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Case Study

Comparative Study of Sleep as a Balance-like Mechanism in Humans and Animals: From Dynamic Homeostatic Regulation to Species-Specific Adaptations

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Abstract

Traditional sleep research has often emphasized the static "restoration-depletion" model within humans, overlooking the essential role of sleep as a dynamic, cross-species regulatory system. Inspired by human balance function-where posture stability is maintained through multi-system coordination-this study proposes the "balance-like mechanism of sleep" hypothesis. Sleep is conceptualized as a dynamic coordination process within the neuro-endocrine-immune network, counteracting circadian disruption, metabolic stress, and environmental threats. First, we construct the Sleep Homeostatic Threshold Model based on human sleep's balance-like features (sensory input-central regulation-effector output loop). Next, we conduct a systematic cross-species comparison of sleep posture, duration, environment, and functional priorities, revealing species-specific adaptive strategies that tune this balance-like mechanism. Finally, we integrate the evidence into a Generalized Balance-like Framework, offering a novel perspective on the evolutionary conservation and functional diversity of sleep.

Introduction

Balance function is a core human ability to maintain upright posture. It is essentially a closed-loop system: multimodal sensory input (vestibular, proprioceptive, visual), central integration (cerebellum-vestibular nucleus networks), and effector output (musculoskeletal adjustments) cooperate to counteract gravitational and inertial perturbations, thereby ensuring postural stability [1]. Interestingly, sleep across humans and animals demonstrates similar dynamic adaptation to internal and external disturbances. For example, humans employ slow-wave sleep to repair synapses and clear metabolic waste; sloths sleep inverted to conserve energy; dolphins engage in unihemispheric sleep to remain vigilant against predators. All of these represent coordinated regulation within neuro-endocrine-immune networks, maintaining cognitive, metabolic, and defensive homeostasis [2-3].

Yet, significant differences exist: human sleep is shaped by socio-cultural constraints (e.g., fixed schedules) and prioritizes cognitive recovery, while animal sleep is more tightly coupled to survival demands, showing diversity in posture, duration, and function [4]. This coexistence of commonality and divergence suggests that the essence of sleep may be understood as a Generalized Balance-like Mechanism-a conserved dynamic regulatory logic (e.g., stress perception, compensatory adjustment, threshold collapse) variably adapted by species-specific strategies (e.g., environmental risks, energy acquisition modes).

This Study Therefore:

a) Uses human sleep as a template to demonstrate balance-like features (multimodal input, central integration, effector output) and threshold-based regulation;

b) Compares humans and animals in terms of posture, time, environment, and function, highlighting adaptive modulation;

c) Proposes a Generalized Balance-like Framework, explaining both evolutionary conservation and adaptive diversity in sleep function.

Balance-like Mechanisms in Human Sleep: Core Logic of Dynamic Homeostasis

Sensory Input Layer: Coordinated Monitoring of Environmental Signals

Circadian Signals (Visual Reference): The Suprachiasmatic Nucleus (SCN) receives retinal input (via ipRGCs), synchronizing circadian phases and regulating rhythmic melatonin and cortisol secretion [4].

Metabolic Pressure Signals (Proprioceptive Analogy): Cognitive activity, energy expenditure, and adenosine accumulation (increasing ~0.5μM/min during wakefulness) diffuse to the VLPO, signaling rising metabolic strain [5].

External Disturbance Signals (Vestibular Analogy): Noise, light, or social stimuli activate thalamo-cortical pathways and the Reticular Activating System (RAS), suppressing sleep propensity.

Central Regulation Layer: Feedback Balance Between Sleep- and Wake-Promoting Systems

Sleep-Promoting Centers: VLPO and MNPO inhibit RAS activity via GABA and galanin, functioning as a "sleep switch" [6].

Wake-Promoting Centers: RAS activity depends on circadian input and metabolic state-orexin neurons sustain alertness during wake but downregulate during sleep [7].

Negative Feedback Loop: Accumulated adenosine during wakefulness suppresses RAS and activates VLPO; during sleep, adenosine clearance restores wake drive [5].

Effector Output Layer: Multi-System Functional Reconstruction

Neuroplasticity Repair: Slow-wave oscillations promote synaptic pruning and memory consolidation [8].

Metabolite Clearance: Glymphatic exchange increases by >60% during sleep, clearing Aβ and tau proteins [9].

Immune Reset: Sleep enhances NK cell activity and anti-inflammatory cytokine secretion, restoring immune homeostasis [10].

Sleep Homeostatic Threshold Model

We formalize these dynamics in the Sleep Homeostatic Threshold Model (Figure 1):

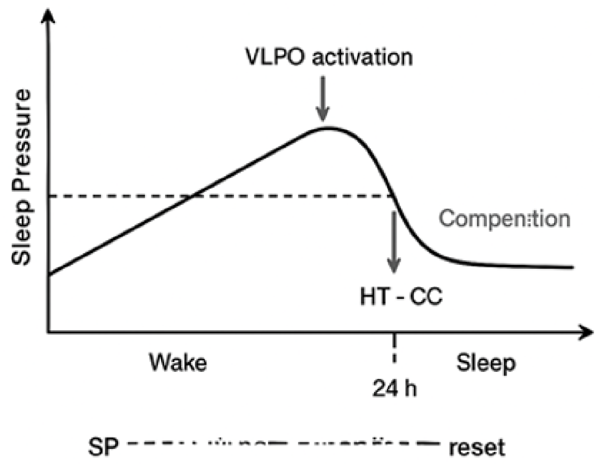

Figure 1: Sleep Homeostasis Threshold Model.

