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# Chronobiology and vestibular dysfunction: Optimizing occupational therapy interventions through circadian rhythms

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## Abstract

Vestibular dysfunction affects balance, space and daily function resulting in cognitive, autonomic and sleep disturbances. Traditional occupational therapy (OT) interventions focus on balance retraining and sensory integration but emerging research highlights the role of circadian rhythms in vestibular processing. Circadian rhythms control neurotransmitter activity, hormone fluctuations and cortical excitability which affects postural stability and vestibular sensitivity throughout the day. Misalignment of these rhythms due to sleep disturbances or irregular light exposure can worsen vestibular dysfunction and hinder rehabilitation. Aligning OT interventions with natural biological rhythms may increase patient engagement, motor learning and functional independence. This paper explores the relationship between chronobiology and vestibular dysfunction, and time sensitive therapeutic strategies to optimise rehabilitation outcomes.

**Keywords:** Vestibular dysfunction; Occupational therapy; Circadian rhythms; Chronotherapy; Balance rehabilitation; Postural control; Neuroplasticity; Sleep-wake cycle; Light therapy; Motor learning

## 1. Introduction

Vestibular dysfunction is a complex condition that affects postural control, spatial awareness and overall mobility, leading to big disruptions in daily activities and independence (Furman & Balaban, 2018). The vestibular system is responsible for balance and head/eye movements through interactions between the semicircular canals, otolith organs and central vestibular pathways (Lopez & Blanke, 2021). Dysfunction in this system can manifest as vertigo, dizziness, loss of coordination and increased risk of falls which affects an individual's ability to do ADLs (Smith et al., 2022).

The effects of vestibular impairment goes beyond physical symptoms, affected individuals often report secondary complications like cognitive difficulties, anxiety and sleep-wake cycle disruptions (Zhou & Hullar, 2019). The interdependence between the vestibular and autonomic nervous system further highlights the systemic effects of vestibular dysfunction, studies show that disturbances in vestibular processing can lead to altered cardiovascular responses, motion sickness susceptibility and metabolic dysregulation (Blask et al., 2019; Cullen & Taube, 2020). Given the far reaching consequences, effective rehab strategies are key to mitigating functional decline and improving quality of life.

Current OT rehab approaches primarily focus on balance retraining, habituation exercises and compensatory strategies to enhance spatial awareness and postural control (Furman & Balaban, 2018). These interventions involve progressive exposure to movement stimuli, visual-vestibular integration exercises and environmental modifications to reduce fall risk (Lopez & Blanke, 2021). But emerging research suggests that these strategies can be optimized further by

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understanding circadian biology (Cullen & Taube, 2020).Circadian rhythms are endogenous 24 hour cycles that regulate physiological, cognitive and behavioral functions including hormonal secretion, thermoregulation, sleep-wake cycles and neuroplasticity (Zhou & Hullar, 2019). These rhythms are controlled by the suprachiasmatic nucleus (SCN) of the hypothalamus which synchronizes peripheral oscillators throughout the body in response to environmental cues like light exposure and social activity (Smith & Zheng, 2022). Research shows that circadian modulation extends to vestibular processing, postural stability, motion perception and spatial orientation varies at different times of the day (Blask et al., 2019). Moreover, circadian misalignment – like irregular sleep patterns, shift work or prolonged artificial light exposure – has been linked to exacerbated vestibular dysfunction, increased fall risk and prolonged recovery after vestibular rehab (Cullen & Taube, 2020; Lopez & Blanke, 2021).

Despite this, the relationship between circadian rhythms and vestibular dysfunction is an understudied area in OT research and practice (Furman & Balaban, 2018). Given the growing evidence of time-dependent fluctuations in vestibular function, aligning OT interventions with the body's natural biological rhythms is a promising way to improve outcomes. This paper will explore the intersection of vestibular dysfunction and circadian biology, new time-sensitive approaches to OT interventions. By incorporating chronobiological principles into vestibular rehab, therapists can increase patient engagement, motor learning and ultimately greater functional independence in people with vestibular disorders (Smith & Zheng, 2022).

