, but also in wakeful animals. Indeed, waking animals show circadian oscillations in rest-activity and in arousal, with concomitant changes in sensory thresholds (47). Given the low specificity of these two traits we will leave them out of our analysis. Contrasting, the total sleeping time and the sleep rebounds are exclusive and unequivocal signs of sleep and, in fact, are two faces of the same coin: the sleep propensity. We know that, to avoid blindness, nocturnal animals showed, and still show, an unstoppable propensity to sleep on approaching light time. But what about the sleep propensity in diurnal mammals? As we proposed in the previous paragraph, we will approach this question by studying the properties of another trait that never fails to be found in sleeping animals: the motor quiescence.

7.1. Behavioral quiescence

Motor rest may appear as passive adaptations to environmental factors. The cool-related inactivity of poikilothermic animals or the rest observed in hibernating animals are good examples of what we will call “functional rest”. Animals also rest to recover from fatigue or after a heavy meal. We may call “restorative” such rest. Also, animals may rest immobile stalking the next meal or may freeze after sighting a predator. We will call “strategic” these types of rest.

Nevertheless, functional, restorative and strategic considerations don’t explain all cases of inactivity. Indeed, zoologists are often puzzled after finding that feeding and defensive activities rarely take more than half of the day, even for species with high energetic demands, like shrews (56, 57) and hummingbirds (58, 59). Indeed, the animals’ most commonly recorded behavioral category is rest and, as it seems to be devoid of recognizable utility, it has been dubbed as “lazy” (60). Interestingly, lazily resting animals may neglect food intake, procreation, and may even neglect predation. Therefore, it seems that lazy rest is non-adaptive and should have been disposed by natural selection. However, the abundance of laziness is so puzzling that the mystery of why all animals do lazy rest parallels the mystery of why all animals do sleep.

7.2. Laziness is adaptive.

The adaptive value of laziness and the answer to the paradoxical “why we rest” question was satisfactorily explained after the “Principle of Stringency” (PS): “*Time-energy budgets evolve to fit to the times of greatest stringency*”. Although, the total time needed for vital activities might be less than 24 h in epochs of surplus, animals don’t try maximizing their biological efficiency using the excess of available time to increase either food intake or reproductive efforts. The genotypes committed to excessively rapid body growth and reproduction would enjoy a temporary advantage during periods of resource surplus, but would suffer severe setbacks during hard times, leading possibly to extinction. Therefore, maximizing the immediate advantages of surplus epochs is a short-sighted strategy and animals have evolved to keep a prudent use of their time-energy budget during favorable epochs, accommodating it to the predictable demands of shortages (61). Hence, they spend the excess of time resting lazily. This explains why predators often ignore killable preys, why foragers often ignore food and why those species engaged in ceaseless reproductive activity don’t exist. Nowadays, the importance of the PS is well recognized among zoologists and ecologists (58, 62-64).

7.3. Relationships between laziness, sleep and pleasure

Although laziness has been repeatedly considered worth of absolute moral condemnation, everybody is happy with the prospect of doing nothing (“il dolce far niente”, the sweet doing nothing) when the environmental stringency is low, for instance, in holidays. Laziness is pleasing for humans and, most likely, it is also pleasing for cats, dogs and, in general, for all animals capable of emotional experiences (65). In fact, the hedonic dimension of laziness tags its importance for the general bodily homeostasis (66), a fact that is confirmed by the innateness and the wide extension of laziness in animals (67-70). Furtherly, the relationships between excessive food intake and the metabolic syndrome (71) constitute a solid proof for the PS. Excessive foraging is lethal. Undoubtedly.

Regarding reproductive efficiency, the impossibility of finding enough food in epochs of scarcity may cause the loss of the entire litter. So, animals keep rather constant their litter size, irrespective of the environmental resources (72). Therefore, the reduction in foraging time and in reproductive activity are not as negative as currently believed.

Regarding to the increased predatory risk, it has been also overstated. In fact, the easiest prey is not a sleeping animal, but the immature, senescent, sick or individuals in poor physical condition (73-75). Contrary to the general belief, preys must not outrun predators; they only must outrun their feeblest mates.

Concluding, the pretended disadvantages of "losing" time by resting lazily or by sleeping are uncertain and we observe. that the advantages and disadvantages of sleep and rest, are undistinguishable. We affirmed that nocturnal mammals invented sleep *to rest* during the illuminated part of the photoperiod. Now, we see that diurnal animals rest lazily to avoid the dangerous excessive foraging or reproduction.

