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THE ILLUSION OF RECOVERY: IMPLICATIONS OF INCOMPLETE PHYSIOLOGICAL RESTORATION FOLLOWING CIRCADIAN MISALIGNMENT FOR SHIFT WORKER HEALTH

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ABSTRACT

Background: Recovery following circadian disruption is commonly inferred from behavioural indicators such as sleep timing, sleep duration, and subjective improvements in fatigue. However, emerging evidence suggests that physiological restoration may not occur simultaneously with behavioural recovery, potentially creating a period of hidden biological vulnerability with implications for both physical and psychological functioning.

Methods: This Perspective Review synthesises evidence from experimental and observational studies examining recovery following circadian misalignment. Particular emphasis is placed on autonomic regulation, neuroendocrine function, circadian biology, cognitive and psychological outcomes, and allostatic load.

Results: Available evidence indicates that circadian misalignment is associated with persistent autonomic dysregulation, altered neuroendocrine activity, and impaired physiological recovery despite apparent behavioural realignment. Emerging evidence further suggests associations between circadian disruption and impairments in cognitive, executive, and decision-making functions, as well as in emotional regulation and psychological resilience. Collectively, these findings support the possibility that behavioural and physiological recovery occur on different timescales.

Conclusion: This Perspective proposes the Recovery Illusion Framework, a conceptual model describing a state in which behavioural recovery precedes complete physiological restoration following circadian disruption. The framework integrates behavioural, physiological, and psychological dimensions of recovery and proposes that repeated recovery gaps may contribute to cumulative allostatic load and long-term health consequences. Although the framework requires empirical validation, it provides a foundation for future research and may inform more comprehensive approaches to recovery assessment in clinical, occupational, and public health settings.

Keywords: Circadian disruption; Shift work; Recovery Illusion Framework; Allostatic load; Heart rate variability; Occupational health.

INTRODUCTION

Shift work is an essential component of modern societies, supporting healthcare services, emergency response systems, transportation networks, manufacturing industries, and other sectors that require continuous operation beyond conventional daytime hours (Boudreau et al., 2013). It has been estimated that approximately

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15%–30% of the adult workforce in industrialised countries engages in shift work (Boudreau et al., 2013). Although indispensable to economic productivity and service delivery, shift work has been associated with adverse health outcomes, including sleep disturbances, impaired cognitive performance, cardiovascular disease, metabolic syndrome, and type 2 diabetes mellitus (Boudreau et al., 2013; Grimaldi et al., 2016; Boivin et al., 2022). Emerging evidence further suggests that chronic circadian disruption may adversely influence attention, memory, decision-making, psychological well-being, and resilience, particularly among healthcare professionals working rotating or permanent night shifts (Lin et al., 2024; Moosavi et al., 2025; Park et al., 2025).

The physiological basis of these associations lies in the circadian timing system. Human biological processes are organised around endogenous circadian rhythms that regulate sleep-wake cycles, hormone secretion, cardiovascular activity, metabolism, and cognitive function (Czeisler & Gooley, 2007). These rhythms are coordinated by the suprachiasmatic nucleus (SCN) of the hypothalamus, which acts as the master pacemaker to synchronise internal biological time with environmental light-dark cycles (Welsh et al., 2010; Dibner et al., 2010). Under normal conditions, this system promotes wakefulness during daylight hours and sleep during the biological night (Dibner et al., 2010).

Circadian misalignment occurs when behavioural schedules become desynchronised from endogenous circadian rhythms, functionally defined as an abnormal phase angle or offset between sleep-wake cycles and clock-regulated internal physiology (Baron & Reid, 2014). Night-shift workers represent one of the most common examples of this phenomenon because they remain awake and active during the biological night while attempting to sleep during the day (Boudreau et al., 2013). Previous studies have demonstrated that circadian adaptation to night-shift schedules is often incomplete, resulting in disturbances in sleep, mood, performance, and autonomic regulation (Boudreau et al., 2013).

Current approaches to recovery following shift work are largely based on behavioural indicators. Workers are generally considered recovered when they return to a conventional sleep schedule, obtain adequate sleep duration, or report subjective improvements in fatigue (Caruso, 2014). Consequently, occupational health recommendations frequently emphasise rest periods, recovery days, and sleep hygiene interventions as primary mechanisms for restoring health following circadian disruption (Caruso, 2014).

Recovery also has an important psychological dimension. In occupational settings, individuals commonly evaluate their readiness to resume work based on subjective improvements in fatigue, alertness, and perceived cognitive functioning (Caruso, 2014; Kalkanis et al., 2023). However, emerging evidence suggests that psychological perceived recovery may not always correspond with complete physiological restoration (Grimaldi et al., 2016; Kalkanis et al., 2023). Consequently, workers may perceive themselves as fully recovered; at the same time, residual physiological dysregulation could continue to influence attention, executive functioning, decision-making, and emotional regulation, potentially in-

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creasing vulnerability to occupational errors and cumulative psychological stress (Lin et al., 2024; Moosavi et al., 2025; Gao et al., 2026).

However, an important question remains insufficiently explored: does behavioural recovery necessarily indicate complete physiological and psychological recovery?

The prevailing assumption is that restoring normal sleep timing restores physiological homeostasis. However, emerging evidence suggests that the autonomic and neuroendocrine systems may remain altered even after behavioural realignment (Grimaldi et al., 2016). In a controlled laboratory study, Grimaldi et al. (2016) demonstrated that sleep restriction combined with circadian misalignment adversely affected autonomic function in healthy young adults. Importantly, several autonomic abnormalities persisted during re-aligned nights following the period of circadian disruption. These findings raise the possibility that physiological recovery may occur more slowly than behavioural recovery.

This distinction may have important implications for shift worker health. If the autonomic and neuroendocrine systems remain dysregulated after sleep schedules are restored, repeated cycles of circadian disruption and apparent recovery could cumulatively strain the physiology (McEwen, 1998). Such a mechanism may help explain why shift workers continue to experience elevated risks of cardiovascular and metabolic disease despite periods of rest and schedule realignment (Boudreau et al., 2013; Reynolds et al., 2017).

The concept of allostatic load provides a useful public health framework for understanding this possibility. Allostatic load refers to the cumulative biological "wear and tear" imposed on body systems by chronic or repeated exposure to physiological stressors (McEwen, 1998). Applied to shift work, recurrent circadian disruption may result in repeated, multi-systemic activation of stress-response pathways (Juster et al., 2010). If recovery remains incomplete between shifts, this biological burden may accumulate over time, accelerating the transition from acute physiological strain to long-term chronic disease (McEwen, 1998; Juster et al., 2010).

