Measuring sleep in complex and simple organisms

K.Æ. Karlsson
Department of Biomedical Engineering, School of Science and Engineering, Reykjavik University, Reykjavik, Iceland, karlsson@ru.is

Recently, surprising statistical regularities have been revealed in the structure of bouts of sleep and wakefulness [1]. This characterization of sleep offers a novel method of measuring and classifying behavioral states. In contrast to the standard in the field, this method renders sleep comparable across phylogeny and ontogeny and, thus, opens new ways of dissecting sleep at the behavioral, pharmacological, and genetic levels.

In spite of being poorly understood phenomenon, sleep comes equipped with virtually undisputed definition, in which sleep is measured and defined as a constellation of physiological events – centered on the electroencephalogram. According to this tradition sleep is measured in 30 second bins and depending on the amplitude and frequency of the electroencephalogram, the amplitude of the electromyogram, and the presence or absence of eye movements, each 30 second epoch is assigned a state: Wake, rapid-eye-movement sleep, or slow-wave-sleep 1-4 [2]. However, strict adherence to this approach, while clinically useful, virtually defines sleep out of existence large in groups of animals and age groups. Invertebrates, such as the fruit fly, which clearly exhibit all behavioral symptoms of sleep cannot be considered sleeping under this traditional method [3]. Moreover, neonates cannot either. A human newborn quietly sleeping at its mother's bosom, the duckling under its mother's wing, or a rat pup huddled against its littermates; these are prototypical examples of sleep. Yet, neither the human neonate, duckling, nor rat pup exhibit all the indices that have become the gold standard for defining sleep. Sleep research, thus, has been conducted almost exclusively in adults; and only in a handful of mammalian species. Sleep was first measured and described in adults [4], the dominant terminology of the field is derived from work done with adults [2], and the neural substrates of sleep have been elucidated from work done with adults [5]. (For an exeption, see [6]). Accordingly, most theories of sleep can only be applied to infants of our own species, or to other species, with great difficulty [7].

In adult humans the duration of sleep bouts exhibit an exponential distribution with the rule $P(t) \sim \exp(-t/\tau)$ where t is an individual sleep bout, whereas, wake bouts exhibit a power-law distribution with the rule $P(t) \sim t^{-\alpha}$ where t is an individual wake bout [1]. Subsequently, it was demonstrated that the wake bouts exhibit a scale-free power law behavior with an exponent, α, that remains constant across species (humans, cats, rats, and mice). In contrast, sleep bout durations follow an exponential distribution where τ represents a characteristic time scale whose main determinants are body size and metabolic rate [8]. In neonatal rats, both sleep and wake bouts exhibit exponential distribution immediately after birth, with a clear power-law behavior of wake bouts emerging only after the second postnatal week; this occurs in spite of very little change in the overall duration of wake bouts; τ, on the other hand, increases with age [9]. Thus, the power-law exponent α is constant across multiple adult species, but switches from exponential to power-law behavior during development. In contrast, the sleep-related time constant τ varies across species and age. Importantly, the only information needed to calculate α and τ is sleep and wake durations; one does not need detailed information about the transitions *between* sleep states or information about events within a given state. Given the right measuring system, this method can be employed to the simple, genetically tractable zebrafish [10]. These efforts could render sleep in humans and zebrafish meaningfully comparable and open new venues in sleep research.

The values, α and τ, thus, represent novel way of thinking about sleep, and offer a novel, simpler method of characterizing sleep states; a method that is based on the stability of behavioral states. This novel method of characterizing sleep states could become the new standard of classifying sleep, its disorders, and its development through the life-span.

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