The Vestibular System as a Circadian Modulator: Neural Pathways to the Hypothalamus Shaping Sleep, Autonomic Activity, and Hormonal Rhythms

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Abstract: Physiological homeostasis in humans relies on the precise integration of autonomic, endocrine, and circadian regulatory mechanisms, largely orchestrated by hypothalamic nuclei [1-3]. These regulatory domains include: (1) autonomic nervous system control through sympathetic and parasympathetic outputs, governing cardiovascular, respiratory, gastrointestinal, and metabolic functions [4, 5]; (2) endocrine secretion via hypothalamic–pituitary axes, modulating stress responses, growth, reproduction, and energy balance [6, 7]; and (3) circadian regulation of sleep–wake cycles and daily physiological rhythms through interactions with the suprachiasmatic nucleus (SCN) [8-10]. Dysregulation of these hypothalamic-controlled variables gives rise to a wide spectrum of somatic and neuropsychiatric symptoms—such as fatigue, sleep disturbances, autonomic instability, metabolic imbalance, anxiety, and mood disorders—which profoundly limit quality of life, particularly in individuals with mental illnesses [11-13].

The vestibular system of the inner ear is classically defined as a sensory system specialized in detecting head motion, spatial orientation, and balance, ensuring postural stability and coordinated eye movements [14]. However, accumulating evidence indicates that vestibular afferent signals extend far beyond motor control. Anatomical and functional studies demonstrate direct and indirect projections from vestibular nuclei to hypothalamic regions involved in autonomic regulation, neuroendocrine secretion, and circadian timing [15-18]. Through these connections, vestibular input appears capable of modulating core physiological functions traditionally attributed to hypothalamic control.

This paper reviews current evidence supporting the role of the vestibular system as a regulator of bodily physiology via its influence on hypothalamic networks. Through vestibulo–hypothalamic interactions, vestibular input may contribute not only to somatic regulation but also to psychological and clinical manifestations frequently observed in anxiety, depressive disorders, stress-related conditions, and sleep disorders, including impaired emotional regulation, altered stress responsiveness, cognitive dysfunction, and reduced quality of life. Finally, future perspectives are discussed, highlighting vestibular stimulation as a promising neuromodulatory approach to indirectly target hypothalamic dysfunction in disorders characterized by autonomic, endocrine, and circadian dysregulation.

Keywords: Vestibular system, Hypothalamic regulation, Authonomic instability, Sleep disorders, Circadian rhythms, Neuropsychiatric symptoms.

INTRODUCTION

Psychophysiology and neuropsychology have long emphasized that mental health depends on the dynamic integration of bodily regulatory systems, including autonomic, endocrine, and circadian processes. These systems shape emotional regulation, stress responsiveness, cognitive functioning, and subjective well-being, and are critically involved in the pathophysiology of anxiety, depression, and sleep disorders. Within this framework, understanding how vestibular signals interact with hypothalamic circuits may provide critical insights into the psychophysiological mechanisms linking bodily regulation with mental health.

The maintenance of internal physiological stability requires continuous multisensory integration at the level of subcortical brain structures [1, 2]. While the hypothalamus has long been recognized as the central coordinator of autonomic, endocrine, and circadian processes [3, 6, 8], the sensory systems that provide regulatory input to hypothalamic circuits remain incompletely understood. Among these, the vestibular system has emerged as a critical yet underappreciated contributor to bodily regulation, linking self-motion perception with visceral and emotional states [15, 19].

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HYPOTHALAMIC REGULATION OF CORE PHYSIOLOGICAL FUNCTIONS

The hypothalamus is a highly conserved diencephalic structure that plays a central role in maintaining internal homeostasis by integrating sensory, visceral, endocrine, and autonomic information [1, 3]. Through its extensive reciprocal connections with the brainstem, limbic system, pituitary gland, and spinal autonomic centers, the hypothalamus exerts hierarchical control over three major physiological domains: autonomic nervous system activity, endocrine regulation, and circadian rhythmicity [2, 6, 8].

