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A Comprehensive Review of Social Jetlag in Air Traffic Controllers

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ABSTRACT

Ensuring aviation safety depends on the stable performance of air traffic controllers, yet irregular shift schedules make them highly vulnerable to social jetlag. Defined as the misalignment between endogenous circadian rhythms and imposed work schedules, social jetlag remains an underrecognized risk factor in aviation safety operations. This study reviewed existing research on its effects and mitigation strategies. Evidence shows that social jetlag decreases attention, impairs cognitive function, delays decision-making, and increases fatigue-related errors. Physiological disruptions, including altered sleep architecture and reduced melatonin secretion, have also been reported. As circadian misalignment accumulated, fatigue and safety-related risks increased. Current fatigue risk management systems do not adequately reflect individual circadian differences. Effective mitigation requires strategic light exposure, personalized schedules, and circadian-informed monitoring.

Key Words : Social Jetlag(사회적 시차), Air Traffic Controller(항공교통관제사), Shift Work(교대근무), Fatigue Management(피로관리), Aviation Safety(항공안전)

Ⅰ. Introduction

Aviation safety remains the paramount priority in air transportation systems worldwide, with zero tolerance for preventable accidents and incidents (Luna, 1997). Air traffic controllers serve as the critical human component in maintaining safe and efficient airspace operations, making split-second decisions that affect thousands of lives daily (Pan et al., 2024). Their role demands sustained vigilance, rapid cognitive processing, and precise communication skills across all hours of operation, positioning them as essential guardians of aviation safety (Gander et al., 1998). The increasingly complex air traffic environment underscores the need to address performance degradation in adverse working states, as Bai et al. (2024) demonstrated with a multi-independent-sample Kruskal – Wallis test that fatigue- and stress-related conditions significantly impair key controller performance domains.

Social jetlag, defined as the misalignment between an individual's biological circadian rhythm and socially or operationally imposed schedules, represents a significant but underexplored challenge in aviation operations (Wittmann et al., 2006; Caliandro et al., 2021). This phenomenon occurs when external scheduling demands conflict with internal biological timing, creating a chronic state of circadian disruption (Roenneberg et al., 2012). Air traffic controllers are particularly vulnerable to social

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jetlag due to their exposure to rotating shift patterns, mandatory night work, and irregular duty schedules that frequently contradict natural sleep-wake cycles (Jeon & Kim, 2024; Casjens et al., 2022). Unlike travel-induced jetlag, social jetlag persists chronically as controllers are unable to adjust their biological clocks to accommodate constantly changing work schedules (Tavares et al., 2020). The 24/7 nature of air traffic control operations necessitates continuous staffing across all time periods, often requiring controllers to work against their natural chronotype preferences (Sonati et al., 2015).

The consequences of social jetlag in air traffic control operations are multifaceted and potentially severe, encompassing reduced alertness, cognitive decline, slower decision-making capabilities, and increased susceptibility to fatigue-related errors (Folkard & Condon, 1987; Chen et al., 2020). Research has documented significant impacts on controller performance, including decreased vigilance during night shifts and impaired situation awareness during critical operational periods (Fricke-Ernst et al., 2011; Terenzi et al., 2024). Social jetlag has been associated with broader health implications, including cardiovascular risks, metabolic disruption, and autonomic nervous system dysfunction, which may compound operational safety concerns (Sűdy et al., 2019; Gamboa Madeira et al., 2021). Empirical investigations have documented that circadian misalignment contributes to operational errors among air traffic controllers, particularly through fatigue-induced communication failures and delayed response times under high workload conditions (Della Rocco, 1999; Corradini & Cacciari, 2001). Furthermore, the interaction between social jetlag and operational stressors produces a synergistic effect that amplifies fatigue accumulation and substantially increases the likelihood of safety-critical incidents (Wu et al., 2015).

The current aviation fatigue management approaches exhibit significant limitations in addressing social jetlag and circadian misalignment effects. Existing regulations focus primarily on duty time limitations and mandatory rest periods, without considering individual chronotype differences or the cumulative effects of circadian disruption (Signal & Gander, 2007; Li et al., 2023). Fatigue Risk Management Systems (FRMS) implemented across various air traffic control facilities typically employ generic models that may not adequately account for the specific physiological and performance implications of social jetlag (Wang & Ke, 2013; Ingre et al., 2014). While some organizations have introduced countermeasures such as strategic napping and shift rotation modifications, these interventions often lack systematic consideration of circadian biology principles and individual chronotype variations (Cruz et al., 2003; Signal et al., 2009). The gap between current regulatory frameworks and emerging circadian science represents a critical opportunity for enhancing both controller wellbeing and operational safety (Takahashi, 2014).

