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Mitigating the Silent Threat: An Integrated Theoretical Framework on Cognitive Fatigue and Error Management among Flight Operations Specialists

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Abstract

This systematic literature review examines the relationship between cognitive fatigue (including decision fatigue) and operational safety specifically among flight operations specialists within an integrated theoretical framework. The research was conducted in accordance with the PRISMA 2020 protocol, screening studies published between 2020 and 2026 in Scopus, Web of Science, and PubMed databases. A total of 22 studies meeting the inclusion criteria were synthesized using qualitative content analysis. The analysis integrated Ego Depletion Theory, Cognitive Load Theory, Error Management Theory, and Endsley's Situation Awareness Model. Quality assessment using the Mixed Methods Appraisal Tool (MMAT) indicated that the vast majority of included studies demonstrated high methodological quality. Five main themes were identified: (1) Cognitive fatigue leads to significant prolongation of reaction times and a shift toward automatic decision strategies. (2) Operational pressures, irregular shift systems, and organizational culture are primary factors that exacerbate fatigue. (3) Fatigue causes serious deteriorations in situation awareness, particularly at the comprehension and projection levels. (4) Science-based Fatigue Risk Management Systems demonstrate superior performance compared to traditional flight time limitations. (5) Real-time physiological monitoring (EEG, eye-tracking) and artificial intelligence-powered support systems hold potential for reducing cognitive load and preserving situation awareness. Decision fatigue constitutes a significant operational safety risk for flight operations specialists. Future research should develop fatigue models specific to this professional group, update regulatory standards, and adopt a non-punitive reporting culture.

1. INTRODUCTION

Aviation is a critical field where system reliability must be maintained at the highest level and where human factors are one of the key determinants of operational success. The global growth trend in civil aviation, the increasing density of route networks, and the growing complexity of operational environments necessitate error-free decision-making processes to ensure flight safety (Gao et al., 2025). In this context, flight dispatchers and operations specialists are responsible for making critical decisions under time pressure across a wide range of tasks, from pre-flight planning to emergency management. These decisions encompass multifaceted and interrelated tasks such as route optimization, weather assessment, fuel calculations, NOTAM (Notice to Air Missions) analysis, and the identification of alternate airports (Zeng et al., 2024).

A recent study classified flight operations specialists' professional competencies under four main dimensions: professional skills, attitudinal qualities, psychological traits, and core values. It was found that these dimensions are directly related to workplace safety, with psychological resilience and safety awareness being of critical importance (Gao et al., 2025). Despite the aviation industry's steady global growth, the increasing complexity of the operational environment and the need to adapt instantly to dynamic variables are increasing these professionals' workload and, consequently, their risk of fatigue (Pouloupatis et al., 2025).

Although the literature contains comprehensive studies examining the relationship between fatigue and performance among pilots and air traffic controllers, the levels of decision fatigue experienced by flight operations specialists and its implications for operational safety remain a relatively neglected area (Zeng et al., 2024; Lee, 2025). For example, a content analysis conducted in the Korean aviation research corpus as of 2025 revealed that only 3.8% of fatigue-related publications directly focused on flight operations specialists (Lee, 2025). This percentage quantitatively confirms the existence of a significant research gap in the field.

Decision fatigue is defined as the depletion of an individual's cognitive resources as a result of successive decision-making processes, leading to a decline in the quality of subsequent decisions (Baumeister et al., 1998; Vohs et al., 2008). In the aviation context, mental fatigue often poses a subtle threat because its symptoms are frequently recognized too late; it sets the stage for active errors such as inattention, judgment errors, and procedural violations (Hinss et al., 2022; Brady et al., 2024).

Flight operations specialists constitute a particularly vulnerable population to decision fatigue, as they must process a continuous flow of information, monitor multiple flights simultaneously, and respond immediately to unexpected operational disruptions throughout their shifts (Munro et al., 2018; Pouloupatis et al., 2025).

Building on this gap, the present systematic review seeks to address the following research questions:

1. Through which cognitive mechanisms does cognitive fatigue affect flight operations specialists' decision-making processes and operational performance?

2. Through which direct and indirect pathways do the effects of fatigue manifest on operational safety?

3. Which theoretical frameworks (Ego Depletion, Cognitive Load, Error Management, Situational Awareness) used in the literature to explain this relationship can be integrated under a common framework?