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a) Regulation of the Autonomic Nervous System

The hypothalamus is a primary command center for autonomic nervous system (ANS) activity, coordinating sympathetic and parasympathetic outputs to ensure adaptive physiological responses to internal and external demands [4, 5]. Sympathetic activity is predominantly regulated by posterior and lateral hypothalamic regions, which project to preganglionic sympathetic neurons located in the intermediolateral cell column of the spinal cord via brainstem relay nuclei [5]. Parasympathetic regulation is mainly associated with anterior hypothalamic and medial preoptic areas, influencing the dorsal motor nucleus of the vagus and nucleus ambiguus [4].

Dysregulation of hypothalamic autonomic control may result in orthostatic intolerance, dysautonomia, cardiac rhythm disturbances, gastrointestinal dysfunction, and impaired thermoregulation [11, 12].

b) Hypothalamic Control of Endocrine Regulation

The hypothalamus constitutes the primary interface between the nervous and endocrine systems via the hypothalamic–pituitary axes [6, 7]. Specialized nuclei—including the paraventricular, arcuate, and supraoptic nuclei—regulate the secretion of cortisol, thyroid hormones, growth hormone, prolactin, and gonadotropins, exerting widespread effects on metabolism, immune function, and stress adaptation [6, 7, 13].

c) Circadian Regulation of Sleep–Wake Cycles

The suprachiasmatic nucleus (SCN) functions as the master circadian pacemaker, synchronizing internal biological rhythms with the environmental light–dark cycle [8–10]. Through multisynaptic projections, the SCN modulates autonomic tone, endocrine secretion (including melatonin and cortisol), sleep–wake behavior, and thermoregulation [9, 10].

THE VESTIBULAR SYSTEM AND ITS ANATOMICAL CONNECTIONS WITH THE HYPOTHALAMUS

Beyond its classical role in balance and gaze stabilization [14], the vestibular system projects extensively to autonomic and homeostatic centers [15, 16]. Vestibular afferents reach the vestibular nuclei, which maintain reciprocal connections with the parabrachial nucleus, reticular formation, periaqueductal gray, raphe nuclei, and hypothalamus [17-19].

Direct vestibulo-hypothalamic projections—particularly from the medial and inferior vestibular nuclei to the paraventricular and lateral hypothalamic nuclei—have been demonstrated in animal models using tract-tracing techniques [15, 16].

In humans, functional MRI studies during caloric and galvanic vestibular stimulation demonstrate co-activation of vestibular nuclei and hypothalamic regions, supporting the translational relevance of these pathways [20].

VESTIBULO-HYPOTHALAMIC PATHWAYS AND AUTONOMIC REGULATION

Vestibular inputs to the paraventricular nucleus, dorsomedial hypothalamus, and lateral hypothalamic area contribute to the vestibulo-sympathetic reflex, a mechanism essential for cardiovascular stability during postural transitions [21-23]. Disruption of these pathways is implicated in vestibular-induced autonomic symptoms such as dizziness, palpitations, nausea, and vasovagal responses [22].

VESTIBULAR INFLUENCE ON ENDOCRINE AND STRESS-RELATED CIRCUITS

Vestibular stimulation has been shown to modulate hypothalamic–pituitary–adrenal (HPA) axis activity, influencing cortisol secretion and stress responsiveness [24, 25]. Animal and human data suggest vestibular involvement in metabolic and immune-related endocrine regulation, potentially linking

Table 1: Autonomic Nervous System Dysregulation: Hypothalamic Control and Vestibular Influence