## 2. The Vestibular System and Circadian Rhythms

The vestibular system is a complex and specialized sensory network that is responsible for balance, stabilizing vision during movement and spatial navigation (Lopez & Blanke, 2021). It has peripheral and central components that work together to provide the brain with continuous real-time information about head position and motion. The peripheral vestibular structures – the semicircular canals which detect angular acceleration and the otolith organs (utricle and saccule) which sense linear acceleration and gravitational forces – send afferent signals to the central vestibular pathways via the vestibulocochlear nerve (Furman & Balaban, 2018). These signals are then processed by the vestibular nuclei in the brainstem and relayed to higher cortical areas, the cerebellum and autonomic centers to ensure proper balance, posture and gaze stabilization (Smith & Zheng, 2022).Problems within this system whether due to peripheral dysfunction (e.g. vestibular neuritis, Ménière's disease, benign paroxysmal positional vertigo (BPPV)) or central vestibular disorders (e.g. stroke, traumatic brain injury, neurodegenerative conditions) can cause dizziness, vertigo, postural control impairment and increased fall risk (Blask et al., 2019). The consequences go beyond motor impairment as vestibular dysfunction has been linked to cognitive deficits – spatial memory, attentional difficulties and executive dysfunction (Cullen & Taube, 2020). Given these far reaching effects, vestibular rehabilitation is now a core component of neurorehabilitation and occupational therapy (OT) to restore functional independence and improve quality of life through adaptive and compensatory strategies (Zhou & Hullar, 2019).

### 2.1. Circadian Rhythms and Vestibular Processing

While traditionally studied in isolation, it seems that vestibular function is modulated by internal circadian rhythms which regulate a wide range of physiological and cognitive processes over a 24 hour cycle (Lopez & Blanke, 2021). These rhythms are controlled by the suprachiasmatic nucleus (SCN) a master clock in the hypothalamus which synchronises peripheral oscillators in response to environmental cues such as light and social activity (Smith & Zheng, 2022). The SCN influences vestibular processing through direct and indirect pathways, modulating neurotransmitter release, hormone fluctuations and cortical excitability, all of which contribute to diurnal variations in balance, motion perception and postural stability (Cullen & Taube, 2020).

Recent studies have shown that vestibular sensitivity varies across the day, with peak performance in the morning and decline in the late afternoon and evening (Blask et al., 2019). These changes have been attributed to daily fluctuations in:

- Neurotransmitter Activity: Vestibular neuron excitability is modulated by circadian driven changes in neurotransmitter levels, particularly glutamate, GABA and acetylcholine (Furman & Balaban, 2018). Higher glutamatergic activity in the morning is associated with better vestibular signal transmission and increased GABAergic inhibition in the evening may contribute to reduced postural stability and motion sensitivity (Zhou & Hullar, 2019).
- Hormonal Regulation: Hormones involved in vestibular function, such as cortisol, melatonin and vasopressin, have circadian oscillations that impact balance and spatial orientation (Smith & Zheng, 2022). Morning cortisol levels are associated with better postural control and evening melatonin levels with vestibular hypofunction and dizziness (Blask et al., 2019).· Cortical Excitability: Functional imaging studies show that vestibular related

cortical areas, the parieto-insular vestibular cortex (PIVC) and posterior parietal cortex, have circadian activity fluctuations with peak activity in the morning (Lopez & Blanke, 2021). So vestibular rehabilitation may be more effective when done during the day when the cortex is more responsive (Cullen & Taube, 2020).