This Perspective Review examines evidence supporting the hypothesis that physiological restoration may lag behind behavioural recovery following circadian misalignment. Drawing upon evidence from circadian biology, autonomic physiology, occupational psychology, and psychophysiological research, the review proposes the Recovery Illusion Framework as a conceptual model describing a state in which behavioural and perceived recovery may precede complete physiological restoration. The review further explores how this framework may improve understanding of shift-worker health, cognitive functioning, occupational performance, and psychological well-being while informing occupational health policies, family medicine, and future psychological research.

To introduce the central concept of this review, the proposed Recovery Illusion Framework is presented in Figure 1. The framework illustrates the hypothesised progression from circadian misalignment to perceived behavioural recovery, incomplete physiological restoration,

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the Recovery Illusion, and the potential accumulation of allostatic load.

Figure 1. Overview of the Proposed Recovery Illusion Framework.

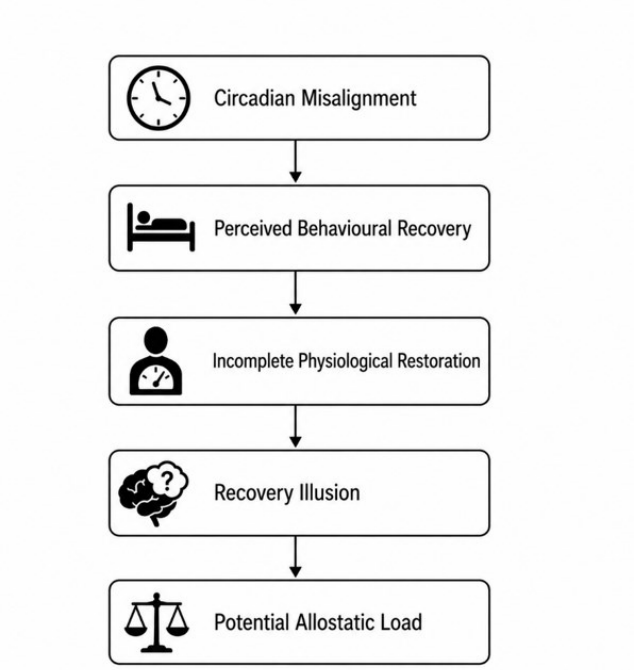

Figure 1 represents Following circadian misalignment, individuals may perceive themselves as recovered based on behavioural indicators such as restored sleep schedules and reduced subjective fatigue (Caruso, 2014; Kalkanis et al., 2023). However, physiological restoration may remain incomplete despite apparent behavioural recovery (Grimaldi et al., 2016). This proposed mismatch forms the basis of the Recovery Illusion Framework, a conceptual model suggesting that repeated cycles of circadian disruption and incomplete physiological restoration may contribute to the potential accumulation of allostatic load over time (McEwen, 1998; Juster et al., 2010).

2. PHYSIOLOGICAL BASIS OF RECOVERY

Recovery during sleep is a complex physiological process involving coordinated autonomic, neuroendocrine, metabolic, and cardiovascular regulation. While sleep is commonly viewed as a period of passive rest, it is increasingly recognised as an active biological state during which essential restorative functions occur (Czeisler & Gooley, 2007). The restoration of physiological homeostasis depends not only on obtaining adequate sleep duration but also on the successful execution of regulatory processes that promote cardiovascular recovery, hormonal regulation, immune function, and metabolic stability (Czeisler & Gooley, 2007; Dibner et al., 2010).

2.1. Autonomic Recovery During Sleep

One of the most important restorative functions of sleep involves the autonomic nervous system. Under normal conditions, sleep is accompanied by a shift from sympathetic dominance towards parasympathetic predominance, particularly during non-rapid eye movement (NREM) sleep (Somers et al., 1993). This transition is characterised by reductions in heart rate, blood pressure, and sympathetic nervous system activity, accompanied by increases in vagally mediated heart rate variability (HRV), a recognised marker of autonomic recovery and cardiovascular health (Somers et al., 1993; Tobaldini et al., 2013).

Among sleep stages, slow-wave sleep (SWS) is particularly important for cardiovascular recovery because it is associated with the highest levels of parasympathetic activity and the lowest levels of sympathetic activation (Somers et al., 1993). During this period, the cardiovascular system experiences reduced physiological demand, facilitating recovery from daytime stressors and maintaining cardiovascular homeostasis (Somers et al., 1993; Tobaldini et al., 2013).

Heart rate variability has emerged as one of the most widely used indicators of autonomic function during sleep (Tobaldini et al., 2013). Higher vagally mediated HRV generally reflects healthy autonomic regulation, whereas reductions

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in HRV are associated with sympathetic predominance, cardiovascular risk, and impaired physiological recovery (Tobaldini et al., 2013). Consequently, HRV provides a useful physiological marker for assessing whether restorative processes have occurred during sleep (Tobaldini et al., 2013). Because autonomic regulation supports optimal cognitive and emotional functioning, incomplete autonomic recovery may also affect attention, executive functioning, and behavioural performance during subsequent wakefulness, although these relationships require further investigation (Boivin et al., 2022; Moosavi et al., 2025).

2.2. Neuroendocrine Restoration During Sleep

Sleep also plays a critical role in regulating neuroendocrine function. The circadian system coordinates the secretion of several hormones involved in metabolism, cardiovascular regulation, immune function, and stress responses (Dibner et al., 2010). Under normal physiological conditions, sleep contributes to the regulation of cortisol, melatonin, growth hormone, and catecholamines, including norepinephrine (Dibner et al., 2010; Van Cauter et al., 2007).

Norepinephrine is particularly relevant to the present review because it reflects sympathetic nervous system activation. During restorative sleep, sympathetic activity generally declines, allowing physiological systems to transition from heightened alertness to recovery and repair (Somers et al., 1993; Van Cauter et al., 2007). Persistent elevations in norepinephrine may therefore indicate incomplete recovery and continued physiological stress (Van Cauter et al., 2007).

Similarly, cortisol follows a circadian rhythm that helps regulate energy balance, cardiovascular function, and stress adaptation. Disruption of normal sleep and circadian timing may alter cortisol secretion patterns, potentially contributing to metabolic and cardiovascular dysfunction (Dibner et al., 2010; Van Cauter et al., 2007).

