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Impact of Pilot Fatigue and Sleep Deprivation on Cognitive Performance and Flight Safety – A Narrative Review

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Abstract

Pilot fatigue and sleep deprivation are two very serious and persistent risks to global aviation safety. In particular night flying and cross-continental travels result in a continuous fatigue build-up and may lead to diminished pilots' performance. This review combines findings from recent research concerning the impact of sleep loss and fatigue on the cognition of pilots. In particular factors like working memory, focusing attention, reaction times, decision making and situational awareness are discussed.

The presented review demonstrated that moderate levels of sleep deprivation lead to measurable decreases in human alertness, psychomotor speed and executive functioning. Moreover, it was proved fatigue played a pivot role in a large number of aviation incidents and accidents. Presented reports indicate that aviation regulatory agencies, airline managers

and researchers should give high priority to reducing pilot fatigue in order to protect both the health of pilots and the safety of passengers.

Key words: pilot fatigue, sleep deprivation, circadian rhythm disruption, aviation safety, cognitive deterioration

1. Introduction

Aviation is one of the most advanced mean of transport in modern society and it's becoming critically important for global economy and development. Advanced modern aircraft designs require high maintenance standards, crew training and safety regulations. According to recent American Federal Aviation Administration (FAA) and the National Transportation Safety Board (NTSB), accidents caused by pilot errors represent about 60–80 percent of total number of accidents when general aviation (private planes) and commercial aviation are taken into account [1]. In view of the above, the extensive research has been carried out on pilot's health monitoring and identifying critical hazards for flight safety. Limited cognitive performance caused by pilot fatigue and sleep deprivation has been recognised as one of most important factors. Unlike acute medical emergencies or equipment failures, human fatigue develops gradually, often stays unrecognized by affected individual, and can be difficult to detect by accompanied persons.

Pilots are exposed to numerous stress inducing factors – including irregular work load schedules, transcontinental flights causing disruption to internal body clock, jet lag syndrome, night operations – that make them particularly susceptible to both acute and cumulative fatigue (2). Research comparing pilots to other professions, such as truck drivers, firefighters, police, and medical stuff has demonstrated that the extremely high cognitive demands of aviation make pilots especially vulnerable to performance decrements resulting from sleep loss (3).

The problem is well recognized by aviation authorities and numerous measures have been taken to minimize and mitigate pilots fatigue and improve flight safety. These actions are: limits in working hours, mandatory rest requirements, and the implementation of fatigue risk management systems (FRMS). Systematic analysis on fatigue countermeasures and individual case studies confirm the necessity for continued research in this domain, both theoretical and evidence-based ones (4). These studies cover evident short term fatigue cases and long term ones, too. The later may contribute to serious health consequences like chronic sleep disruption, cardiovascular health, metabolic disturbances, and overall work capacity (5,6,7).

Numerous studies confirm that even minor sleep disruptions may affect basic cognitive functions like data processing performance, sustained attention, decision making, and emotional control (8), as well as degradation in working memory (9).

Given the importance of these issues for flight safety and crew members' health and mental well-being this review aims to synthesize current findings on critical factors like human fatigue and sleep deprivation affecting pilots' cognitive performance. Moreover, underlying physiological mechanisms, and available mitigation strategies are discussed and commented. It is expected that collecting findings from diverse research contexts and different approaches to the topic this study will provide a comprehensive and clinically relevant overview of the problem.

2. Methodology

The purpose of this narrative review is to evaluate and summarize the empirical literature discussing how pilot fatigue and sleep deprivation affect pilots' cognitive function and the safety of flight operations. A comprehensive computerized literature search was conducted using all major electronic databases, including MEDLINE (PubMed) as a primary one as well as CINAHL, SCOPUS, and Web of Science. The results spanned a period of recent 10 years, from 2015-2025. The rationale behind selecting these time frames was to include the most up-to-date research, but also few foundational studies published prior to 2015 were also included.

The selection of literature was done following the Medical Subject Heading (MeSH) index and terms like "pilot fatigue", "aircrew fatigue", "aviation fatigue", "sleep deprivation", "sleep restriction", "quality of sleep", "performance of cognition", "performance neurobehavioral", "time reaction", "vigilance psychomotricity", "decision making", "awareness of situation", "disruption of circadian rhythms", "work shift", "aviation safety" and "management of risk of fatigue" were used. Boolean logic operators ("OR", "AND") were applied to narrow search outcomes. Finally, only the papers meeting the criteria below were taken into consideration:

- They were published in an English language peer reviewed journal.
- Articles were focused either on pilot/aircrew or -where appropriate- on another group working shifts if they produced produce findings that can apply to the aviation sector.