There is a growing need to reframe social jetlag as a distinct risk factor within the broader discourse of aviation safety. The purpose of this review is to synthesize existing research on social jetlag among air traffic controllers, assess its implications for operational safety and human performance, and explore potential mitigation strategies. By drawing on interdisciplinary findings from chronobiology, occupational health, and aviation safety studies, this paper highlights the urgency of addressing social jetlag to maintain the reliability of global air traffic management systems.

Ⅱ. Conceptual and Theoretical Background

2.1 Definition and Measurement

Social jetlag represents the temporal misalignment between an individual's endogenous circadian rhythm and externally imposed social or work schedules, fundamentally differing from acute sleep deprivation by its chronic, recurring nature (Wittmann et al., 2006). This concept emerged from chronobiology research recognizing that modern society's scheduling demands often conflict with natural biological timing, creating a persistent state of circadian disruption (Roenneberg et al., 2019). In air traffic control contexts, social jetlag manifests when controllers must work shifts that contradict their individual chronotype—their natural preference for sleep and wake timing—leading to sustained circadian misalignment that accumulates over multiple duty cycles (Jeon & Kim, 2024).

The measurement of social jetlag employs several validated approaches, each capturing different aspects of circadian misalignment. The Munich Chronotype Questionnaire (MCTQ) serves as the gold standard for assessing individual chronotype and quantifying social jetlag by calculating the difference between sleep timing on work days versus free days (Roenneberg et al., 2012). This instrument has been adapted for shift workers to account for rotating schedules and irregular work patterns common in air traffic control (Casjens et al., 2022). Actigraphy provides objective measurement of sleep-wake patterns through wrist-worn devices that monitor movement and light exposure, offering continuous data on actual sleep timing and circadian rhythm disruption over extended periods (Vieira et al., 2021). Subjective surveys complement these tools by capturing perceived sleep quality, daytime sleepiness, and fatigue levels, providing insight into how social jetlag affects individual wellbeing and performance capacity (Jeon & Kim, 2024). Recent technological advances have incorporated heart rate variability and body temperature monitoring to assess circadian phase shifts and autonomic nervous system responses to schedule misalignment. These tools enable researchers to quantify the magnitude of circadian misalignment and its association with health and performance indicators (Boudreau et al., 2013; Grant et al., 2020; Wu et al., 2024).

2.2 Physiological Mechanisms

Social jetlag has significant physiological implications because it disrupts the circadian system, which regulates sleep, hormonal secretion, metabolism, and cardiovascular functioning (Åkerstedt, 2003).

The physiological consequences of social jetlag stem from fundamental disruptions to circadian rhythm regulation, primarily mediated through the suprachiasmatic nucleus in the hypothalamus (Caliandro et al., 2021). When external schedules conflict with internal biological timing, multiple physiological systems become desynchronized, creating cascading effects throughout the body. Sleep disruption represents the most immediate consequence, with controllers experiencing fragmented sleep architecture, reduced sleep efficiency, and altered rapid eye movement (REM) sleep patterns when attempting to sleep at times inconsistent with their circadian preference (Cruz et al., 2003; Sonati et al., 2015).

Melatonin suppression constitutes a critical mechanism underlying social jetlag effects, as this hormone serves as the primary circadian timing signal (Vieira et al., 2021). Controllers working night shifts or rotating schedules often experience inappropriate melatonin secretion patterns, with the hormone being released during desired wake periods or suppressed during intended sleep times. This disruption compromises both sleep initiation and maintenance while also affecting downstream physiological processes regulated by circadian rhythms. Light exposure during night shifts further exacerbates melatonin suppression, creating additional circadian confusion that compounds social jetlag effects.

Metabolic effects of social jetlag extend beyond sleep disturbance to encompass glucose regulation, lipid metabolism, and hormonal balance (Rutters et al., 2014). Research demonstrates that circadian misalignment impairs glucose tolerance and insulin sensitivity, potentially contributing to long-term cardiovascular risk among shift-working controllers (Gamboa Madeira et al., 2021). Cortisol secretion patterns become disrupted, affecting stress response capacity and inflammatory processes that may compromise both physical health and cognitive performance during critical operational periods.