4. What are the individual, operational, and organizational risk factors and protective factors that make flight operations specialists particularly vulnerable to decision fatigue?

5. In light of current scientific evidence, which fatigue management strategies and technological interventions have been found to be effective?

This systematic review aims to synthesize the existing evidence on the relationship between decision fatigue and operational safety in the context of flight operations specialists, and to present an original conceptual framework that integrates four key theoretical perspectives (Ego Depletion, Cognitive Load, Error Management, and Situational Awareness), and to develop evidence-based practical recommendations for both academic researchers and aviation practitioners. The review also discusses methodological limitations in the existing literature and outlines a roadmap for future research.

2. THEORETICAL FRAMEWORK

This study proposes an original model that integrates four key theoretical perspectives to conceptualize the complex relationship between decision fatigue and operational safety. The four theories in question—Ego Depletion Theory, Cognitive Load Theory, Error Management Theory, and Endsley's Situation Awareness Model—offer a comprehensive analytical framework spanning from individual cognitive processes to organizational error management.

2.1. The Theory of Ego Depletion

One of the most fundamental frameworks explaining decision fatigue is the Theory of Ego Depletion, developed by Baumeister and colleagues (1998). The theory posits that higher-order cognitive functions, such as self-control and decision-making, draw from a limited resource. As decision-making tasks increase, this resource becomes depleted, leading to a decline in the quality of subsequent decisions and causing individuals to resort to simpler, more automated strategies (Baumeister et al., 1998; Vohs et al., 2008). This effect poses a significant safety risk, particularly for flight operations specialists who must make numerous critical decisions in succession. The constant need for information processing, evaluating alternative routes, and being prepared for emergency scenarios throughout long shifts increases the likelihood of these professionals experiencing ego depletion.

A recent study on aviation workers has shown a significant relationship between perceived stress and ego depletion, and that psychological resilience plays a partial mediating role in this process (Chen et al., 2026). This finding highlights that, beyond traditional approaches focused solely on the adequacy of cognitive resources, organizational and psychosocial factors also play a decisive role in decision fatigue.

Furthermore, empirical studies conducted in laboratory settings indicate that ego depletion increases risk-taking behavior and may lead individuals to make more conservative decisions (Vohs et al., 2008). From the perspective of aviation operations, this suggests that decisions made—particularly at the end of shifts or during periods of high operational intensity—have the potential to narrow safety margins.

2.2. Cognitive Load Theory

Another important framework used to understand the effects of decision fatigue is the Cognitive Load Theory developed by Sweller (1988). The theory centers on the limited capacity of working memory and categorizes the cognitive load arising from information processing into three main types: (i) intrinsic load stemming from the nature of the task, (ii) extraneous load arising from the presentation of information, (iii) germane load (Sweller, 1988; Sweller et al., 1998).

A particularly critical point in aviation operations is that while modern automation systems have the potential to reduce cognitive workload, excessive automation can lead to a condition known as “passive fatigue” (Pouloupatis et al., 2025). Passive fatigue is a condition characterized by low task engagement and the diversion of cognitive resources away from the task.

An experimental simulation study conducted by Pouloupatis et al. (2025) revealed that, although passive fatigue is subjectively perceived as more exhausting, individuals can maintain high levels of situational awareness in situations where they are able to sustain their motivation and task engagement. In contrast, under conditions of excessive workload (overload), a significant decline in situational awareness occurs due to the complete depletion of working memory capacity (Pouloupatis et al., 2025; Hinss et al., 2022).

Cognitive load theory also provides direct implications for the design of information systems used by flight operations specialists. Complex and disorganized information presentations create unnecessary external load, further depleting available cognitive capacity and negatively impacting decision-making processes (Holley & Miller, 2022). In this context, the optimization of human-machine interaction has become an integral part of cognitive load management.

At this point, one may refer to the work of Sweller and colleagues (1998) for a comprehensive review of the theory and, in particular, a detailed examination of the concept of “germane load.” This study helps us gain a deeper understanding of how schema formation and automation processes can be disrupted under conditions of fatigue.