Autonomic Symptoms (ANS Dysregulation)	Hypothalamic Areas Involved	Vestibular Pathways and Supporting Evidence
Orthostatic intolerance / dizziness	Paraventricular nucleus; posterior hypothalamus	Vestibular nuclei → PVN → sympathetic preganglionic neurons (vestibulo-sympathetic reflex) essential for blood pressure regulation (Yates, 1996; Carter *et al*., 2008; Holstein *et al*., 2014).
Palpitations / autonomic instability	Posterior and lateral hypothalamus	Vestibular nuclei → parabrachial nucleus → hypothalamus → brainstem autonomic centers (Balaban & Porter, 1998; Yates *et al*., 2014).
Gastrointestinal dysmotility	Anterior hypothalamus; PVN	Vestibular projections to hypothalamic autonomic centers modulate vagal tone and GI function (Benarroch, 1993; Ruggiero *et al*., 1996).
Thermoregulatory dysfunction / sweating abnormalities	Preoptic and anterior hypothalamic areas	Vestibular input influences hypothalamic thermoregulatory circuits via brainstem relays (Smith, 2017; Fuller PM *et al*.,

Table 2: Endocrine Dysregulation Frequently Observed in Psychiatric Disorders: Hypothalamic Control and Vestibular Modulation

Endocrine-Related Symptoms	Hypothalamic Areas Involved	Vestibular Pathways and Supporting Evidence
Hypercortisolemia / altered stress response (HPA axis)	Paraventricular nucleus (CRH neurons)	Vestibular nuclei → PVN influence HPA axis activity; vestibular stimulation modulates cortisol secretion in humans (Kuwabara *et al.*, 2007; Eisenhofer *et al.*, 2004).
Fatigue and low energy states	Arcuate nucleus; lateral hypothalamus	Vestibular input to hypothalamic metabolic and arousal circuits; vestibular dysfunction associated with chronic fatigue-like symptoms (Smith, 2017).
Altered melatonin secretion	SCN; pineal regulatory pathways	Vestibular modulation of SCN output affects melatonin rhythmicity and circadian endocrine signaling (Fuller CA *et al.*, 2002; Bayer *et al.*, 2004).
Neuroendocrine dysregulation in mood disorders	PVN; arcuate nucleus	Vestibular–hypothalamic interactions influence stress hormones and may contribute to bodily symptoms in depression and anxiety (McEwen, 1998; Horowitz *et al.*, 2020).

vestibular dysfunction to chronic fatigue and stress-related disorders [26].

VESTIBULAR CONTRIBUTIONS TO CIRCADIAN AND SLEEP REGULATION

Vestibular input appears to act as a non-photic modulator of circadian timing through interactions with the raphe nuclei and SCN [27-29]. Serotonergic projections from the dorsal and median raphe nuclei constitute a key interface between vestibular signals and circadian regulation, modulating sleep–wake transitions and phase resetting [28, 29].

Experimental vestibular stimulation has been associated with alterations in sleep architecture, melatonin rhythms, and thermoregulation in both animal models and humans [30-32].

FUNCTIONAL IMPLICATIONS AND TRANSLATIONAL PERSPECTIVE

From a psychophysiological standpoint, the integration of vestibular input into hypothalamic networks offers a compelling model to understand how bodily regulation influences emotional, cognitive, and behavioral processes.

Collectively, these findings support a model in which the vestibular system functions as a critical sensory regulator of hypothalamic networks governing autonomic stability, endocrine secretion, and circadian organization. This framework provides a strong neurobiological rationale for exploring vestibular stimulation as a non-invasive neuromodulatory strategy in disorders characterized by hypothalamic dysregulation.

LIMITATIONS, RELEVANCE, AND FUTURE DIRECTIONS

Despite the growing body of evidence supporting vestibulo–hypothalamic interactions, several limitations of the present review should be acknowledged. First, much of the available data derives from animal models and experimental vestibular stimulation paradigms, which may not fully capture the complexity of vestibular–hypothalamic regulation in humans. Second, the heterogeneity of methodological approaches—

Table 3: Circadian Sleep–Wake Dysregulation: Hypothalamic Control and Vestibular Modulation