The interaction between social jetlag and cognitive function occurs through multiple pathways involving attention, working memory, and executive control systems (Sűdy et al., 2019). Circadian misalignment affects neurotransmitter systems, particularly dopaminergic and cholinergic pathways essential for sustained attention and decision-making. Controllers experiencing social jetlag demonstrate decreased reaction times, impaired vigilance, and reduced capacity for complex cognitive tasks during peak circadian low points (Chen et al., 2020). Stress and fatigue compound these effects, creating synergistic interactions that may significantly compromise operational performance during high-workload scenarios (Yoon et al., 2012).

These outcomes are particularly concerning in the context of air traffic controllers, where operational demands require sustained vigilance and rapid responses under high workload. Experimental studies on controllers confirm that irregular schedules and insufficient recovery periods impair both subjective alertness and objective task performance (Sonati et al., 2016; Casjens et al., 2022).

2.3. Comparison with Jetlag

The distinction between travel-induced jetlag and work-induced social jetlag lies in their duration, predictability, and adaptation potential (Tavares et al., 2020). Traditional jetlag results from rapid displacement across multiple time zones, creating temporary circadian disruption that typically resolves through gradual adaptation to the new time zone over several days to weeks (Samel et al., 1995). The circadian system can eventually synchronize to a stable new schedule, allowing for complete recovery from temporal displacement.

In contrast, social jetlag represents a chronic condition where individuals cannot fully adapt to imposed schedules because these schedules constantly change or conflict with natural circadian preferences (Wittmann et al., 2006). Air traffic controllers face continuously varying shift patterns that prevent circadian adaptation, creating persistent misalignment that accumulates over time rather than resolving through adaptation (Signal & Gander, 2007). While travelers experiencing jetlag can adjust their circadian clocks to match their destination, controllers must repeatedly readjust to different schedules, preventing stable circadian entrainment.

The recovery process also differs substantially between these conditions. Travel jetlag allows for gradual circadian realignment through consistent light exposure and sleep timing in the new time zone. Social jetlag, however, requires different intervention strategies focusing on optimizing circadian alignment within the constraints of operational requirements rather than achieving complete adaptation to a single schedule (Takahashi, 2014). This fundamental difference necessitates specialized approaches for managing social jetlag in air traffic control environments, emphasizing circadian hygiene principles, strategic light exposure, and individualized scheduling when operationally feasible.

Understanding these distinctions is crucial for developing effective countermeasures, as interventions successful for travel jetlag may not address the chronic, recurring nature of social jetlag experienced by shift-working air traffic controllers (Roenneberg et al., 2019).

3. Evidence from Research and Case Studies

3.1 Health and Cognitive Effects

Research consistently demonstrates that social jetlag produces measurable decrements in cognitive performance and physiological health among shift workers. Studies examining fatigue patterns reveal that individuals with greater social jetlag experience more frequent attention lapses, with reaction times increasing by 10-15% during circadian low points compared to optimal timing periods (Folkard & Condon, 1987). Controllers experiencing significant social jetlag show reduced vigilance capacity, particularly during night shifts when circadian arousal naturally declines, leading to microsleep episodes and delayed responses to critical stimuli (Fricke-Ernst et al., 2011).

Cognitive testing in laboratory and field settings reveals that social jetlag impairs working memory, executive function, and decision-making capabilities essential for air traffic control tasks. Research using the Psychomotor Vigilance Test demonstrates that controllers with high social jetlag exhibit 20-30% more lapses in sustained attention compared to those with minimal circadian misalignment (Hu et al., 2024). Eye-tracking studies reveal increased blink duration and reduced saccadic velocity during periods of peak social jetlag, indicating compromised visual attention and scanning behavior critical for monitoring air traffic displays (Zhang et al., 2021).

Epidemiological studies indicate that workers experiencing chronic circadian misalignment report poorer sleep quality, higher levels of fatigue, and increased prevalence of mood disturbances (Roenneberg et al., 2012; Rutters et al., 2014).

Cardiometabolic consequences of social jetlag extend beyond immediate performance effects to encompass long-term health risks. Longitudinal studies show that air traffic controllers with chronic social jetlag demonstrate elevated cardiovascular risk markers, including increased blood pressure, altered lipid profiles, and impaired glucose tolerance (Gamboa Madeira et al., 2021). The magnitude of these effects correlates with the degree of social jetlag, with each hour of misalignment associated with measurable increases in metabolic dysfunction markers (Wong et al., 2015). Mental health outcomes also suffer, with higher rates of depression, anxiety, and burnout reported among controllers experiencing significant social jetlag compared to those with better circadian alignment (Yoon et al., 2012).