7.4. Rest and sleep lack positive advantages.

Surprisingly, the functions we described for sleep and rest of nocturnal and diurnal animals, respectively, only are negative, as they provide no physiological improvements. Nocturnal mammals invented the unproductive sleep during light time to avoid blindness, but their vision was never improved by sleeping. Likewise, diurnal mammals sleep to avoid the excesses of foraging or reproduction but, in no case, sleep improves their digestive and/or reproductive systems. If we are right in believing that sleep serve either to avoid blindness or to avoid excessive activity, no animal obtains positive advantages from whatever physiological process be running while it is asleep.

7.5. Why sleep deprivation cause rebounds

It is currently believed that sleep deprivation impairs the physiological function that is attained by sleeping, whatever it be. If sleep, for instance, would serve for improving the consolidation of memories -a positive result- the deprivation should impair the memory and the recovery of sleep would recover the provisional memory. However, if sleep is only negative, what the rebounds may serve for?

We may propose two answers for this question. First, sleep may have gained additional secondary positive functions in modern mammals, irrespective of being nocturnal or diurnal. For instance, the primary function of breathing is the gaseous interchange, but all animals also use -secondarily- the respiratory sounds for communication. Likewise, all animals take profit -secondarily- for skeletal purposes, of the primary and universal need of calcium stores. Therefore, other functions may have been secondarily added to the primary one and, if experimentally confirmed, most functions proposed for sleep may be real. Nevertheless, it must be clear that any claimed new function must be a secondary adaptation and never the much sought "Holy Grail" for the function of sleep.

A recent report however, posted another interesting answer: *"Is sleep rebound a way to make up for a loss of an otherwise impaired biological process or is it instead merely a "punishment" phenomenon, evolved to guarantee that a constant, largely species-specific amount of sleep is met?"* [76]. It is interesting to remember now the relationships between laziness, sleep and pleasure we described in § 7.3. If both laziness and sleep are pleasing, the deprivation of sleep and rest must be displeasing and, in fact, so it is. Moreover, if the rebounds would be indictive of the impairment in some yet unknown biological process, why some animals need only 4 h of sleep, while others need 19 h to obtain the same result? Assuming the punishment option is more parsimonious that inventing functions and then explaining that they solely would be attained during sleep and solely recovered after rebounds.

8. The reptilian behavioral continuum and how the NREM-REM cycles appeared

Ectothermy, collecting heat from external sources, mostly solar radiation, was essential to attain a high BT in early terrestrial vertebrates (77). Heliothermy, however, is only possible during light time. Therefore, diurnal activity and nocturnal rest were the norm in early amniotes (78, 79). Accordingly, the suprachiasmatic clock of basal reptiles is daily entrained with the rising phase of environmental temperature to promote diurnal activity (80).

However, reptiles begin their active phase only when ambient temperature, season, reproductive state, insolation, predatory risk, etc. Otherwise, they may remain immobile in their burrows during several days or even weeks (81-83).

When BT is lower than the animal's preferred one, the switch puts on the basking behavior and upon approaching the preferred temperature the switch puts it off to begin the Goal Directed Behavior (GDB), with active body displacements, foraging, social, reproductive, agonistic and defensive activities (84). Nevertheless, GDB is always preceded by a short phase of Risk Assessment Behavior (RAB), with passive, exploratory head dipping movements, eye scanning, rearing and stretching postures to analyze the risk of predation and the possibilities of foraging and reproductive activities (85, 86). Noteworthy, reptiles cannot choose the properties of the site were food, predators, competitors and reproductive partners can be found. Therefore, GDB must be performed disregarding the thermal properties of the current environment (87, 88) and, after eventual BT descents, the return to bask is mandatory (89). In summary, the reptilian daily activity consists in a chain of Bask-RAB-GDB cycles.