- Articles reported outcomes that are associated with any of the five areas: (a) cognitive performance (b) sleep quality (c) circadian rhythm disruptions (d) fatigue related incidents (e) strategies to mitigate fatigue.
- Papers meeting original research criteria that are the ones that contain systematic review, meta-analysis, and narrative and critical discussion. Short abstract articles or articles which are available online but do not have retrievable full texts were not be considered.

Since this review is only a qualitative study the quantitative synthesis of discussed effects size or meta-analysis were skipped. When sufficient information regarding aviators was not available for, it was supplemented by data from military personnel, long distance truckers and shift workers in order to add mechanistic content. Articles were evaluated for their methodological quality in a narrative format, with special emphasis on whether the authors may have introduced bias through use of self-report measures or through sampling methodologies with small samples and nonrepresentative samples.

3. Results

3.1. Effects of Sleep Deprivation on Cognitive Performance in Pilots

Sleep loss has been shown to have a wide-ranging impact on multiple aspects of cognition and this impact is significant. Reported experimental studies show that focussing and keeping attention is among the most consistently affected domains. In particular reducing nightly sleep to six hours or even fewer leads to serious deterioration in both sustained and selective attention, but the most noticeable decline was observed for caution and vigilance (10).

Neurologically, sleep loss has also been shown to decrease activity in brain networks related to prefrontal and parietal regions which degrade attentional ability as well as executive functioning (10). While this has been extensively documented through lab-based research, it refers very well into real world aviation settings. A recent randomized double-blind clinical trial involving cabin crew members demonstrated a large amount of decreased vigilance when they were performing night-time duties (12); another study, focusing solely on air force pilot's performance after limited sleep showed there was a noticeable decrease in pilot's ability to control their attention not only while cruise flying but during the high-work load flight stages as well (13). Additionally, other human’s brain functionalities like working memory capacity, data processing speeds, and ability to inhibit unnecessary information were all negatively affected. This triggered factors that clearly compromised pilot's ability to perform their duties up to highest standards. Lastly, the fact that these deficits are dose-related (i.e., the larger the deficit in sleep, the larger the deficit in performance) emphasizes the need for pilots to receive ample opportunity for rest.

3.2. Impact of Fatigue on Decision-Making and Situational Awareness

The two most difficult and hazardous cognitive tasks for pilots, decision making and situational awareness, are equally impacted by fatigue. Subjective evaluations of fatigue (question asked to pilots: how tired you feel) have been studied through observational research methods. Results indicated that subjective levels of alertness decreased throughout flight time. The highest levels of experienced fatigue were reported during critical periods of flight including approach and landing (14). Another research that was conducted in flight simulator environments showed that pilots experiencing fatigue often skipped some steps in formal procedures. Meanwhile they were frequently focused exclusively on one piece of data or a single topic, while ignoring other aspects of the situation – the effect that has been referred to as cognitive tunnelling. However, many times the pilots were fully unaware they had been engaged in this type of behaviour.

Randomized trials in aircrew confirm that night-time operations under sleep limits are associated with measurable deterioration in vigilance and cognitive performance compared to well-rested reference group (12). In addition, risk assessments and situation judgments under uncertainty are negatively affected by fatigue since sleep deprived pilots tend to use more familiar heuristics to assess a given situation rather than developing adaptive strategies to address new or unfamiliar situations. Fatigue also disrupts attentional regulation - an essential aspect of executive control necessary for effective decision-making (13). Furthermore, individual differences in susceptibility to fatigue are a significant factor in terms of operational considerations. For example, pilots who are susceptible to fatigue experience larger performance reductions relative to those who are more resistant to fatigue (15). Thus, uniformly applied scheduling standards may be insufficient to provide adequate protection for all pilots since individual predispositions are disregarded.

3.3. Reaction Time and Psychomotor Performance under Fatigue

Psychomotor performance which includes reaction time; manual coordination, and precision of motor responses is the most objectively measurable domain of psychomotor performance. Meanwhile, this is one of the domains of performance that is consistently impacted by sleep deprivation and fatigue. To address these issues commercial airlines introduced the in-flight sleep cabins for the crew. However, the following studies revealed this rest period is often not sufficient and over extended operations deterioration of pilots' performance is still observed, but delayed (16). The objective measure leading to these conclusions was the Psychomotor Vigilance Test (PVT), and adopted the response time limit exceeding 500 ms.