Circadian Sleep–Wake Symptoms	Hypothalamic Areas Involved	Vestibular Pathways and Supporting Evidence
Insomnia (sleep initiation and maintenance difficulties)	Suprachiasmatic nucleus (SCN); lateral hypothalamus; paraventricular nucleus (PVN)	Vestibular nuclei → raphe nuclei → SCN (non-photic circadian modulation). Vestibular stimulation alters sleep architecture and circadian phase (Fuller *et al.*, 2002; Morin & Allen, 2006; Horowitz *et al.*, 2020).
Hypersomnia / excessive daytime sleepiness	Lateral hypothalamus (orexin/hypocretin neurons); SCN	Vestibular afferents → vestibular nuclei → lateral hypothalamus and brainstem arousal systems; vestibular deprivation reduces arousal and vigilance (Fuller *et al.*, 2006; Bayer *et al.*, 2004).
Circadian rhythm sleep–wake disorder (phase delay/advance)	SCN; dorsomedial hypothalamus	Vestibular input acts as a non-photic zeitgeber via serotonergic raphe projections to the SCN (Glass *et al.*, 2003; Fuller CA *et al.*, 2002).
Fragmented sleep / poor sleep efficiency	SCN; anterior hypothalamus	Vestibular stimulation modulates melatonin secretion and thermoregulation influencing sleep continuity (Bayer *et al.*, 2004; Horowitz *et al.*, 2020).

ranging from tract-tracing and electrophysiology to functional neuroimaging and clinical observations—limits the ability to establish direct causal relationships between vestibular inputs and specific hypothalamic outputs. Importantly, the hypothalamus represents a highly integrative hub that coordinates physiological functions through the convergence of multiple regulatory signals, including metabolic, immune, hormonal, visceral, and environmental inputs [33-35]. The vestibular system should therefore be conceptualized as one of several modulatory influences acting on hypothalamic networks, rather than as a single or exclusive regulatory mechanism.

Nevertheless, the relevance of this review lies in highlighting the vestibular system as a previously underrecognized sensory gateway capable of influencing hypothalamic function and, consequently, autonomic, endocrine, and circadian regulation. This perspective is particularly meaningful given that dysregulation of these physiological domains is a hallmark of many neuropsychiatric disorders, including major depression, anxiety disorders, and stress-related conditions, in which patients frequently experience disabling bodily symptoms such as sleep disturbances, fatigue, autonomic instability, and hormonal imbalance [11-13, 36]. These functional bodily alterations often impose substantial limitations on daily life and remain insufficiently addressed by conventional pharmacological or psychotherapeutic approaches.

From a translational standpoint, future research should aim to clarify the specificity, directionality, and clinical relevance of vestibulo–hypothalamic pathways in humans. Longitudinal studies combining vestibular assessment, autonomic and endocrine biomarkers, circadian measures, and neuroimaging will be essential to delineate the conditions under which vestibular signals meaningfully modulate hypothalamic activity. Moreover, controlled clinical trials are needed to determine whether targeted vestibular stimulation can serve as a reliable neuromodulatory strategy to indirectly influence hypothalamic dysfunction in selected patient populations. While acknowledging the multifactorial regulation of hypothalamic physiology, the identification of the vestibular system as a modifiable sensory input opens an intriguing avenue for understanding and potentially treating disorders in which altered bodily regulation profoundly constrains functional recovery and quality of life.

From a psychotherapeutic perspective, vestibulo–hypothalamic modulation provides a neurobiological framework linking bodily regulation with emotional and cognitive processes, supporting the integration of vestibular-based neuromodulation within psychosomatic treatment approaches.

In summary, the evidence reviewed supports the vestibular system as a relevant psychophysiological modulator of hypothalamic networks underlying autonomic balance, endocrine regulation, and circadian organization. Given the central role of these systems in emotional regulation, stress responsiveness, sleep quality, and cognitive functioning, vestibulo–hypothalamic interactions may represent a clinically meaningful pathway contributing to both mental health and psychopathology. Future research integrating vestibular assessment with psychological, autonomic, and circadian measures may open new avenues for psychotherapeutic and neuromodulatory interventions targeting mind–body dysregulation.

CONFLICTS OF INTEREST

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AUTHORS' CONTRIBUTION

AMS elaborate the paper, CA review the article.

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