Core Parameters: Sleep Pressure (SP), Compensatory Capacity (CC, e.g., napping, caffeine), and Homeostatic Threshold (HT).

Regulation: SP rises linearly during wakefulness; when SP<HT-CC, wakefulness persists. Approaching HT-CC triggers VLPO activation; exceeding HT induces uncontrollable sleep drive. During sleep, SP is reduced via SWS-driven clearance. Incomplete sleep lowers next-day HT [5].

Cross-Species Comparison: Adaptive Modulation of Balance-like Mechanisms

Although humans and animals share the core balance-like logic (input-integration-output), species-specific strategies produce distinctive adaptations.

Sleep Posture: Morphological Adaptations to Survival

Humans: Supine, lateral, or prone positions emphasize comfort and spinal protection.

Animals: Birds sleep standing on one leg to conserve energy; horses lock their limbs to enable rapid escape; sloths sleep inverted to exploit gravity; dolphins employ unihemispheric sleep to balance vigilance and rest [4].

Sleep Duration: Trade-offs Between Energy and Risk

Humans: Adults require 7-9h, constrained by social schedules.

Animals: Wide variation reflects ecological trade-offs-sloths (15-20h/day) conserve energy, giraffes sleep only 2-4h due to predation risk, bears hibernate for months, and dolphins compress sleep into 5-8h through unihemispheric strategies [4,11].

Sleep Environment: Evolutionary Choices for Safety and Comfort

Humans: Prefer quiet, dark, temperature-controlled environments, actively modified by cultural tools.

Animals: Environments are survival-driven hares sleep in burrows, lions cluster socially, bats roost inverted, penguins huddle in polar cold [4].

Functional Priorities: Evolutionary Differentiation

Humans: Sleep emphasizes cognitive restoration and emotional regulation, reinforced by cultural expectations of "high-quality sleep."

Animals: Sleep prioritizes survival-defensive vigilance (dolphins, hares), energy conservation (sloths, bears), or reproductive regulation (birds, bees) [11-12].

Generalized Balance-like Framework: Integrative Cross-Species Perspective

This framework (Figure 2) defines sleep as a dynamic homeostatic process conserved across species.

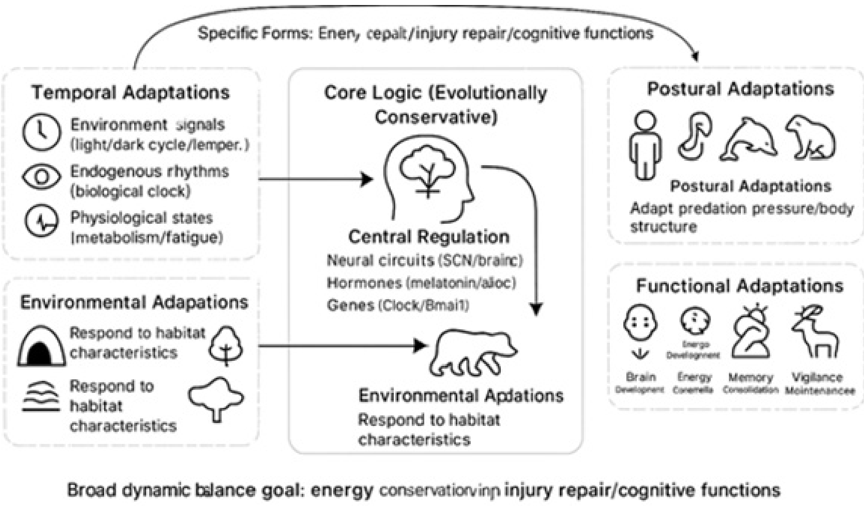

Figure 2: Board Balance Framework Dynamic homeostatic regulation model of sleep functions across species to across species.

Evolutionary Conservation

Neural Duality: VLPO-RAS antagonism is present in mammals, birds, and some reptiles [6].

Metabolic Regulation: Energy reduction (10-30%) and metabolite clearance are universal [9].

Circadian Synchronization: SCN-like structures and light entrainment are conserved across taxa [4].

Functional Diversity

High-Risk Environments: Unihemispheric sleep (dolphins) and group vigilance (lions).

Low-Energy Diets: Prolonged sleep and hibernation (sloths, bears).

High Cognitive Demand: Enhanced plasticity-related sleep functions in primates [8].

Discussion and Future Directions

This Study Highlights the Dual Essence of Sleep:

a. A conserved dynamic regulatory mechanism (balance-like homeostasis);

b. A system fine-tuned by species-specific adaptations (posture, time, environment, functional priorities).

Implications include:

Evolutionary Roots of Sleep Disorders: Human insomnia may stem from cultural interference with natural rhythms, while disrupted hibernation may reflect climate change.

Future research:

Molecular Bases: Comparative genomics of VLPO-RAS networks and orexin homologs.

Ecological Drivers: Field experiments testing environmental manipulation (e.g., light/temperature on sloth sleep).

Translational Strategies: Applying adaptive features (e.g., dolphin unihemispheric mechanisms) to novel therapies for insomnia or sleep apnea [13].

In subsequent research, the author will adhere to the principle that "a sharp tool saves no time in the work" (proverbially meaning "preparation improves efficiency"), utilizing a diverse range of artificial intelligences with distinct characteristics to write academic papers.

Conflict of Interest

None.

Acknowledgments

During the preparation of this manuscript, I utilized Tencent Hunyuan's large language model "Yuanbao" and the free version of GPT-5 to optimize the text, including grammar correction, sentence structure adjustment, and terminology standardization, as well as to design Figures 1 and 2. Parts of the content were assisted by artificial intelligence.

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