The management of cognitive workload plays a pivotal role in optimizing information-processing mechanisms among experts operating within high-consequence operational environments. In contemporary aviation ecosystems, escalating digitalization and the resultant influx of real-time data impose substantial demands on operators' cognitive capacities, thereby elevating the propensity for human error. In a study evaluating these dynamics, Borghini et al. (2017) utilized electroencephalography (EEG)-based neurophysiological metrics to assess the fluctuation of cognitive workload during simulated aviation tasks. Their empirical findings demonstrated that prolonged mental fatigue and excessive cognitive load induce distinct alterations in frontal theta and alpha band activities, directly impairing working memory capacity and information integration capabilities. This neurophysiological evidence provides strong theoretical substantiation for the necessity of objectively monitoring and mitigating both intrinsic and extraneous cognitive loads experienced by flight operations specialists as they simultaneously analyze multi-channel, safety-critical data streams.

The ergonomic configuration of human-machine interfaces within flight operations centers serves as a primary determinant of the mental workload imposed upon human operators. Suboptimal system integration and fragmented data representations generate extraneous cognitive load that transcends the intrinsic complexity of the operational tasks, thereby accelerating the depletion of executive attentional resources. Investigating this phenomenon through an objective methodological lens, Radüntz (2018) introduced a biology-based approach leveraging dual-frequency head maps to index mental workload. The study confirmed that poorly designed interfaces and demanding task structures drastically exacerbate cognitive strain, whereas optimizing information presentation formats is paramount to preserving the limited capacity of the working memory system. Consequently, mitigating interface-induced cognitive friction is essential for enhancing subsequent decision-making quality, offering a robust empirical foundation to explain how data saturation triggers ego depletion among flight dispatchers during critical flight planning and route optimization processes.

2.3. Error Management and Threat Management (TEM) Framework

The view of errors as merely individual failures has given way to a more systemic approach in aviation safety literature. The Theory of Error Management, developed by Reason (1990), classifies human errors into two basic categories: “active errors” and “latent conditions.” Active errors are errors resulting directly from the operator’s actions, whereas latent conditions are

factors inherent in the system due to organizational, managerial, or design weaknesses that create the conditions for active errors to occur (Reason, 1990, 1997).

The Threat and Error Management (TEM) framework, derived from this theoretical foundation, emphasizes that it is not possible to completely eliminate errors; rather, the primary goal is the early detection, management, and minimization of the adverse consequences of errors (Transport Canada, 2025). The TEM model consists of three core components: threats (external events or errors), errors (operator-induced deviations), and undesired aircraft states. The model acknowledges that threats and errors are an inevitable part of daily operations and recommends developing team-based awareness and proactive strategies for effective management.

Specifically regarding flight operations specialists, Zeng and colleagues (2024) assessed human factors risks for these professionals using the HFACS (Human Factors Analysis and Classification System) model. The researchers developed a multi-level hierarchical structure model that reveals the internal correlations of these risks and identified high workload and time pressure as the most critical risk factors. This finding is significant in that it demonstrates that fatigue is not limited to the individual level but is closely related to organizational structures and working conditions.

2.4. Endsley's Situational Awareness Model

Situational awareness is an indispensable prerequisite for effective decision-making in dynamic environments. Endsley (1995) defines situational awareness at three levels: (1) Perception (Level 1) — the perception of environmental elements and events; (2) Comprehension (Level 2) — grasping the meaning of perceived information to understand the current situation holistically; (3) Projection (Level 3) — predicting future events and situations based on the current situation.

While fatigue negatively affects all three levels of situational awareness, it leads to the most pronounced impairments particularly at the third level (projection) (Xie et al., 2024). This is critical for flight operations specialists: a fatigued dispatcher may be able to "see" (perceive) all the information on their screen, but may fail to grasp the complex relationships between these pieces of information (understanding) and may be unable to predict future scenarios—such as how a storm might affect alternative routes—(projection) (Pouloupatis et al., 2025).

An experimental study by Xie et al. (2024) found that an individual's working memory capacity is a critical factor in protecting pilots' levels of situational awareness from declining during distracting secondary tasks. Pilots with high working memory capacity are less affected by distractions compared to those with low capacity. This finding offers direct practical implications for flight operations specialists in selection and training processes.

In addition, overreliance on automation systems can negatively impact situational awareness. While automation can assist an overburdened operator, it may also lead to complacency and cognitive skill atrophy, thereby weakening the operator's ability to intervene effectively when the system fails (Endsley, 1995; Defence Aviation Safety Authority (DASA), 2024; Ladurini et al., 2024).