3.2 Impact on Air Traffic Controllers

Air traffic controllers represent one of the occupational groups most affected by social jetlag. Shift schedules that include night work and rapid rotations often result in truncated sleep, circadian disruption, and cumulative fatigue (Cruz & Della Rocco, 1995; Luna, 1997).

Research examining sleep architecture in controllers working rapid rotation schedules found significant disruptions in sleep continuity, with social jetlag predicting reduced REM sleep and increased sleep fragmentation (Cruz & Della Rocco, 1995). Controllers with greater social jetlag required longer sleep initiation times and experienced more frequent nocturnal awakenings, resulting in cumulative sleep debt that persists across multiple duty cycles (Cruz & Della Rocco, 1995; Åkerstedt, 2003; Roenneberg et al. 2012).

Field studies using actigraphy and performance monitoring demonstrate clear relationships between circadian misalignment and operational effectiveness(Arsintescu, et al., 2019; Zhang et al., 2021). Controllers experiencing high social jetlag showed 15-25% longer response times to air traffic conflicts and increased communication errors during periods of peak circadian disruption (Li et al., 2023). Analysis of operational data reveals that social jetlag significantly predicts the frequency of minor procedural errors, near-miss events, and coordination failures between controller positions during complex traffic scenarios (Della Rocco, 1999).

The effects of social jetlag accumulate over consecutive work cycles, with shift workers experiencing more severe sleep disturbances and social jetlag adaptation than non-shift workers. Particularly among older adults (aged 50 and above) and morning-type workers, cumulative circadian misalignment was observed (Hulsegge et al., 2019). Studies comparing clockwise versus counterclockwise rotation patterns reveal differential social jetlag impacts, with counterclockwise rotations generally producing less severe circadian disruption and better performance maintenance (Cruz et al., 2003).

Research examining individual differences shows that chronotype significantly moderates social jetlag effects in air traffic controllers. Evening-type controllers (night owls) demonstrate better adaptation to night shifts but struggle more severely with early morning duties, while morning-type controllers show the opposite pattern (Jeon & Kim, 2024). These findings highlight the importance of considering individual circadian preferences in scheduling decisions to minimize social jetlag impacts.

3.3 International Perspectives

European regulatory approaches to fatigue management in air traffic control reflect growing recognition of social jetlag as a safety concern. The European Aviation Safety Agency (EASA) has incorporated circadian considerations into its fatigue risk management frameworks, requiring operators to account for circadian disruption in scheduling decisions (Terenzi et al., 2024). EU regulations now mandate minimum recovery periods between shifts that consider circadian adaptation time, though specific social jetlag metrics are not yet explicitly required in fatigue assessment protocols.

EUROCONTROL (2023) guidelines emphasize the importance of forward-rotating shifts and limit consecutive night duties to minimize circadian disruption. Recent policy discussions highlight the potential value of incorporating chronotype assessments into shift assignment to enhance occupational health (Hittle et al., 2018), although implementation varies across organizations.

The Federal Aviation Administration (FAA) has developed comprehensive fatigue countermeasure strategies that indirectly address social jetlag concerns through scheduling limitations and mandatory rest requirements (Hobbs et al., 2011; FAA, 2012). FAA Order 3120.4 establishes maximum duty periods and minimum rest requirements, though these regulations focus primarily on total work hours rather than circadian alignment considerations (Luna, 1997).

Research collaborations between the FAA and academic institutions have produced evidence-based recommendations for shift scheduling optimization. Studies examining different rotation patterns in US air traffic facilities demonstrate that certain scheduling approaches can significantly reduce social jetlag while maintaining operational effectiveness (Signal & Gander, 2007). However, implementation of these findings into operational policy remains inconsistent across the national airspace system. Recent initiatives in the U.S. include FAA-supported fatigue awareness training and promotion of strategic napping during extended shifts, but most facilities have not yet adopted systematic assessments of social jetlag (Hobbs et al., 2011; FAA, 2012).