2.3. Sleep Architecture and Physiological Restoration

The restorative value of sleep depends not only on its duration but also on its architecture. Sleep comprises distinct stages, each contributing differently to physiological and cognitive recovery (Czeisler & Gooley, 2007).

NREM sleep, particularly slow-wave sleep, is associated with cardiovascular restoration, autonomic recovery, metabolic regulation, and immune function (Somers et al., 1993; Tobaldini et al., 2013). Rapid eye movement (REM) sleep contributes to emotional processing, learning, memory consolidation, and cognitive performance (Czeisler & Gooley, 2007). Emerging evidence further suggests that disturbances in sleep quality and circadian alignment may be associated with impaired memory, reduced cognitive functioning, and diminished psychological resilience among shift-working populations (Lin et al., 2024; Moosavi et al., 2025; Park et al., 2025). Together, these stages support the maintenance of both physical and psychological health (Czeisler & Gooley, 2007).

Consequently, recovery should be viewed as a multidimensional process involving both be-

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haviour and physiological components. Sleeping for an adequate number of hours may not necessarily indicate that autonomic and neuroendocrine restoration have been fully achieved. Assessing recovery solely through behavioural indicators may coordinated autonomic and neuroendocrine retherefore overlook important physiological processes that continue beyond the restoration of sleep timing.

To summarise, successful physiological recovery requires gulation during sleep, particularly during NREM stages where cardiovascular restoration is most pronounced. Understanding these normal recovery mechanisms provides an essential foundation for evaluating evidence that recovery may remain incomplete following circadian misalignment. These recovery mechanisms also provide a physiological basis for exploring how incomplete biological restoration may influence cognitive functioning, emotional regulation, and psychological well-being, themes that are developed in the proposed Recovery Illusion Framework.

3. EVIDENCE FOR INCOMPLETE PHYSIOLOGICAL RECOVERY FOLLOWING CIRCADIAN MISALIGNMENT

The physiological processes described in the previous chapter provide the basis for evaluating whether recovery following circadian misalignment is complete. This chapter reviews evidence from experimental and observational studies on autonomic and neuroendocrine recovery, as well as emerging evidence on cognitive and psychological outcomes following circadian disruption. Collectively, these findings suggest that perceived behavioural recovery and underlying physiological restoration may not occur simultaneously, providing the scientific foundation for the proposed Recovery Illusion Framework.

3.1 Persistent Autonomic Dysfunction Following Circadian Misalignment

Despite the well-established restorative functions of sleep, emerging evidence suggests that physiological recovery may not occur immediately following circadian realignment. While behavioural indicators such as sleep timing and duration may return to baseline, autonomic and neuroendocrine systems may remain partially dy-

Table 1. Major physiological processes involved in normal sleep-related recovery.

System	Recovery Function During Sleep	Key Indicators	References
Autonomic	Parasympathetic predominance and sympathetic withdrawal	Heart rate variability (HRV)	Somers et al. (1993); Tobaldini et al. (2013)
Cardiovascular	Reduced cardiovascular workload; blood pressure dipping	Blood pressure, heart rate	Somers et al. (1993)
Neuroendocrine	Hormonal regulation and stress pathway recovery	Norepinephrine, cortisol	Dibner et al. (2010); Van Cauter et al. (2007)
Metabolic	Energy regulation and glucose homeostasis	Insulin sensitivity	Dibner et al. (2010); Van Cauter et al. (2007)
Immune	Cellular repair and systemic immune regulation	Inflammatory markers	Czeisler & Gooley (2007)

HRV, heart rate variability; NREM, non-rapid eye movement; REM, rapid eye movement.

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sregulated (Boudreau et al., 2013). This distinction is critical because recovery is frequently inferred in clinical and field settings from superficial behavioural outcomes rather than objective physiological markers (Grimaldi et al., 2016).

The autonomic nervous system is a primary mediator of cardiovascular recovery during sleep. Consequently, objective measures of autonomic function provide valuable insight into whether physiological restoration has been fully achieved following circadian disruption.

Grimaldi et al. (2016) investigated the combined effects of sleep restriction and circadian misalignment on autonomic function in healthy young adults. Participants were exposed to experimental protocols involving either circadian alignment or misalignment under restricted sleep conditions. Autonomic recovery and tone were subsequently assessed during scheduled sleep periods.

The study demonstrated that the combination of sleep restriction and circadian misalignment significantly impaired autonomic regulation compared with sleep restriction alone(Grimaldi et al., 2016). Notably, individuals exposed to circadian misalignment exhibited pronounced reductions in vagally mediated heart rate variability (HRV) and concurrent elevations in nocturnal heart rate during the misaligned sleep periods (Grimaldi et al., 2016). These findings suggest that the simple presence or restoration of a sleep window does not automatically guarantee autonomic homeostasis if that window is misaligned with the endogenous clock (Grimaldi et al., 2016).

Heart rate variability is widely recognised as a non-invasive marker of autonomic balance, sympathovagal fluctuation, and overall cardiovascular health (Tobaldini et al., 2013). Reduced vagally mediated HRV generally reflects diminished parasympathetic (vagal) activity and persistent sympathetic predominance (Tobaldini et al., 2013). Consequently, the persistence of these alterations during sleep highlights that autonomic recovery may lag behavioural stabilisation, creating a vulnerable window during which cardiovascular regulatory systems remain uncompensated (Grimaldi et al., 2016; Tobaldini et al., 2013).

Persistent autonomic dysregulation may also have functional implications beyond cardiovascular regulation. Because vagally mediated autonomic activity contributes to cognitive flexibility, attentional control, and adaptive behavioural responses, incomplete autonomic recovery may influence cognitive performance during subsequent wakefulness. Although direct evidence linking post-shift autonomic recovery to cognitive outcomes remains limited, recent studies suggest that circadian disruption is associated with impaired cognitive functioning and decision-making among shift workers (Boivin et al., 2022; Moosavi et al., 2025; Gao et al., 2026).

(Table 2, p. 85)

3.2. Persistent Neuroendocrine Activation Following Circadian Misalignment

In addition to autonomic dysfunction, circadian misalignment may adversely affect neuroendocrine regulation. The circadian timing system coordinates the secretion and temporal orga-

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Table 2. Key evidence relevant to physiological recovery following circadian misalignment.