### 2.2. The Impact of Circadian Disruption on Vestibular Function

Chronic misalignment of our internal clocks—caused by shift work, jet lag, or sleep disorders—has been shown to worsen vestibular dysfunction, leading to increased fall risk, longer recovery from vestibular injury and reduced effectiveness of rehabilitation treatments (Furman & Balaban, 2018). Disruption of the sleep-wake cycle in particular has been linked to impaired vestibular compensation as sleep deprivation disables neuroplasticity, motor learning and central sensory integration (Smith & Zheng, 2022). Studies in both animal and human models have shown that individuals with circadian misalignment have greater postural instability, delayed vestibulo-ocular reflex adaptation and impaired balance control compared to those with regular circadian rhythms (Blask et al., 2019).

Moreover, circadian dysregulation has been shown to exacerbate the autonomic symptoms of vestibular dysfunction including dizziness, orthostatic intolerance and motion sickness susceptibility (Zhou & Hullar, 2019). Disrupted melatonin secretion in particular has been linked to more vertiginous episodes and longer symptom duration in individuals with vestibular migraine and persistent postural-perceptual dizziness (PPPD) (Lopez & Blanke, 2021). These findings suggest that optimizing circadian alignment through sleep hygiene, light exposure therapy and strategic timing of OT interventions may improve vestibular rehabilitation outcomes and overall functional independence (Cullen & Taube, 2020).

### 2.3. Clinical Implications for Occupational Therapy

The interaction between vestibular function and circadian biology means that time sensitive approaches to OT are possible. By timing therapy sessions when vestibular function is most sensitive clinicians may be able to engage more, reduce fatigue and facilitate better motor learning (Smith & Zheng, 2022). Environmental modifications such as controlling light exposure and structuring activities based on patients' circadian profiles may also be helpful in optimising therapy outcomes (Zhou & Hullar, 2019).

Future research should continue to investigate the mechanisms by which circadian modulation of vestibular function works and explore individualised rehabilitation strategies that incorporate chronobiological principles into OT practise. Longitudinal studies of circadian aligned interventions may lead to evidence based guidelines that improve vestibular rehabilitation and patient outcomes (Furman & Balaban, 2018).

## 3. Implications for Occupational Therapy Interventions

The evidence linking circadian rhythms to vestibular function is huge for occupational therapy (OT). Given the time-of-day fluctuations in physiological performance, incorporating chronobiological principles into vestibular rehab may optimise outcomes and improve patient function (Furman & Balaban, 2018). Research shows that cognition and motor performance follow a circadian pattern, with peak performance at specific points in the 24 hour cycle (Smith et al., 2022). Aligning OT strategies with those natural oscillations may enhance engagement, motor learning and adaptive response in people with vestibular dysfunction (Zhou & Hullar, 2019).

Several studies show that people with vestibular dysfunction have diurnal variations in postural stability, with increased instability in the late afternoon and evening (Blask et al., 2019). This is consistent with evidence that vestibular sensitivity is lowest during those times, possibly due to circadian driven changes in cortical excitability, neurotransmitter availability and vestibular compensation mechanisms (Lopez & Blanke, 2021). Research on diurnal fluctuations in balance and vestibulo-ocular reflex (VOR) gain supports the idea that vestibular function follows a circadian rhythm, with peak performance in the morning and early afternoon (Cullen & Taube, 2020).Neurotransmitter fluctuations may contribute to this, as the availability of key neurotransmitters involved in vestibular processing, such as glutamate and GABA, follows a circadian pattern. Increased excitatory activity in the morning and inhibitory activity in the evening may explain why balance and spatial orientation tasks are performed better in the morning (Furman & Balaban, 2018). Functional neuroimaging studies have shown that cortical regions involved in vestibular processing, including the parieto-insular vestibular cortex (PIVC) and superior temporal gyrus, have circadian variations in excitability. Morning is when the brain is more responsive, so patients may do better with OT sessions in the morning (Lopez & Blanke, 2021). Additionally, hormonal influences such as cortisol, which peaks in the morning and declines throughout the day, play a big role in modulating vestibular function. As cortisol has been shown to improve vestibular compensation and postural stability, its natural rhythm may justify morning and early afternoon scheduling of OT (Blask et al., 2019).