Another important outcome of the performed survey is the significant difference in subjective and objective assessment of the physical and mental condition done by pilots (17). The referenced PVT has also demonstrated its practical operational utility not only for overall fatigue assessment, but has been also helpful in identifying periods of flight with elevated risk and requiring more focused attention (18).

3.4. Fatigue-Related Errors and Incidents in Aviation

The impact of pilots fatigue on their cognitive impairment and subsequently on aviation incidents and accidents is perhaps the most appealing causal relationship. Numerous reports from incident/accident investigations and aviation safety datafiles have identified fatigue as a key contributing factor to a large number of different types of hazards and threatening events occurring in aviation (19). Particularly dangerous are sleep episodes during duty – including ones during flight. The research by Marqueze and his research group confirmed the direct impact of extended working hours and reduced recovery time on these kinds of incidents (20). Similar findings regarding the long haul flights and insufficient recovery breaks as well as decreased pilots' alertness were reported by Sallinen et al (14).

Another important but often overlooked risk factors related to fatigue are sleep disorders. For example; obstructive sleep apnea, insomnia and/or sleepiness are observed among commercial airline pilots at much higher rates than previously estimated. However, the outcomes of the Alzehairi et al. studies revealed the older and more experienced pilots were less likely to suffer from listed ailments (21).

3.5. Circadian Rhythm Disruption and Its Effects on Pilot Performance

Another critical factor affecting pilots' performance is circadian rhythm disruption experienced by pilots, especially ones operating on long-haul routes (22). Disturbances in humans' biological clock, irregular cycles of sleep-wakefulness, non-cyclic hormone secretion affect their cognitive performance. Pilots working in multiple time zones, working on alternating day/night duties are constantly at risk of the circadian rhythm disruptions.

Interesting results were reported by Li et al. (23) and Zhou et al. (24). These research groups conducted the comparative studies under COVID-19 pandemic regulatory exemptions regarding mandatory layover time and on-duty flight time. Authors found that crew members' fatigue increased as flight progressed and were at peak in the final phase of duty. Moreover, intercontinental pilots showed compound circadian disruption implications for long-term health and wellbeing. Notably, the processing speed, attentional capacity and psychomotor precision associated with circadian misalignment appears to be independent of total on-duty hours. This means current limitations based on flight hours alone do not adequately capture the fatigue risk factors.

Another numerous studies consistently demonstrated that travel to the east induces a higher fatigue risk factor than westward travel (25). Furthermore, repeated transmeridian operations may cause long lasting effects like chronic circadian misalignment with alterations in sleep timing even during rest periods (26).

3.6. Sleep Duration and Sleep Quality among Pilots

Pilots' reports from surveys show most pilots sleep less than 7 hours a night and do not get enough rest. Most of them complain about their sleep quality; many of them suffer from insomnia, poor sleep maintenance, night awakenings and feel sleepiness or exhaustion during the day (27). The degree of excessive daytime sleepiness is reported through various studies and is clinically significant in pilot populations independently of countries or geographic regions (28). Similarly, lower sleep quality is caused by irregular scheduling and multiple duty days, independently of other factors (29). Additionally, objective measurements results recorded by actigraphy devices or polysomnographs typically demonstrate poorer sleep patterns if compared to pilots self-evaluation reports. This confirms previous observation on pilots overestimating their physical and mental performance (30). Factors contributing to sleep problems among pilots also relate to environmental conditions such as noise, vibration, heavy workloads and psychological/psychosocial issues including employment instability, demonstrating the complex and multicausal character of sleep disorders (31).

3.7. Cumulative Fatigue and Long-Term Performance Decline

Apart from short term influence of sleep quality on pilots fatigue numerous investigators studied the long-term effects caused by cumulative sleep deficits, multiple consecutive duty days, and lack of rest/recovery after each duty day (19). The fatigue build up caused by these factors is likely as significant as acute fatigue. It influences pilots' operational effectiveness in a very similar way. In addition, a recent study reported by Pellegrino et al. demonstrated that reduced sleep quality experienced by pilots who have been on multiple duty days is directly correlated with their decreased ability to perform work tasks effectively and contributes to increased chance of error or performing below safety standards (32). Several other environmental factors and aircraft or mission specific features can also contribute to the discussed problem. Examples to these might be helicopter flights when pilot is exposed to high noise and structural vibrations or fixed wing operations at high altitudes. Other examples might be difficult weather conditions and seasonal factors (33). A separate group of factors contributing to the accumulation of pilot fatigue consists of circumstances not directly related to their profession. These include, for example, family obligations, the individual's personal state of health or others (34).