Study	Population	Exposure	Recovery Marker	Principal Finding
Grimaldi et al. (2016)	Healthy young adults	Sleep restriction + circadian misalign-ment	HRV	Persistent reduction in vagally mediated HRV during re-aligned sleep
Grimaldi et al. (2016)	Healthy young adults	Sleep restriction + circadian misalign-ment	Nocturnal urinary norepinephrine excre-tion	Elevated nocturnal norepinephrine du-ring circadian misa-lignment
Boudreau et al. (2013)	Night-shift workers	Night-shift adaptation	Autonomic modula-tion	Incomplete circadian adaptation observed

HRV = heart rate variability.

nisation of numerous hormones involved in metabolism, cardiovascular regulation, immune function, and stress responses (Dibner et al., 2010). Consequently, disruption of normal circadian timing can alter neuroendocrine homeostasis and affect physiological recovery processes.

Among the neuroendocrine markers investigated in circadian research, norepinephrine is particularly relevant because it serves as an indicator of sympathetic nervous system activity and physiological stress. Under normal physiological conditions, the autonomic and neuroendocrine systems exhibit coordinated circadian rhythms that contribute to the regulation of cardiovascular and metabolic function (Dibner et al., 2010). Disruption of this temporal organisation may therefore have consequences that extend beyond sleep disturbance alone.

Experimental evidence supports this possibility. In a controlled laboratory study involving healthy young adults, Grimaldi et al. (2016) examined the effects of sleep restriction combined with circadian misalignment on autonomic and neuroendocrine function. The investigators reported a significant increase in nocturnal urinary norepinephrine excretion during circadian misalignment compared with circadian alignment. These findings indicate that circadian misalignment induces a measurable neuroendocrine stress response beyond the effects of sleep restriction alone.

The observed increase in norepinephrine is noteworthy because sympathetic activation represents a key component of the physiological stress response. Persistent activation of stress-response pathways has been implicated in the development of adverse cardiovascular and metabolic outcomes (McEwen, 1998; Juster et al., 2010). Consequently, recurrent neuroendocrine activation may represent one pathway through which circadian disruption contributes to long-term disease risk.

From a recovery perspective, these findings raise an important question. If circadian misalignment can produce significant neuroendocrine activation (Grimaldi et al., 2016), how rapidly do these systems return to baseline once normal sleep schedules are restored? Although autonomic impairments have been documented during re-aligned sleep following circadian misalignment (Grimaldi et al., 2016), the recovery trajectory of neuroendocrine markers following

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behavioural realignment remains incompletely characterised.

This uncertainty is particularly relevant to shift-working populations. Recovery is frequently assumed once workers return to conventional sleep schedules or complete designated rest periods (Caruso, 2014; Kalkanis et al., 2023). However, if neuroendocrine restoration occurs more slowly than behavioural adaptation, periods commonly regarded as recovery may not represent complete physiological restoration (Grimaldi et al., 2016; Boivin et al., 2022). Persistent neuroendocrine activation may also have implications for cognitive performance, psychological stress, and behavioural adaptation, although the extent to which these outcomes persist following behavioural realignment remains insufficiently understood (Boivin et al., 2022; Lin et al., 2024). Taken together, the available evidence suggests that circadian misalignment influences not only autonomic regulation but also neuroendocrine function (Dibner et al., 2010; Grimaldi et al., 2016). While additional research is required to determine the precise duration of neuroendocrine recovery following circadian disruption, existing findings support the need for a broader understanding of recovery that extends beyond sleep timing and subjective perceptions of rest.

3.3. Behavioural Recovery Versus Physiological Recovery

Recovery following circadian disruption is commonly assessed using behavioural indicators, including the restoration of normal sleep schedules, adequate sleep duration, and subjective improvements in fatigue (Caruso, 2014). In occupational health settings, workers are often considered recovered once they have completed designated rest periods and resumed conventional sleep–wake patterns (Caruso, 2014). However, the evidence reviewed in the preceding sections suggests that behavioural recovery may not necessarily coincide with physiological restoration.

The distinction between behavioural and physiological recovery is important because they represent different biological processes. Behavioural recovery refers to observable outcomes such as sleeping during the night, obtaining sufficient sleep duration, and reporting reduced tiredness. Physiological recovery, in contrast, involves the restoration of autonomic, neuroendocrine, cardiovascular, metabolic, and other regulatory systems that contribute to homeostasis (Czeisler & Gooley, 2007; Dibner et al., 2010).

Evidence from experimental studies suggests that these processes may occur on different timelines. Grimaldi et al. (2016) demonstrated that autonomic alterations persisted during re-aligned sleep following circadian misalignment, despite the restoration of conventional sleep schedules. These findings indicate that the return of normal sleep timing does not necessarily imply immediate restoration of autonomic function.

The available evidence also suggests that circadian disruption activates broader physiological stress pathways. Increased nocturnal urinary norepinephrine during circadian misalignment indicates a measurable neuroendocrine response to circadian disruption (Grimaldi et al., 2016). However, while persistent autonomic impairment has been documented during re-aligned sleep, the

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extent to which neuroendocrine markers remain altered following behavioural realignment remains incompletely characterised. Further research is therefore required to determine whether autonomic and neuroendocrine systems recover at similar rates following circadian disruption.

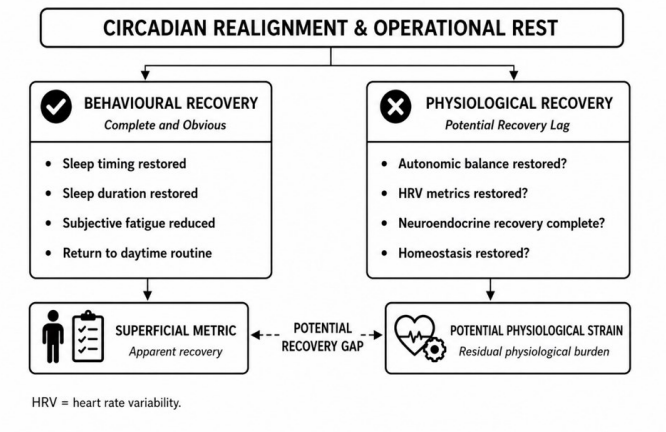
This distinction may help explain why recovery following shift work is often more complex than behavioural indicators alone suggest. Workers may report feeling rested and appear behaviourally recovered while underlying physiological systems continue to undergo restoration. This mismatch between perceived recovery and physiological status may have important implications for attention, executive functioning, emotional regulation, and occupational decision-making, particularly among individuals repeatedly exposed to rotating or night-shift schedules (Lin et al., 2024; Moosavi et al., 2025; Gao et al., 2026). Consequently, assessments based solely on sleep duration or sleep timing may underestimate the biological consequences of circadian disruption.