Based on these findings, occupational therapists should schedule vestibular rehab sessions in the morning or early afternoon to take advantage of peak vestibular function and cognitive alertness (Smith & Zheng, 2022). Therapies adjusted to these circadian fluctuations may improve patient engagement and participation because of increased alertness, enhance motor learning and adaptive response through optimal neuroplasticity conditions and reduce fatigue related performance decline especially in tasks that require sustained postural control and spatial awareness (Lopez & Blanke, 2021).

Besides session timing, environmental modifications can play a big role in optimizing OT interventions for people with vestibular dysfunction (Furman & Balaban, 2018). Recent research is showing the impact of light on both circadian regulation and vestibular function and we can use this to our advantage (Zhou & Hullar, 2019). Morning light exposure has been linked to improved postural control, increased vestibular reflex response and reduced dizziness (Smith & Zheng, 2022). Light exposure reinforces circadian stability by synchronizing the suprachiasmatic nucleus (SCN) and downstream vestibular pathways (Cullen & Taube, 2020). Occupational therapists can incorporate light therapy protocols and recommend outdoor exposure or artificial bright light in the morning to support vestibular rehabilitation (Lopez & Blanke, 2021).

On the other hand, evening blue light exposure disrupts circadian rhythms and has been linked to increased dizziness, postural instability and impaired spatial orientation in people with vestibular dysfunction (Blask et al., 2019). Patients with vestibular disorders, especially those with vestibular migraine, PPPD or motion sensitivity may benefit from reduced blue light exposure in the hours leading up to sleep (Zhou & Hullar, 2019). Occupational therapists can integrate environmental modifications such as adjusting screen exposure, recommending blue light filters or optimizing bedroom lighting to align with circadian rhythms and reduce symptoms (Smith & Zheng, 2022).

Another important factor in OT interventions is aligning vestibular exercises with circadian rhythms. Research in sensorimotor integration shows that circadian rhythms influence vestibular-motor adaptation and the effectiveness of balance training and gaze stabilization exercises (Lopez & Blanke, 2021). Patients undergoing vestibular habituation therapy (VHT) may show enhanced neuroplasticity and faster adaptation when exercises are done during circadian peaks (Cullen & Taube, 2020). Morning sessions focusing on dynamic balance training and spatial reorientation may yield better outcomes than evening sessions where cortical excitability is reduced (Smith & Zheng, 2022).Incorporating chronotherapeutic principles into OT practice is a bright spot for vestibular rehabilitation (Furman & Balaban, 2018). Future research should look into longitudinal studies of circadian driven rehabilitation schedules to determine the optimal intervention windows (Blask et al., 2019). Personalized chronotherapy approaches, where we tailor the intervention to the individual's circadian profile using actigraphy and biomarkers could lead to more effective and patient centered treatment plans (Zhou & Hullar, 2019). Technology assisted circadian interventions, including wearable devices for monitoring light exposure, sleep quality and vestibular stability may further refine our therapeutic approaches and improve patient outcomes (Smith & Zheng, 2022).

By using chronobiology and vestibular neuroscience we can fine tune our interventions to get the most benefit, reduce symptoms and improve quality of life for people with vestibular dysfunction (Lopez & Blanke, 2021).

## 4. Future Research Directions

So far, research has shown that circadian rhythms may impact vestibular function but more research is needed to fully understand the neurophysiological mechanisms, clinical implications and translational applications in occupational therapy (Blask et al., 2019). Studies have found diurnal fluctuations in postural stability, vestibulo-ocular reflex (VOR) gain and spatial orientation but there are gaps in understanding how these variations impact rehabilitation outcomes in different patient populations (Smith et al., 2022). Future research should aim to determine the specific circadian phases when vestibular function is most stable and the times of vulnerability to postural instability. Also, the interaction between circadian driven changes in neurotransmitter activity, hormonal regulation and vestibular processing need to be explored to develop targeted interventions that optimize rehabilitation timing and enhance therapeutic efficacy (Cullen & Taube, 2020).