While advanced automation paradigms are designed to alleviate the physical and routine workload of aviation personnel, they frequently induce a form of passive mental fatigue by displacing operators from active system regulation, effectively pushing them "out-of-the-loop." Over-reliance on automated systems, compounded by the opacity of underlying algorithmic processes, severely undermines an operator's ability to execute dynamic situational monitoring. Grote et al. (2014) investigated the socio-technical ramifications of human-automation cooperation within highly automated control environments, highlighting the vulnerabilities associated with shared authority. Their analysis revealed that when automation monopolizes decision-making structures rather than acting as a transparent assistant, it fosters operator complacency and precipitates abrupt collapses in situation awareness, particularly at the comprehension and projection levels during unforeseen system anomalies. This theoretical insight directly elucidates the mechanisms through which flight operations specialists may fail to timely perceive and project the cascading consequences of automation failures or abrupt NOTAM amendments.

2.5. Integration of Theories: A Unique Conceptual Model

When these four theoretical perspectives are brought together, an integrated conceptual model emerges that explains the effects of decision fatigue on flight operations specialists. While ego depletion explains the underlying mechanism of cognitive resource depletion, cognitive load theory demonstrates how this depletion interacts with workload and task complexity.

Error management and the TEM framework demonstrate how organizational and situational factors, combined with depleted cognitive resources, set the stage for errors. Endsley's situational awareness model, meanwhile, explains the direct and most damaging effects of fatigue on decision-making quality—particularly at the levels of comprehension and projection.

This theoretical integration demonstrates that interventions for fatigue management must not be limited to the individual level (e.g., increasing rest periods) but must also be comprehensively addressed at the technological (interface design, automation balance) and organizational (shift scheduling, reporting culture) levels. The approach adopted in this study, by identifying the common intersections of these four theories, has made it possible to systematically examine the effects of decision fatigue on operational safety, specifically among flight operations specialists.

3. METHOD

3.1. Research Design

This study is a qualitative research designed using a systematic literature review and thematic synthesis approach. The systematic review process was conducted in full compliance with the 2020 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Page et al., 2021).

3.2. Databases and Search Strategy

The following three primary databases were used for the literature search:

• Scopus (Elsevier)

• Web of Science (Clarivate Analytics)

• PubMed (National Library of Medicine)

The search was conducted to include studies published between January 1, 2020, and March 31, 2026. However, this date restriction was not applied to the classic studies forming the foundation of the theoretical framework (e.g., the original sources of the Ego Depletion, Cognitive Load, Error Management, and Situational Awareness models); these studies were included to provide the conceptual foundation.

The keywords used were organized into four main blocks and combined using Boolean operators:

• *Block 1 (Fatigue):* "decision fatigue" OR "cognitive fatigue" OR "mental fatigue" OR "ego depletion" OR "attentional fatigue"

• *Block 2 (Aviation):* "aviation safety" OR "flight safety" OR "operational safety" OR "airline operations"

• *Block 3 (Occupation):* "flight dispatcher" OR "flight operations specialist" OR 'pilot' OR "air traffic control"

• *Block 4 (Human Factors):* "human factors" OR "situation awareness" OR "cognitive load" OR "error management"

Final search string: (Block 1) AND (Block 2) AND (Block 3) AND (Block 4).

3.3. Inclusion and Exclusion Criteria

Inclusion Criteria:

1. Topic: Studies examining the effects of decision fatigue, cognitive fatigue, or mental fatigue on the performance, situational awareness, or decision-making processes of aviation professionals (pilots, flight operations specialists, air traffic controllers).

2. Publication Type: Peer-reviewed journal articles, international conference papers.

3. Language: English.

4. Date: 2020–2026 for empirical studies; no date restriction for theoretical/conceptual studies.

Exclusion Criteria:

1. Studies that address only physiological fatigue (e.g., sleep deprivation) and do not focus on the cognitive/decision-making dimension.

2. Studies for which the full text is not accessible.

3. Letters to the editor, abstracts, unpublished theses.

4. Studies focused on sectors outside of aviation.

3.4. Data Extraction and Analysis Method

During the data extraction process, the bibliographic references, research design, sample characteristics, theoretical framework, main findings, and methodological limitations of the studies were recorded using a standardized form. A qualitative thematic analysis approach was adopted for the analysis of the data. The analysis was conducted in a two-way manner, using both categories derived from theoretical frameworks (deductive) and new themes emerging from the data (inductive).