The divergence between behavioural and physiological recovery also has important implications for long-term health risk. If physiological systems recover more slowly than behavioural indicators suggest, repeated episodes of circadian disruption may occur before complete physiological restoration has been achieved (Kalkanis et al., 2023; Grimaldi et al., 2016). Over time, this mismatch may increase cumulative physiological burden while simultaneously influencing behavioural adaptation and psychological resilience, providing further support for the proposed Recovery Illusion Framework (Park et al., 2025). Such a pattern may contribute to the accumulation of physiological strain over time, particularly among individuals exposed to rotating shift schedules or chronic night work, consistent with the concept of allostatic load (McEwen, 1998; Juster et al., 2010).

Although further research is required to determine the precise duration and extent of physiological recovery following circadian misalignment, the available evidence supports a broader conceptualisation of recovery. Rather than viewing recovery as a single event achieved once sleep schedules normalise, recovery may be better understood as a gradual physiological process involving multiple biological systems operating on different timescales.

The distinction between behavioural and physiological recovery following circadian misalignment is illustrated in Figure 2.

Figure 2. Behavioural Recovery Versus Physiological Recovery Following Circadian Misalignment.



Behavioural indicators of recovery, including restoration of sleep timing, sleep duration, and subjective reductions in fatigue, may return follo-

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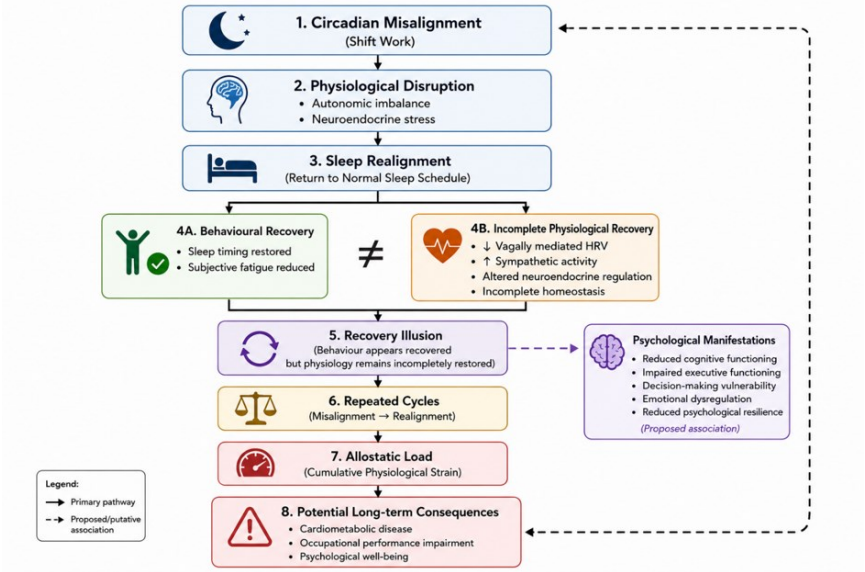
wing circadian realignment (Caruso, 2014; Kalkanis et al., 2023). However, evidence suggests that physiological recovery may occur on a different timescale than behavioural recovery (Grimaldi et al., 2016; Boivin et al., 2022). While autonomic impairments have been documented during re-aligned sleep following circadian misalignment, the extent and duration of neuroendocrine recovery remain incompletely characterised (Grimaldi et al., 2016). This mismatch may also have downstream implications for cognitive functioning, decision-making, emotional regulation, and occupational performance, although further empirical validation is required (Lin et al., 2024; Moosavi et al., 2025; Gao et al., 2026). This divergence may create a potential recovery gap between apparent behavioural recovery and complete physiological restoration, with repeated exposure potentially contributing to cumulative physiological burden over time, consistent with the concept of allostatic load (McEwen, 1998; Juster et al., 2010).

4. THE RECOVERY ILLUSION FRAMEWORK

The evidence presented in the preceding chapters suggests that recovery following circadian misalignment may be more complex than traditionally assumed. Current approaches to assessing recovery in both clinical practice and occupational health primarily rely on behavioural indicators, including the restoration of conventional sleep schedules, adequate sleep duration, and subjective improvements in fatigue (Caruso, 2014; Kalkanis et al., 2023). While these measures are practical and clinically useful, they may not fully reflect the recovery status of the underlying physiological systems affected by circadian disruption (Grimaldi et al., 2016; Boivin et al., 2022).

The conceptual relationships underpinning the proposed Recovery Illusion Framework are summarised in Figure 3. Integrating evidence from circadian biology, sleep physiology, occupational health, and emerging psychological research, the framework illustrates how behavioural recovery

Figure 3. The Recovery Illusion Framework.



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and physiological restoration may occur on different timescales following circadian misalignment.

Figure 3 represents the proposed Recovery Illusion Framework illustrates the conceptual sequence through which circadian misalignment may lead to apparent behavioural recovery despite incomplete physiological restoration. It proposes that repeated cycles of circadian disruption and behavioural realignment may contribute to cumulative physiological strain through mechanisms consistent with allostatic load. The framework also highlights potential psychological manifestations of incomplete physiological recovery, including altered cognitive, executive, and decision-making functions, as well as emotional regulation and psychological resilience. Importantly, the framework represents a conceptual synthesis of the current evidence rather than an established biological pathway and is intended to guide future empirical investigation.

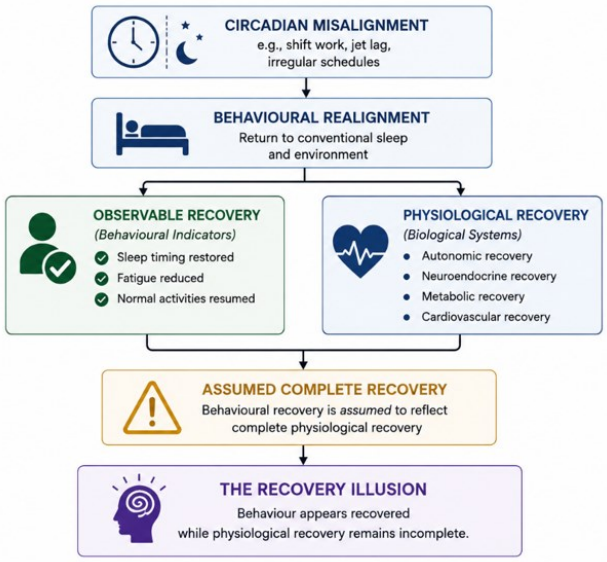
The individual components of the framework and the evidence supporting each stage are discussed in the following sections.