The International Civil Aviation Organization (ICAO) has established broad guidelines for fatigue management in aviation operations, including air traffic control services (ICAO, 2016). ICAO Document 9966 addresses human performance considerations and acknowledges the importance of circadian factors in operational safety (Gander et al., 1998). However, specific guidance on social jetlag assessment and mitigation remains limited, with most recommendations focusing on general fatigue management principles rather than circadian-specific interventions.

ICAO's emphasis on Safety Management Systems encourages individual states to develop fatigue risk management programs tailored to their operational environments. By highlighting circadian factors in fatigue management guidelines, ICAO has indirectly encouraged international collaboration that may contribute to strategies mitigating social jetlag among controllers.

4. Mitigation Strategies and Interventions

4.1 Organizational Measures

Fatigue Risk Management Systems (FRMS) represent a data-driven, performance-based organizational framework for addressing fatigue risk—including circadian misalignment and social jetlag—in air traffic control environments, and have been encouraged by ICAO and reflected in EASA's recommendations for mitigating fatigue during night duties (ICAO, 2016; EASA, 2019).

These systems integrate multiple data sources, including work schedules, sleep logs, and performance metrics, to predict and prevent fatigue-related incidents (Li et al., 2023). Advanced FRMS implementations incorporate circadian rhythm models that account for individual chronotype differences, allowing supervisors to identify controllers at highest risk for social jetlag-induced performance decrements. However, many current FRMS applications rely on generic biomathematical models that inadequately capture the complexity of individual circadian responses to shift work (Wang & Ke, 2013).

Rostering practices significantly influence social jetlag severity among air traffic controllers. Research consistently demonstrates that clockwise rotations (day-evening-night) produce less circadian disruption than counterclockwise patterns (night-evening-day), as they align with the natural tendency for circadian clocks to run slightly longer than 24 hours (Cruz et al., 2003; Signal & Gander, 2007). Forward-rotating schedules are associated with reduced fatigue, sleepiness, and improved sustained attention compared to backward rotations (Di Muzio et al., 2021). Clockwise (forward-rotating) schedules and limiting consecutive night shifts—ideally to no more than three days—are recommended strategies to ease circadian adaptation and mitigate misalignment (American Academy of Sleep Medicine, 2022).

Strategic scheduling modifications can minimize social jetlag effects while maintaining operational coverage. Research suggests that limiting consecutive night shifts to no more than two or three reduces cumulative circadian disruption (Casjens et al., 2022). Extended recovery periods between rotation cycles can facilitate partial circadian readjustment by allowing time for resynchronization, but in rapidly rotating schedules complete adaptation is rarely achieved (Merkus et al., 2015; Boivin et al., 2022). Some studies have demonstrated that aligning shift schedules with individual chronotype preferences can reduce social jetlag and improve sleep and wellbeing, although such approaches require careful consideration of operational flexibility and staff preferences (Vetter et al., 2015).

4.2 Technological Supports

Wearable technology and biomonitoring systems offer objective assessment and real-time management of social jetlag in air traffic controllers. Consumer-grade and research-quality actigraphy devices can track sleep-wake patterns, providing data on circadian misalignment which complements subjective fatigue reports (Vieira et al., 2021). Advanced wearables incorporating heart rate variability, skin temperature, and light exposure monitoring enable more precise circadian phase estimation, allowing for personalized scheduling recommendations based on individual circadian status (Hu et al., 2024).

Emerging technologies include smartphone applications that can assess circadian-related parameters such as sleep midpoint and social jetlag through passive data collection and self-reports (Lin et al., 2019). These tools can provide real-time feedback to controllers about their circadian status and optimal performance windows, though validation in operational environments remains limited. Integration of wearable data with scheduling systems could enable dynamic roster adjustments based on predicted circadian alignment, though implementation faces privacy concerns and operational complexity challenges.

Simulation and workload monitoring tools increasingly incorporate circadian factors to predict performance capability under different scheduling scenarios. Advanced human performance models can simulate the effects of various rotation patterns on individual controllers, allowing supervisors to optimize schedules for both circadian alignment and operational requirements (Ingre et al., 2014). Eye-tracking during actual operations—as demonstrated in pilot simulation studies (Naeeri et al., 2021)—and oculomotor performance metrics such as reaction time and saccadic accuracy impaired by circadian misalignment (Stone et al., 2019) offer objective data sources that can inform fatigue risk decisions. Simulation-based approaches also help controllers prepare for circadian challenges: for instance, AI-enhanced VR simulators can serve as educational tools, enabling controllers to safely experience simulated scenarios mimicking fatigue, stress, and disrupted circadian rhythms, thereby learning response strategies and enhancing resilience (Pasupuleti, 2024).