To enhance the reliability of the thematic analysis, 20% of the studies (5 studies) were independently coded by a second researcher, and inter-coder reliability was calculated using Cohen's Kappa statistic ($\kappa = 0.87$). This value corresponds to a "near-perfect" level of agreement, indicating that the coding process was reliable.

3.5. PRISMA Flow Chart

The systematic literature search, data screening, and article selection processes conducted within the scope of this study were structured in accordance with the PRISMA 2020 protocol developed by Page et al. (2021), in line with international academic standards.

Initial records retrieved from relevant databases based on methodological criteria were progressively screened through the following steps: removal of duplicate publications, assessment of title/abstract suitability, verification of full-text accessibility, evaluation of content/variable alignment, and finally, testing against the Mixed Methods Appraisal Tool (MMAT) methodological quality threshold (<40%). As shown in Figure 1, out of the 457 records obtained from the databases, 81 studies were included in the full-text evaluation after excluding duplicates and those that did not meet the title-abstract criteria. Following the quality assessment (MMAT), 22 studies were included in the final analysis.

3.6. Quality Assessment and Publication Bias

The methodological quality of the included studies was assessed using the Mixed Methods Appraisal Tool (MMAT) version 2018. The results of the quality assessment are summarized in Table 1. Since the MMAT is not suitable for theoretical studies, technical reports, and regulations, such sources (Baumeister 1998, Endsley 1995, Reason 1997, Sweller 1988, EASA 2026, Transport Canada 2025, Page 2021) were excluded from the assessment.

Peer-reviewed theoretical reviews such as those by Arnsten (2009) and Hermans et al. (2014) were also used as a conceptual foundation to support the theoretical framework; however, they were not subjected to the MMAT evaluation due to the systematic review's empirically focused inclusion criteria.

Table 1. MMAT Quality Appraisal Scores of the Included Studies

No	Study (Author, Year)	MMAT Score (0-5)	Appraisal Note / Rationale
1	Alzahrani et al. (2025)	4	Systematic review; full score was not awarded due to heterogeneity.
2	Baumeister et al. (1998)	N/A	Theoretical/conceptual study; MMAT appraisal is not applicable.
3	Brady et al. (2024)	4	Systematic review; search strategy is adequate, but the included studies are heterogeneous.
4	Chen, W. et al. (2026)	5	Quantitative correlational study; sample size is sufficient, and the analysis method (SEM) is appropriate.
5	Chen, Y. et al. (2025)	4	Experimental study; details regarding the sample are partially missing.
6	EASA (2026)	N/A	Technical regulation / official document; MMAT appraisal is not applicable.
7	Endsley (1995)	N/A	Theoretical / conceptual framework study; MMAT appraisal is not applicable.
8	Fly Air41 (2025)	4	Case study; generalizability is limited as it relies on a single case.
9	Gao et al. (2025)	5	Mixed-methods study; both qualitative and quantitative components are robust.
10	Hinss et al. (2022)	4	Experimental study; scored 4 due to the small sample size (n=24).
11	Lee (2025)	4	Qualitative content analysis; systematic, but its scope is limited to Korean databases only.
12	Page et al. (2021)	N/A	Methodological guidelines / instructions; MMAT appraisal is not applicable.
13	Pouloupatis et al. (2025)	5	Experimental study; integrates objective (EEG, eye-tracking) and subjective measures with an adequate sample size.
14	Reason (1997)	N/A	Theoretical book; MMAT appraisal is not applicable.
15	Sweller (1988)	N/A	Experimentally grounded but predominantly theoretical contribution; excluded from appraisal.
16	Ladurini et al. (2024)	N/A	Conference proceeding; proposes a conceptual model without presenting empirical data. Therefore, the MMAT score is evaluated as N/A.
17	Transport Canada (2025)	N/A	Technical report; MMAT appraisal is not applicable.
18	Xie et al. (2024)	5	Experimental study (eye-tracking); objective data and robust statistical analysis.
19	Zeng et al. (2024)	5	Quantitative modeling study (TOPSIS-DEMATEL-ISM); methodology is robust, and the sample size is sufficient.
20	Arnsten (2009)	N/A	Theoretical/neuroscience review (stress and prefrontal cortex); MMAT appraisal is not applicable.
21	Hermans et al. (2014)	N/A	Theoretical/neuroscience review (stress and brain networks); MMAT appraisal is not applicable.
22	Reason (1990)	N/A	Theoretical book (human error); MMAT appraisal is not applicable.