Mathematical models of pilots' fatigue and performed numerical simulations also show that the length of duty, the timing of departure with respect to the individual's natural circadian rhythm and the number of flight segments flown are the major contributors to an operator's state of fatigue. These models provide an objective basis for optimizing flight scheduling and rest periods (17, 35).

3.8. Physiological and Neurobehavioral Mechanisms of Fatigue

Fatigue is the result of interactions between two major biological processes: the sleep homeostasis (the homeostatic sleep drive) and the circadian rhythm regulation. The first one increases as you stay awake but decreases as you sleep; the later one acts independently and regulate physical, mental, and behavioural changes, primarily responding to light and dark and individuals daily cycle. The interplay between these two physiological mechanisms can be seriously disordered in people who work on night shifts or irregularly. These disruptions manifest in affected individuals in chronic fatigue states that differ in quality (7). Results published by Griggs and his research group showed that at the molecular level, during periods of prolonged vigilance, an organic compound adenosine accumulates in wake-promoting brain regions. It is supposed this leads to the cognitive impairments of sleep deprivation and induce pattern of cognitive degradation (8). These studies were repeated testing diverse populations and each time measurable progression of cognitive deterioration was observed.

Interesting results on individuals' ability to assess risks were published by Khan et al. (9). Authors showed the direct impact of pilots sleep deprivation on situation assessment, their inappropriate reaction to impulses, and shortcomings in their working memory. Further studies on brain functions using neuro-imaging have found reduced activity in networks located in the frontal-parietal lobe when performing attention-based tasks after sleep loss (10,11) providing a direct evidence of relation between molecular changes caused by sleep deprivation and observed behavioural deficits.

Another study by Dolev and his research group investigated individual variations in susceptibility to adverse neuro-behavioural effects related to genetic polymorphisms. The given conclusions report that some pilots can maintain relatively good performance while under sleep restriction compared to other pilots (13). These observations may have considerable implications on how pilots should be screened and on relevant legal regulations.

3.9. Mitigation Strategies and Fatigue Risk Management Systems (FRMS)

Fatigue prevention in pilots can be addressed in different ways, including introduction of official codes limiting pilot flying hours, pharmaceutical treatments for fatigue, implementation of objective tools monitoring fatigue and other measures.

Comprehensive analysis of numerous papers on measures undertaken to counteract pilots fatigue revealed that although there are many promising interventions, the majority of research papers on these topics lacks sufficient quality and generalizability to support implementation of relevant regulations on a national level (4).

Several studies have also shown that both caffeine and modafinil, apart from their well-known effects in mitigating daytime sleepiness and improving alertness during nighttime duty hours, may help to prevent or at least mitigate the negative effects of restricted sleep on humans' performance. A double-blind randomized controlled study conducted on crew members indicated that both caffeine and modafinil significantly reduced fatigue related decreases in performance compared to a placebo group (12). Additionally, modafinil maintained its effectiveness over a longer period of time. Importantly, when taken appropriately, modafinil did not affect subsequent recovery sleep (36).

As such, it would appear that individuals who tend to be more susceptible to fatigue will benefit more from pharmacologic treatments than those who tend to be resistant to fatigue. This supports the concept of developing individualized strategies to manage fatigue (15). The Psychomotor Vigilance Test (PVT) may provide a significant help in elaborating this kind of programmes, in particular in identifying and validating high-risk times frames for fatigue build-up and types of controls to be selected to address those risks (18).

Wearable consumer sleep technology devices represent another area of emerging interest for possible use as a means of nonintrusive continuous monitoring fatigue of an individual. However, additional in-depth research is required before they can be considered viable options. Currently they lack sufficient accuracy and reliability. The next issue are regulatory approvals and how well they will interface with existing FRMS systems (37). Effective fatigue management ultimately requires systemic FRMS that integrate sleep science with operational risk management, balancing safety imperatives with scheduling and mission requirements (36).

4. Discussion

Pilot fatigue, and sleep deprivation, cause impairments in the cognitive areas (attention, working memory, reaction time, decision making and situational awareness) relevant to flight safety (2). Importantly, all these impairments interact with each other and their cumulative impact is much stronger than if the pilot was just impaired in those areas individually. This finding is similar to studies done on other high-stress professions such as surgeons etc., because the stresses imposed on a pilot by his job hinder his top performance while fatigued (3).