8.1. The Bask-RAB-GDB cycles and the NREM-REM cycles

The reptilian behavioral cycles have been compared with the mammalian NREM-REM cycles (90) proposing, first, that basking and NREM are homologous states. Both begin searching a safe and thermally convenient place. Both depart from a low BT and both are under closed loop hypothalamic thermal control. Regarding RAB-GDB and REM, both would be behaviorally identical if it were not for the behavioral output, full of body displacements in RAB-GDB and a total muscular relaxation in REM. However, the difference disappears in humans with REM behavior disorder (91) and in animals with pontine lesions (92). It is believed that the rapid eye movements and the muscular twitching of REM are incomplete startles, orienting reflexes and fear responses (93, 94), which constitutes, in fact, a precise description of the partially suppressed GDB. Concluding, it seems that the programmed reptilian behavioral sequence of Bask-RAB-GDB cycles still holds in NREM-REM cycles (90) and the high (relative) incidence of spontaneous REM Behavior Disorder (RBD) in humans and animals is strongly suggestive of an evolutionary regression. Indeed, the mechanisms warranting immobility for REM sleeping mammals could be too modern, frail and prone to failure.

8.2. The so-called reptilian sleep is not true sleep

As defined in previous paragraphs, the mammalian sleep is unrelated to what is currently tagged as the reptilian nocturnal sleep. Indeed, the nocturnal quiescence of reptiles is a passive state, strongly dependent on environmental factors and in fact, reptiles may rest safely in their burrows for several days or may come outside to become active.

Noteworthy, the reptilian BT coincides with the temperature of the burrow during the supposed reptilian nocturnal sleep (81), which means that reptiles are true poikilotherms during nocturnal sleep and their BT is quite variable. In fact, the so-called reptilian nocturnal sleep is a passively cooled state, with the consequent reductions in metabolism, breathing frequency and heart rate, like those observed in endothermic hibernators (81, 90). Nevertheless, two recent reports studied, during night time, the main electrographic traits of supposedly sleeping Australian bearded dragons (95) and Argentine tegu lizards (96). However, the experimental animals were kept at 25-28 ºC during night time, i.e., at temperatures that coincide with the range of the daytime temperatures of their habitat, the arid and semi-arid desserts of Australia and El Chaco (Brazil-Paraguay-Argentina). It is noteworthy that, in these places, the nocturnal temperatures often fall below 10-12ºC in summer and under the freezing point during winter. Therefore, instead of studying the reptilian sleep, these reports only described the electrographic traits of an artifactual state, with the normal BT of waking, but during a time in which the animals were prepared to reduce the main physiological functions. If the studies would have been performed at the normal, nocturnal BT, the recorded EEG would have been, most likely, flat (97, 98). It is clear that, with a BT so high, no lizard would be capable of sleeping. Therefore, the so-called nocturnal sleep of reptiles is not true sleep and bears no relation at all with the described diurnal quiescence that early mammals developed to avoid blindness.

9. Discussion

It should be noted first, that the function we propose here for the mammalian sleep is not merely a new hypothesis; it is the single and complete description of when, how and why sleep appeared in mammals and is the single logical conclusion of well-known facts. The extraordinary duration of the nocturnal bottleneck (~134 Ma) was long enough to invent sleep to fill the dangerous light time and to survive under the strongest evolutionary pressure by remaining immobile with closed eyes, day after day, along the entire life. Imagining that those early mammals would remain in a state other than sleep would is simply preposterous. We may thus affirm that the primary and vital function of the early mammals sleep was the enforcement of rest to avoid blindness, a function that is still essential in extant nocturnal mammals (27). It has been found, for example that, to avoid irreversible retinal damage, the light levels must be kept below 60 lux during light time in pigmented rats and below 20–25 lux in albino (99, 100).

The present review also searched additional function(s) for the sleep of diurnal mammals that support high intensities of light without harmful consequences. We observed that the single trait that never fails to appear in sleeping mammals, irrespective of being nocturnal or diurnal, is the behavioral quiescence. We can say therefore that, leaving apart the motor quiescence, the entire set of traits accompanying sleep are as much irrelevant as the colors of cars. It is evident that evolution is never a proactive process. No animal says: "it would be wonderful if I would use sleep for…" filling the dots with any of the proposed functions. Evolution lacks foresight capacity. It only promotes immediate responses to environmental challenges.

As a final note, and contrary to most expectations, sleep seems to be polyphyletic. The nocturnal bottleneck has been never claimed for non-mammalian animals. Therefore, if sleep truly exists in non-mammals, it may have appeared as a result of evolutionary convergence. therefore, we conclude that sleep is trivial: laypersons were right: sleep is rest and sleep is for rest (92).

Total: 3893 words

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