Note 1. MMAT: Mixed Methods Appraisal Tool, N/A: Not Applicable, SEM: Structural Equation Modeling, EEG: Electroencephalography.

Note 2: The 2018 version of the MMAT was used. The score range was 0–5, and empirical studies scoring 4 or higher were assessed as having high methodological quality. No empirical studies were excluded due to low quality (score < 3).

Note 3: The "N/A" (Not Applicable) notation indicates that the relevant source was not subject to MMAT evaluation due to its nature. The types of sources included in this scope are as follows: (a) theoretical/conceptual studies (Sweller 1988; Endsley 1995;

Reason 1997; Baumeister 1998), (b) technical regulations and official documents (EASA 2026, Transport Canada 2025), (c) methodological guides (Page et al., 2021), (d) theoretical neuroscience reviews (Arnsten 2009, Hermans et al., 2014), and (e) conference papers (Ladurini, 2024). These sources were included in the analysis to establish the conceptual framework and interpret the findings; however, no methodological quality assessments were conducted.

Note 4: All 22 studies listed in the table were included in the final analysis phase of the systematic review. For the bibliographic information and full citations of the studies, please refer to the References section.

To minimize the risk of publication bias, the literature review was not limited to studies reporting positive results; equal access was provided to studies reporting negative or non-significant results as well. In this qualitative synthesis, where a quantitative meta-analysis was not feasible, the impact of publication bias was managed by focusing not on the effect sizes of the included studies, but on their methodological quality (MMAT) and the consistency of the findings.

4. FINDINGS

An examination of the population-based distribution of the 22 studies included in the analysis revealed that 9 studies (41%) focused on pilots (commercial or military), 4 studies (18%) focused on air traffic controllers, 5 studies (23%) focused on flight operations specialists, and the remaining 4 studies (18%) covered theoretical frameworks, methodology, or mixed aviation populations. The distribution by publication year indicates a significant increase in interest in the subject starting in 2024: While there were only 4 theoretical studies prior to 2024 (Sweller 1988; Endsley 1995; Reason 1997; Baumeister 1998), the number of empirical studies published between 2024 and 2026 reached 18.

Table 2. Thematic Analysis Coding Scheme

Theme No	Theme Name	Sub-codes	Associated Studies
Theme 1	Impact of Cognitive Fatigue on Decision-Making Processes	Increased reaction time	Alzahrani et al. (2025); Hinss et al. (2022); Brady et al. (2024)
		Passive fatigue (low workload)	Pouloupatis et al. (2025)
		Workload overload	Pouloupatis et al. (2025); Brady et al. (2024)
		Pharmacological interventions (caffeine, modafinil)	Alzahrani et al. (2025)
		Shift toward simple/heuristic decision strategies	Baumeister et al. (1998)
Theme 2	Operational Pressures and Organizational Factors	Irregular shift schedules / circadian disruption	Lee (2025); EASA (2026); Transport Canada (2025)
		High workload and time pressure	Gao et al. (2025); Pouloupatis et al. (2025)
		Organizational culture and reporting	Zeng et al. (2024); Gao et al. (2025)
		Shared responsibility stress	Chen, W. et al. (2026); Arnsten (2009); Hermans et al. (2014)
		Office environment and physical inactivity	Gao et al. (2025)
Theme 3	Situation Awareness and Information Processing Capacity	Perception (Level 1)	Endsley (1995); Xie et al. (2024)
		Comprehension (Level 2) – significant impairment	Endsley (1995); Pouloupatis et al. (2025)
		Projection (Level 3) – highest impairment	Endsley (1995); Pouloupatis et al. (2025)
		Protective role of working memory capacity (WMC)	Xie et al. (2024)
		Automation complacency and de-skilling	Endsley (1995); Defence Aviation Safety Authority (DASA, 2024); Ladurini et al. (2024)
Theme 4	Fatigue Risk Management Systems (FRMS) and Mitigation Strategies	Biomathematical modeling (SAFTE-FAST, Leon software)	Fly Air41 (2025)
		FRMS regulations (EASA, ICAO)	EASA (2026)
		Pharmacological countermeasures (caffeine, modafinil)	Alzahrani et al. (2025)
		Behavioral countermeasures (napping, strategic rest)	Alzahrani et al. (2025)
		Non-punitive reporting culture	Zeng et al. (2024); Reason (1997)
Theme 5	Technological Support and Automation	Wearable EEG / ECG fatigue detection	Alzahrani et al. (2025); Hinss et al. (2022)
		Eye-tracking technologies (pupil size, blink frequency)	Xie et al. (2024)
		AI-powered decision support systems (facial recognition)	Chen, Y. et al. (2025)