4.1. Conceptual Basis of the Recovery Illusion

The evidence reviewed throughout this Perspective suggests that recovery following circadian misalignment may involve behavioural and physiological processes that recover on different timescales (Grimaldi et al., 2016; Boivin et al., 2022). While behavioural indicators such as restored sleep timing, adequate sleep duration, and reduced subjective fatigue may indicate apparent recovery (Caruso, 2014; Kalkanis et al., 2023), autonomic, neuroendocrine, metabolic, and cardiovascular systems may continue to undergo physiological restoration (Dibner et al., 2010; Van Cauter et al., 2007). This divergence between perceived behavioural recovery and underlying physiological restoration forms the conceptual basis of the proposed Recovery Illusion Framework.

The framework integrates evidence from circadian biology, sleep physiology, occupational health, and emerging psychological research to conceptualise recovery as a multidimensional process rather than a single behavioural event.

Figure 4. Conceptual Basis of the Recovery Illusion Framework.



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The conceptual relationships underpinning the framework are illustrated in Figure 4.

Following circadian misalignment, behavioural recovery is commonly inferred from observable indicators such as restored sleep timing, reduced fatigue, and the resumption of normal daily activities (Caruso, 2014; Kalkanis et al., 2023). However, physiological recovery may continue beyond behavioural realignment as autonomic, neuroendocrine, metabolic, and cardiovascular systems undergo ongoing restoration (Dibner et al., 2010; Van Cauter et al., 2007; Grimaldi et al., 2016; Boivin et al., 2022). The framework proposes that assuming behavioural recovery reflects complete physiological recovery gives rise to the Recovery Illusion, whereby apparent recovery masks incomplete physiological restoration.

The framework presented in Figure 4 represents a conceptual synthesis of the current evidence and is intended to guide future empirical investigation rather than depict an established biological pathway.

The proposed framework also suggests that incomplete physiological recovery may have important psychological implications. Persistent physiological dysregulation following circadian disruption may influence cognitive functioning, executive functioning, decision-making, emotional regulation, and psychological resilience, particularly among individuals repeatedly exposed to rotating or permanent night-shift schedules (Lin et al., 2024; Moosavi et al., 2025; Park et al., 2025; Gao et al., 2026). These psychological dimensions complement the physiological components of the framework and are further explored in the following section.

4.2. Behavioural Recovery Versus Physiological Recovery

Behavioural recovery is typically assessed using observable or self-reported indicators, including restored sleep timing, adequate sleep duration, reduced subjective fatigue, and the resumption of normal daily activities (Caruso, 2014; Kalkanis et al., 2023). These measures are practical and widely used in clinical and occupational settings to evaluate recovery following shift work (Caruso, 2014; Boivin et al., 2022). However, they primarily reflect perceived recovery rather than the restoration of the underlying physiological systems affected by circadian disruption (Grimaldi et al., 2016; Boivin et al., 2022).

In contrast, physiological recovery involves the restoration of autonomic, neuroendocrine, metabolic, and cardiovascular function following circadian misalignment (Dibner et al., 2010; Van Cauter et al., 2007; Boivin et al., 2022). Experimental evidence suggests that these biological systems may recover more slowly than behavioural indicators, with autonomic alterations persisting despite behavioural realignment (Grimaldi et al., 2016). Consequently, behavioural recovery may precede complete physiological restoration, creating a temporary mismatch between perceived recovery and underlying biological status (Boivin et al., 2022; Grimaldi et al., 2016).

This distinction also has important psychological implications. Individuals who report feeling rested may perceive themselves as ready to resume cognitively demanding tasks following circadian realignment. However, if physiological recovery remains incomplete, perceived readiness

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may not accurately reflect underlying biological recovery (Grimaldi et al., 2016; Boivin et al., 2022). Emerging evidence suggests that circadian disruption is associated with impaired cognitive functioning, executive functioning, decision-making, emotional regulation, and psychological resilience, particularly among individuals repeatedly exposed to rotating or permanent night-shift schedules (Boivin et al., 2022; Lin et al., 2024; Moosavi et al., 2025; Park et al., 2025; Gao et al., 2026).

Within the proposed Recovery Illusion Framework, behavioural recovery should therefore not be considered synonymous with complete physiological recovery. Rather, the divergence between perceived recovery and biological restoration provides a plausible explanation for how individuals may appear functionally recovered while remaining vulnerable to persistent physiological strain and its associated cognitive and psychological consequences. Further research integrating objective physiological biomarkers with cognitive and psychological assessments is required to determine the duration and clinical significance of this proposed recovery gap.

4.3. From the Recovery Illusion to Allostatic Load

The Recovery Illusion Framework proposes that incomplete physiological recovery may become clinically relevant when circadian disruption recurs over time. Individuals may resume normal activities following behavioural recovery while autonomic, neuroendocrine, metabolic, and cardiovascular systems continue to undergo physiological restoration (Dibner et al., 2010; Van Cauter et al., 2007; Grimaldi et al., 2016). Repeated episodes of circadian disruption before complete physiological recovery may therefore result in successive recovery gaps (Boivin et al., 2022; Grimaldi et al., 2016).

This concept is consistent with the Allostatic Load Model, which describes the cumulative biological burden associated with repeated activation of physiological stress-response systems (McEwen, 1998; Juster et al., 2010). If physiological restoration remains incomplete between successive episodes of circadian disruption, cumulative physiological strain may develop over time, potentially increasing susceptibility to cardiometabolic disease (McEwen, 1998; Juster et al., 2010; Reynolds et al., 2017).

This pathway remains conceptual and requires longitudinal validation to determine whether repeated recovery gaps contribute to progressive allostatic load and long-term health outcomes.

4.4. Psychological and Clinical Significance of the Recovery Illusion Framework

Within the proposed framework, behavioural recovery may mask persistent physiological dysregulation when recovery is assessed primarily using subjective fatigue, sleep timing, or perceived readiness to resume work (Caruso, 2014; Kalkanis et al., 2023). Consequently, the biological burden associated with recurrent circadian disruption may be underestimated.