Strong evidence of a relationship between the subjectively perceived level of fatigue and objectively demonstrated levels of impairment has been reported in numerous studies. Often pilots will underreport their fatigue levels due to decreased ability to perceive and identify their own fatigue. Therefore, the use of self-report data as a reference data to determine whether a pilot is impaired due to fatigue is highly unreliable. Consequently, implementation of objective methods for assessing a pilot's performance level is ruthless necessity (17,30).

Apart from total sleep time disruptions in circadian rhythm emerge as an additional source of fatigue-related risks. Even pilots that receive sufficient amounts of total sleep time are still at risk of performing poorly when flying at times corresponding to their biologically expected "night" or when undergoing jet-lag phenomenon after crossing several time zones. Studies examining the effects of shift-work on pilot performance indicate that circadian rhythm disruptions induce a separate adverse physiologic state that cannot be fully mitigated by extending rest periods and longer breaks (6). Regarding crossing time zones numerous studies have shown its different impact on pilots' performance depending on the travel direction. Specifically, traveling towards east is generally harder to adapt for an individual than westward journeys (25). Thus, this observation must be carefully considered when scheduling flights and creating crew rosters. Nevertheless, the current hours-based regulations seem to be inadequate to mitigate all the risk resulting from disrupted pilots' circadian rhythms (7).

Numerous strategies for mitigating fatigue has been comprehensively studied underlining their potential benefits and cautionary concerns. Both pharmacological agents (caffeine and modafinil) and behavioural strategies (such as adjusting crew schedules based on circadian timing) have been found to help maintain alertness while awake and reduce fatigue related performance impairments. However, both of these types of strategies do not address the fundamental physiologic need for sleep. Caffeine and modafinil can potentially delay the detection of accumulated fatigue but cannot substitute breaks for rest and sleep. On the other hand, behavioural strategies may provide more long-term and broad applicability in terms of reducing fatigue related performance impairments.

There are many factors that contribute to individual differences in susceptibility to fatigue including; work schedule, personal health status, lifestyle habits and genetic predispositions. All of these factors are typically not accounted for in population-wide averaged regulatory guidelines; i.e. hours worked per day/week/month etc. (34). Personalized approaches that consider an individual's specific vulnerability may ultimately prove to be more effective and equitable (15).

Additionally, there are many limitations of the current literature into fatigue related performance impairments among commercial pilots. Many experimental studies have been conducted within controlled laboratory environments that do not sufficiently well simulate all of the cognitive demands and environmental complexities associated with real-world flight operations. Aviation specific fatigue research sample sizes are typically relatively small; in some reports military pilots versus civilian ones are compared, which even further reduces the research sample. Therefore, results may not be generalized beyond any specific group and are not fully representative. Lastly, studies vary greatly in terms of adopted outcome measures (from self-report questionnaires to neuroimaging and physiological assessments) and used tools like tests methods or questionnaires. Ultimately, future research should focus on conducting large-scale, prospectively designed studies that are grounded in real world flight operations using valid objective measures of outcomes, measuring individual variability in sleep requirements and chronotypes, and tracking participants' performance across realistic duty cycles.

5. Conclusion

Fatigue due to lack of sleep has been demonstrated to be a serious threat to aviation safety, in particular during long haul commercial operations. This review of published literature supports the conclusion that sleep deprivation adversely affects several cognitive functions critical to flight safety. Among them attention, working memory, reaction time, decision-making, and situational awareness are the most important ones. These factors are most often examined since they significantly contribute to pilots' errors resulting in incidents or accidents.

The risk associated with fatigue also varies as an interactive function of cumulative sleep debt, quality of sleep obtained at night, and each individual's inherent susceptibility to fatigue.

Therefore, current regulations limiting duty and/or flight time hours are shown to be insufficient to ensure the expected flight operations safety providing the complete range of factors affecting fatigue is considered. A better understanding of how fatigue is regulated physiologically (homeostasis and circadian rhythm) provides a strong logical foundation for developing a more complete set of risk management tools. As such, there is a need for regulatory frameworks that incorporate knowledge of circadian rhythms and individual risk assessment combined with objective measures of performance to support or enhance the traditional reliance on fixed limits of duty and/or flight time.

In addition to establishing improved regulatory standards, it will be necessary in the future to develop comprehensive mitigation strategies to manage fatigue. These should not be limited to the already developed tools and policies like pharmacologic countermeasures, Flight Risk Management Systems [FRMS] or emerging consumer technology for improving sleep. However, much of this work will require additional research and operational testing before it can be effectively implemented by carriers.

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Writing – rough preparation: ZZ, KC, MS, JK
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The authors used artificial intelligence-based tools to improve the language quality and grammar of the manuscript. After using this service, the authors have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

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