A area of future research is to investigate how circadian misalignment, common in individuals with sleep-wake cycle disruption, shift work or neurodegenerative conditions, impacts vestibular processing and compensation mechanisms (Lopez & Blanke, 2021). Since vestibular dysfunction is often associated with conditions like Parkinson's disease, multiple sclerosis and traumatic brain injury (TBI), understanding if circadian desynchronisation worsen balance impairments, spatial disorientation or dizziness could be valuable for tailoring interventions in these populations (Furman & Balaban, 2018). Studies using actigraphy, melatonin profiling and polysomnography may help to determine if circadian phase shifts correlate with changes in vestibular sensitivity so we can have personalized rehabilitation strategies (Zhou & Hullar, 2019).

Longitudinal studies are needed to examine the effect of time dependent occupational therapy interventions on functional outcomes in individuals with vestibular dysfunction (Smith et al., 2022). Current rehabilitation protocols focus on balance retraining and compensatory strategies without considering circadian influences, but emerging evidence suggests that tailoring therapy to individual chronotypes may enhance vestibular compensation and neuroplasticity (Blask et al., 2019). Research should compare morning vs evening vestibular rehabilitation sessions, motor learning, symptom reduction and adaptive postural control (Cullen & Taube, 2020).Another area of research is the role of sleep-wake cycles in vestibular adaptation and neuroplasticity. Sleep disturbances like insomnia, fragmented sleep and sleep apnea are common in individuals with vestibular disorders and poor sleep quality may hinder vestibular compensation and prolong recovery (Lopez & Blanke, 2021). The bidirectional relationship between sleep regulation and vestibular function is not well understood but studies show that sleep deprivation affects sensorimotor integration, equilibrium control and cognitive processing related to spatial orientation (Furman & Balaban, 2018). Experimental research using electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) can further explore how slow-wave sleep and REM sleep contribute to vestibular recalibration and adaptation (Zhou & Hullar, 2019).

Also, since light exposure has been shown to impact vestibular sensitivity and circadian alignment, future studies should look into light-based therapies in vestibular rehabilitation (Smith & Zheng, 2022). Research has shown that morning light exposure might improve postural control and evening blue light exposure might worsen symptoms like dizziness, visual-vestibular conflict and spatial disorientation (Blask et al., 2019). Randomized controlled trials to test light therapy as an adjunct to vestibular rehabilitation or as a standalone treatment could be a new non-invasive way to manage symptoms (Cullen & Taube, 2020).

And there are technological opportunities to explore further. Wearable sensors, mobile health apps and AI-driven algorithms could monitor vestibular stability, circadian rhythms and sleep patterns in real-time and make therapy adjustments based on individual fluctuation in vestibular function (Lopez & Blanke, 2021). Virtual reality (VR) based vestibular rehabilitation integrated with circadian-adaptive protocols could be a new way to optimize balance training and gaze stabilization exercises (Furman & Balaban, 2018).

Personalized chronotherapy approaches incorporating biomarkers of circadian alignment such as melatonin secretion patterns, core body temperature fluctuations and heart rate variability could further refine vestibular rehabilitation strategies (Zhou & Hullar, 2019). Individualized circadian profiles and aligning therapy sessions could produce better outcomes especially for patients with persistent postural-perceptual dizziness (PPPD), vestibular migraine and vestibular hypofunction (Smith et al., 2022). Future research should also look into pharmacological interventions targeting circadian pathways such as timed melatonin supplementation or chronobiotic agents to enhance vestibular adaptation and recovery (Blask et al., 2019).In summary, while the research looks promising, much more research is needed to turn it into evidence-based occupational therapy practice. Future research should focus on finding the optimal timing of therapy, the effect of sleep and light on vestibular processing, using new technologies for personalized treatment and chronotherapeutic approaches for vestibular rehabilitation. By understanding circadian-vestibular interactions better occupational therapists can develop more effective individualized interventions for balance, spatial orientation and overall quality of life for people with vestibular dysfunction (Lopez & Blanke, 2021).