The proposed framework may also assist occupational psychologists, clinical psychologists, and other mental health professionals in interpreting persistent cognitive or emotional symptoms among individuals exposed to recurrent circadian disruption, even when behavioural indicators sug-

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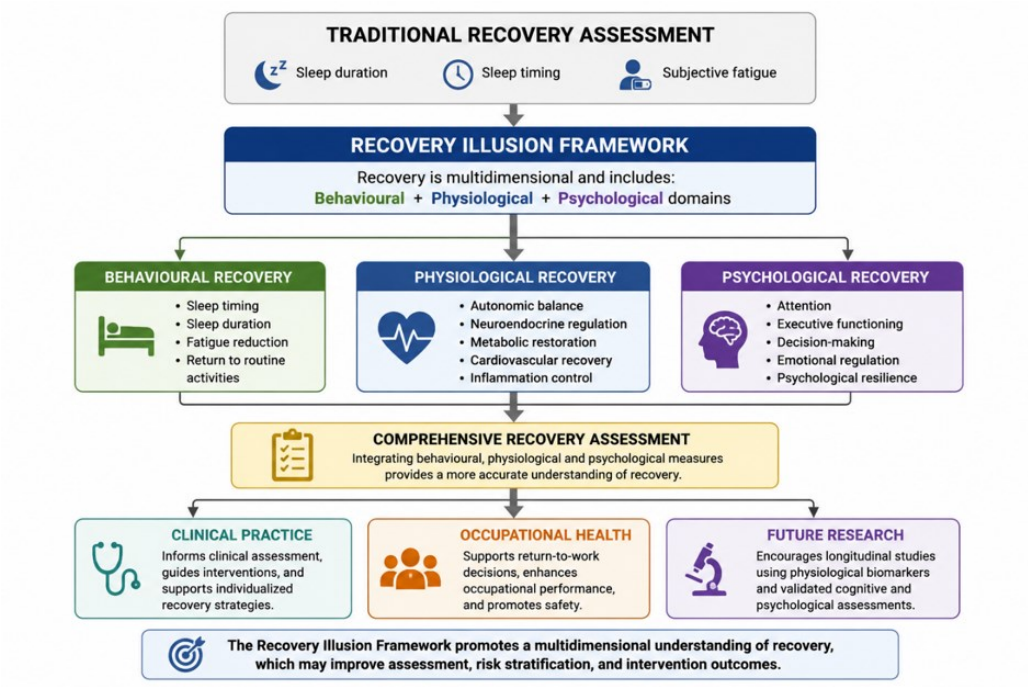
Figure 5. Translational Implications of the Recovery Illusion Framework.



gest adequate recovery.

The broader implications of the proposed framework are illustrated in Figure 5, which emphasises recovery as a multidimensional process integrating behavioural, physiological, and psychological domains.

Figure. 5 represents the Recovery Illusion Framework extends conventional behavioural assessment by incorporating physiological and psychological dimensions of recovery. This multidimensional approach highlights potential applications in clinical assessment, occupational health evaluation, and future research by integrating objective physiological biomarkers with validated cognitive and psychological measures.

The Recovery Illusion Framework provides a conceptual basis for re-evaluating recovery assessment following circadian disruption. Future longitudinal studies integrating physiological biomarkers with cognitive and psychological assessments will be essential to determine the duration and clinical significance of recovery gaps and to evaluate whether multidimensional recovery assessment improves clinical decision-making, occupational health practice, and preventive interventions.

5. IMPLICATIONS FOR SHIFT WORKER HEALTH

The Recovery Illusion Framework provides a conceptual perspective for understanding why adverse health outcomes associated with shift work may persist despite scheduled rest periods and apparent behavioural recovery. Conventional assessments of recovery primarily rely on behavioural indicators, including sleep duration, sleep timing, and subjective improvements in fatigue (Caruso, 2014; Kalkanis et al., 2023). However, the evidence reviewed throughout this perspective suggests that physiological restoration may occur on a different timescale from behavioural

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recovery (Grimaldi et al., 2016; Boivin et al., 2022). Consequently, repeated exposure to circadian disruption before complete physiological restoration may contribute to cumulative biological burden and increased vulnerability to long-term health consequences (McEwen, 1998; Juster et al., 2010; Grimaldi et al., 2016). The following sections discuss the potential implications of the proposed framework for cardiometabolic health, clinical practice, occupational health, and future research.

5.1. Cardiometabolic Consequences of Repeated Recovery Gaps

Cardiovascular and metabolic disorders are among the most consistently reported adverse health outcomes associated with shift work and circadian disruption (Boudreau et al., 2013; Reynolds et al., 2017). While several biological mechanisms have been proposed, the Recovery Illusion Framework suggests that repeated periods of incomplete physiological restoration may represent an additional pathway contributing to cumulative cardiometabolic risk.

Experimental evidence indicates that circadian misalignment may impair autonomic, neuroendocrine, and metabolic recovery despite apparent behavioural realignment (Grimaldi et al., 2016; Van Cauter et al., 2007; Dibner et al., 2010). Repeated exposure to circadian disruption before complete physiological restoration may therefore increase cumulative physiological burden over time, consistent with the concept of allostatic load (McEwen, 1998; Juster et al., 2010).

The Recovery Illusion Framework does not propose that circadian disruption alone causes cardiometabolic disease. Rather, it suggests that incomplete physiological restoration may represent an under-recognised mechanism contributing to long-term cardiovascular and metabolic vulnerability. Further longitudinal studies are needed to determine whether repeated recovery gaps influence disease risk among shift-working populations.

5.2. Clinical and Occupational Implications

The Recovery Illusion Framework suggests that recovery following circadian disruption may be more complex than conventional behavioural indicators alone imply. Although sleep duration, sleep timing, and subjective fatigue remain important components of clinical assessment, they may not fully reflect ongoing physiological recovery (Caruso, 2014; Grimaldi et al., 2016; Boivin et al., 2022).

For clinicians managing shift-working populations, the framework highlights the importance of considering recovery as a multidimensional process. Family physicians, occupational physicians, and multidisciplinary occupational health teams may benefit from recognising that apparent behavioural recovery does not necessarily indicate complete physiological restoration. This perspective may be particularly relevant when evaluating workers with persistent fatigue, reduced concentration, impaired decision-making, or recurrent cardiometabolic risk factors despite apparently adequate recovery (Lin et al., 2024; Moosavi et al., 2025; Reynolds et al., 2017).