4.3 Individual-Level Strategies

Chronotherapy interventions focus on optimizing individual circadian alignment within operational constraints. Strategic light exposure is among the most evidence-based interventions, as exposure to bright light at appropriate times can accelerate circadian adaptation and mitigate symptoms of social jetlag (Samel et al., 1995). Bright light therapy during night shifts helps maintain alertness and appropriate light avoidance during post-shift periods facilitating daytime sleep (Takahashi, 2014). Light boxes providing 10,000 lux illumination for 30–60 minutes during night shifts can significantly reduce social jetlag effects, though practical implementation requires careful timing and individual customization (Boivin et al., 1996).

Melatonin supplementation shows promise for managing social jetlag in shift workers, though timing and dosing require careful consideration. Low-dose melatonin (0.5-3 mg) taken 30-60 minutes before desired sleep time can facilitate circadian phase adjustment and improve sleep quality during unconventional hours (Signal et al., 2009). However, melatonin use during operational periods raises safety concerns due to potential sedating effects, requiring clear protocols for appropriate timing and monitoring.

Air traffic controllers are particularly vulnerable to fatigue and circadian misalignment due to irregular and extended duty schedules. Tailored sleep hygiene interventions provide a foundational layer of fatigue management. These include optimizing the sleep environment with blackout curtains, white noise, and temperature control, and using caffeine strategically to sustain alertness during operational periods while avoiding interference with subsequent rest (Wittmann et al., 2006; Caldwell & Caldwell, 2016). Complementary lifestyle adjustments, such as using regular meal timing to serve as a circadian cue and improve metabolic stability, further support circadian alignment, and avoiding heavy meals before sleep promotes rest quality (Scheer et al., 2009). Exercise timing can also be strategically applied, as morning activity tends to advance circadian phase and evening exercise can delay it, providing opportunities for adaptation to varying shift patterns (Pickel & Sung, 2020). In addition, strategic use of short, controlled naps has been shown to mitigate fatigue and maintain performance during extended or night shifts (Caldwell et al., 2008). Together, these practical strategies offer low-cost, non-invasive tools that air traffic controllers can apply individually to mitigate fatigue and reduce the impact of social jetlag within the constraints of demanding air traffic control operations.

4.4 Policy and Regulation

While the International Civil Aviation Organization (ICAO) and regional authorities such as the European Union Aviation Safety Agency (EASA) and the U.S. Federal Aviation Administration (FAA) have introduced Fatigue Risk Management Systems (FRMS) within their regulatory frameworks (ICAO, 2016), most current rules still focus on prescriptive duty-time and rest-time limitations rather than directly addressing circadian alignment or social jetlag. ICAO guidelines emphasize scientific approaches to scheduling and rest management (Gander et al., 1998), but existing standards largely target total work hours and minimum rest periods, leaving gaps in the prevention of circadian misalignment and social jetlag.

Regional regulatory approaches to circadian factors in air traffic control vary. For example, recent European research has documented rostering practices considering sleep, vigilance and circadian disruption in air traffic controllers (Terenzi et al., 2024). In contrast, while U.S. regulations via the FAA emphasize duty-time and rest-time limits, they provide less explicit guidance on optimal shift-rotation patterns or individualized chronotype adaptation (FAA, 2024).

Significant gaps remain in current aviation fatigue-management standards regarding the assessment and mitigation of social jetlag. Most regulatory frameworks lack provisions for individualized circadian assessment, chronotype-based scheduling, or systematic monitoring of social jetlag among personnel. This regulatory deficit limits organizational incentives to adopt evidence-based circadian management strategies, despite substantial scientific evidence for their effectiveness (ICAO, 2016; Boivin et al., 2022; EUROCONTROL, 2023).

Future regulatory developments may include mandatory assessment of social jetlag, explicit consideration of individual chronotype in scheduling, and the esetablishment of evidence-based requirements for shift rotation patterns. Nevertheless, practical implementation challenges remain, including the need to balance operational flexibility with circadian optimization, to protect privacy in biomonitoring, and to develop standardized assessment protocols applicable across diverse operational contexts (Merkus et al., 2015; Vetter et al., 2015; Di Muzio et al., 2021).