## 5. Conclusion

Integrating circadian considerations into vestibular rehabilitation is a game changer for OT interventions and patient outcomes. Traditional vestibular rehabilitation programs have focused on balance retraining, habituation exercises and compensatory strategies without considering the impact of circadian rhythms on vestibular processing and motor function. But research is emerging that vestibular sensitivity, postural stability and spatial orientation fluctuate over a 24hr cycle due to circadian driven changes in neurotransmitter activity, hormonal regulation and cortical excitability. By timing therapy with a patient's natural physiological rhythms, occupational therapists can enhance motor learning, reduce fatigue and facilitate more effective rehabilitation strategies, ultimately improving functional independence and quality of life.

One of the big implications of incorporating chronobiology into vestibular rehabilitation is time sensitive intervention strategies that adjust therapy based on circadian fluctuations in vestibular function. Research shows vestibular processing efficiency varies throughout the day, peak postural control and vestibulo-ocular reflex (VOR) function often occurs in the morning or early afternoon, while vestibular sensitivity declines in the late afternoon and evening hours. So scheduling OT interventions during peak vestibular function may lead to better patient engagement, better adaptation to balance training exercises and more effective compensation mechanisms for vestibular deficits. Conducting therapy during times of diminished vestibular sensitivity may lead to increased symptom exacerbation, dizziness and delayed motor learning, which further highlights the importance of circadian informed rehabilitation planning. And environmental and behavioral interventions that support circadian stability can further boost vestibular rehabilitation outcomes. Light has been shown to modulate circadian rhythms and vestibular compensation, morning bright light exposure improves postural stability and spatial orientation, while excessive artificial blue light in the evening is linked to vestibular symptoms like dizziness and gaze stability impairment. Occupational therapists can use this to their advantage by incorporating light based interventions, optimizing therapy environments to have natural daylight and educating patients on sleep hygiene that aligns with their circadian rhythms. This may be especially helpful for people with vestibular disorders who have disrupted sleep wake cycles, as poor sleep quality is linked to prolonged vestibular dysfunction, increased fall risk and impaired cognitive processing of spatial awareness.

Additionally personalized chronotherapy approaches may change the game for OT interventions by tailoring the rehab protocols to an individual's unique circadian profile. With advances in wearables, actigraphy and biomarker assessments of circadian rhythms (melatonin secretion patterns and core body temperature fluctuations) clinicians can determine the best time to deliver therapy on a case by case basis. By incorporating these data driven strategies occupational therapists can move towards precision medicine and neuroplasticity, vestibular compensation and overall rehab efficacy.

While circadian science in vestibular rehab is a new concept, the implications go beyond individual patient care to broader clinical and research applications. Future research should establish evidence based guidelines for time sensitive OT interventions, evaluate the long term effects of circadian informed therapy on functional independence and explore interdisciplinary collaborations between chronobiologists, neurologists and rehab specialists to develop new treatment models. Research should also investigate if pharmacological chronotherapy (timing of vestibular suppressant meds or melatonin supplementation) can enhance vestibular adaptation and symptom management.

In conclusion, understanding the impact of circadian rhythms on vestibular function provides a foundation for advancing OT practice and developing new rehab strategies. By incorporating chronobiology into vestibular rehab occupational therapists can time therapy, use light and behavioral interventions and explore personalized chronotherapy approaches that enhance vestibular compensation and neuroplasticity. As research in this field continues to grow it has the potential to change OT interventions and lead to more effective, individualized and patient centered care for individuals with vestibular dysfunction.

## Compliance with ethical standards

*Disclosure of conflict of interest.*

No conflict of interest to be disclosed.

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