The proposed framework also supports continued efforts to optimise fatigue-management programmes, ergonomic shift scheduling, and pre-

ventive occupational health strategies. Future studies should determine whether incorporating objective physiological biomarkers alongside cognitive and psychological assessments improves recovery assessment and the early identification of workers at increased risk of long-term health consequences.

5.3. Future Research Directions

The Recovery Illusion Framework generates several testable hypotheses that warrant further investigation. Future longitudinal studies should determine whether behavioural recovery consistently precedes physiological restoration following circadian disruption and whether repeated recovery gaps contribute to cumulative allostatic load and long-term health outcomes.

Further research should evaluate objective markers of recovery, including heart rate variability, neuroendocrine biomarkers, inflammatory markers, and wearable physiological monitoring technologies, alongside validated cognitive and psychological assessments (Somers et al., 1993; Tobaldini et al., 2013; Juster et al., 2010). Integrating these multidimensional measures may improve the identification of individuals at increased risk of adverse health outcomes despite apparent behavioural recovery.

Intervention studies are also needed to determine whether optimising shift schedules, recovery periods, and fatigue-management strategies can reduce recovery gaps and improve long-term physiological and psychological health among shift-working populations. Such evidence will be essential for validating the proposed Recovery Illusion Framework and determining its relevance to occupational health policy and clinical practice.

Several limitations should be acknowledged. The Recovery Illusion Framework is derived from heterogeneous experimental and observational studies rather than direct longitudinal evaluation of recovery dynamics. Furthermore, the proposed relationship between incomplete physiological restoration and subsequent psychological outcomes remains hypothetical and requires prospective validation using multidimensional recovery measures.

6. CONCLUSION

Recovery following circadian disruption has traditionally been evaluated using behavioural indicators such as sleep duration, sleep timing, and subjective improvements in fatigue. However, the evidence reviewed in this Perspective suggests that behavioural recovery may not always coincide with complete physiological restoration. Experimental and observational studies indicate that autonomic, neuroendocrine, metabolic, and cardiovascular recovery may persist beyond apparent behavioural realignment, while emerging evidence also suggests potential implications for cognitive functioning, emotional regulation, and psychological resilience.

The Recovery Illusion Framework provides a conceptual perspective for understanding why behavioural recovery may precede complete physiological restoration following circadian disruption. By integrating evidence from circadian biology, sleep physiology, occupational health, and psychological research, it proposes that recovery should be viewed as a multidimensional process

rather than a single behavioural event. Although the framework requires empirical validation, it offers a foundation for future studies investigating recovery gaps, cumulative allostatic load, and their implications for long-term health outcomes in shift-working populations.

Recognising recovery as a coordinated process of behavioural, physiological, and psychological restoration may ultimately improve recovery assessment, clinical decision-making, occupational health practice, and preventive strategies aimed at reducing the long-term health burden associated with recurrent circadian disruption.

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ІЛЮЗІЯ ВІДНОВЛЕННЯ: НАСЛІДКИ НЕПОВНОГО ФІЗІОЛОГІЧНОГО ВІДНОВЛЕННЯ ПІСЛЯ ЦИРКАДНОЇ ДЕСИНХРОНІЗАЦІЇ ДЛЯ ЗДОРОВ'Я ПРАЦІВНИКІВ ПОЗМІННОЇ ПРАЦІ

АНОТАЦІЯ

Передумови. Відновлення після циркадної десинхронізації традиційно оцінюється за поведінковими показниками, зокрема нормалізацією режиму сну, його тривалості та суб'єктивним зменшенням втоми. Водночас сучасні дослідження свідчать, що фізіологічне відновлення може відбуватися повільніше за поведінкове, створюючи прихований період біологічної вразливості, який потенційно впливає на фізичне та психологічне функціонування працівників змінного графіка.

Мета. Узагальнити сучасні наукові дані щодо фізіологічного відновлення після циркадної десинхронізації, обґрунтувати концепцію **Recovery Illusion Framework (**Концептуальна модель ілюзії відновлення) та визначити її потенційне значення для розуміння механізмів відновлення здоров'я працівників позмінної праці.

Методи. Проведено концептуальний огляд сучасних експериментальних та обсерваційних досліджень, присвячених наслідкам циркадної десинхронізації. Проаналізовано результати досліджень автономної регуляції, нейроендокринних механізмів, циркадної біології, когнітивного функціонування, психологічних наслідків та концепції алостатичного навантаження з подальшою інтеграцією отриманих даних у єдину концептуальну модель.

Результати. Аналіз літератури показав, що після відновлення звичного режиму сну фізіологічні системи можуть залишатися частково дисрегульованими, незважаючи на суб'єктивне відчуття відновлення. Наведені дані свідчать про збереження автономної та нейроендокринної дисфункції, а також про можливий негативний вплив циркадної десинхронізації на когнітивні функції, прийняття рішень, емоційну регуляцію та психологічну стійкість. На основі узагальнення сучасних досліджень запропоновано концептуальну модель **Recovery Illusion Framework**, яка описує феномен випередження поведінкового відновлення над повним фізіологічним відновленням та пояснює потенційний механізм накопичення алостатичного навантаження при повторних циклах циркадної десинхронізації.

Наукова новизна. Запропоновано нову інтегративну концептуальну модель **Recovery Illusion Framework**, яка поєднує поведінкові, фізіологічні та психологічні аспекти відновлення після циркадної десинхронізації та розширює сучасні уявлення про механізми розвитку довготривалих негативних наслідків змінної роботи.

Практичне значення. Запропонована концепція може бути використана для вдосконалення систем оцінювання відновлення працівників змінного графіка, розроблення програм охорони праці, оптимізації режимів праці та відпочинку, а також планування майбутніх досліджень із використанням об'єктивних фізіологічних, когнітивних і психологічних показників.

Висновки. Поведінкове відновлення після циркадної десинхронізації не завжди відображає завершення фізіологічного відновлення організму. Концепція **Recovery Illusion Framework** пропонує розглядати відновлення як багатовимірний процес, що включає поведінкові, фізіологічні та психологічні компоненти. Подальші емпіричні дослідження необхідні для перевірки запропонованої моделі та визначення її клінічного й практичного значення.

Ключові слова: циркадна десинхронізація; змінна робота; фізіологічне відновлення; психологічне

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відновлення; алостатичне навантаження; варіабельність серцевого ритму; психічне здоров'я; медицина праці.

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