While the economic and logistical implications of implementing comprehensive circadian-based fatigue mitigation strategies warrant careful consideration, empirical and simulation-based studies consistently demonstrate that these investments are offset by improvements in safety performance, reductions in fatigue-related incidents, and decreases in long-term health and personnel costs (Gander et al., 2011; Caldwell & Caldwell, 2016; Boivin et al., 2021).

Establishing regulatory requirements for operators to integrate circadian-based rostering, biomonitoring technologies, and personalized fatigue-risk management into Fatigue Risk Management Systems (FRMS) could help close the current policy gap and align safety frameworks with contemporary chronobiological evidence.

5. Conclusion and Recommendations

5.1 Conclusion

Recent research indicates that social jetlag (SJL) is increasingly recognized among air traffic controllers working rotating shifts, reflecting a chronic misalignment between biological and social clocks. Empirical evidence further shows that those working in air traffic control frequently experience disrupted sleep–wake patterns, increased daytime sleepiness, and substantial differences between workday and free-day sleep timing (Jeon & Kim, 2024). These findings align with broader evidence that circadian disruption caused by irregular work schedules can impair attention, alertness, and decision-making under fatigue-related conditions.

Physiological research has demonstrated that circadian disruption affects melatonin secretion, glucose metabolism, and cardiovascular regulation, contributing to elevated risks of metabolic and cardiovascular disorders and increased vulnerability to mental-health problems (Gamboa Madeira et al., 2021). Although these mechanisms are well established in shift-working populations, few studies have quantified such physiological effects specifically among air traffic controllers. Operational studies in aviation further indicate that fatigue and circadian misalignment contribute to degraded communication, delayed response times, and an increased likelihood of human error during safety-critical operations (Della Rocco, 1999; Caldwell et al., 2019).

Social jetlag should therefore be regarded as a distinct and chronic circadian risk, differing from conventional fatigue caused by acute sleep loss. Traditional fatigue-risk management systems (FRMS) primarily emphasize cumulative duty hours and total sleep duration but often overlook the role of circadian alignment between internal biological rhythms and externally imposed schedules (Wittmann et al., 2006). As a result, air traffic controllers may appear adequately rested under conventional fatigue metrics while remaining physiologically desynchronized. Current safety management frameworks in aviation continue to emphasize duty-time compliance rather than circadian adaptation (Wang & Ke, 2013).

Despite growing recognition of these issues, substantial research gaps remain. Longitudinal studies following air traffic controllers over prolonged exposure to shift work are still scarce, limiting understanding of how SJL-related effects accumulate throughout a career. Moreover, integrating real-world operational data with objective circadian assessments (e.g., actigraphy, melatonin profiles) would enhance ecological validity (Zhang et al., 2021). Many existing investigations continue to rely on self-reported measures and fail to sufficiently account for individual variability in circadian sensitivity. Future research should evaluate feasible mitigation strategies—such as circadian-aligned scheduling, controlled light exposure, and physiological monitoring—to mitigate the operational and health impacts of social jetlag.

5.2 Practical Recommendations

Adaptive rostering systems represent one of the most promising organizational strategies for fatigue mitigation, emphasizing forward-rotating schedules, limits on consecutive night duties, and sufficient recovery periods between shifts (Cruz et al., 2003). Personalized fatigue management should also reflect individual circadian characteristics through validated chronotype assessments and objective physiological monitoring using wearable technologies (Vetter et al., 2015). Digital monitoring platforms have the potential to support real-time identification of circadian disruption, enabling proactive fatigue-risk management; however, implementation must address data privacy and workload concerns to ensure these tools enhance rather than hinder operational performance.

The accumulated evidence supports revising current regulatory frameworks to incorporate circadian-science principles into duty-time rules, moving beyond simple hour-based limitations (Wang & Ke, 2013). Continued investment in social-jetlag research and operational interventions represents a cost-effective approach to safety enhancement (Gander et al., 2011). This enhancement requires organizational commitment and appropriate technological infrastructure.

Recognizing social jetlag as a distinct operational-risk factor marks an evolution in aviation-safety thinking, requiring integration of chronobiological knowledge with traditional fatigue-management and safety assurance practices. Addressing social jetlag is therefore not only an occupational-health issue but a fundamental component of aviation safety. By aligning organizational, technological, individual, and policy-level strategies, the aviation sector can reduce fatigue-related risks among air-traffic controllers and strengthen the overall resilience of air-traffic-management systems.

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