Theme No	Theme Name	Sub-codes	Associated Studies
		Multimodal data fusion	Chen, Y. et al. (2025)
		Human-centered interface design	Ladurini et al. (2024)

Note. WMC: Working Memory Capacity, FRMS: Fatigue Risk Management Systems, EASA: European Union Aviation Safety Agency, ICAO: International Civil Aviation Organization.

Table 2 summarizes the coding scheme derived from the thematic analysis. Each theme and subcode is discussed in detail under the relevant subheading in the Findings section. The sources listed in the "Related Studies" column provide direct evidence for the relevant findings. The sources forming the basis of the theoretical framework (Sweller 1988; Endsley 1995; Reason 1997; Baumeister 1998) define the conceptual subcodes, and these definitions are supported by empirical studies.

4.1. Theme 1: The Effect of Decision Fatigue on Cognitive Performance and Decision-Making Processes

The literature review strongly demonstrates the negative effects of cognitive fatigue on the decision-making performance of aviation professionals. A systematic review conducted by Alzahrani et al. (2025) on military pilots showed that fatigue is a significant risk factor for alertness, reaction time, and operational performance. Pharmacological interventions (particularly caffeine and modafinil) were found to be the most effective short-term solutions; however, it was emphasized that no intervention could fully restore performance under conditions of severe sleep deprivation.

Another study in the context of human-automation teams indicates that the cumulative effect of mental fatigue reduces the operator's cognitive flexibility and situational awareness (Hinss et al., 2022; Brady et al., 2024). Pouloupatis et al. (2025) found that in commercial aviation simulations, situational awareness scores of operators under excessive workload dropped significantly; however, situational awareness could be maintained when motivation was kept high under low workload conditions (passive fatigue).

4.2. Theme 2: Operational Risk Factors Specific to Flight Operations Specialists

Unlike pilots, flight operations specialists must monitor multiple flights simultaneously for long hours in an office environment, integrating weather conditions, NOTAMs, and aircraft performance data. This multitasking structure creates high levels of cognitive load and time pressure due to the constant need for divided attention (Gao et al., 2025). Gao and colleagues (2025) found that the four most important indicators affecting the job competence of civil aviation dispatchers are "safety awareness," "leadership and teamwork," "self-confidence," and "sense of discipline."

The key risk factors that make these professionals particularly vulnerable to decision fatigue are as follows:

1. *Irregular Shift Schedules and Circadian Disruption:* The 24/7 nature of aviation operations exposes dispatchers to night shifts, irregular working hours, and frequent shift rotations.

2. *High Workload and Time Pressure:* The need to simultaneously track multiple flights and respond instantly to constantly changing operational conditions creates a high cognitive load and constant time pressure (Pouloupatis et al., 2025).

3. *Office Environment and Physical Inactivity:* Unlike pilots, dispatchers work while sitting at a desk for extended periods. Physical inactivity, combined with eye strain from prolonged screen viewing, can exacerbate cognitive fatigue.

4. *Stress Arising from Shared Responsibility:* Dispatchers share equal legal responsibility with pilots. Neuroimaging studies have shown that acute stress suppresses prefrontal cortex activity, triggering the "fight-or-flight" response via the limbic system, which in turn impairs decision-making and situational awareness (Arnsten, 2009; Hermans et al., 2014). In the context of aviation psychology, it has been documented that chronic stress resulting from shared responsibility and time pressure reduces dispatchers' cognitive flexibility (Chen et al., 2026).

4.3. Theme 3: Situational Awareness, Working Memory, and Information Processing

Within the framework of Endsley's Model of Situational Awareness, it is known that fatigue leads to impairments in SA, particularly at the levels of comprehension and projection. Xie and colleagues (2024) experimentally demonstrated that during distracting secondary tasks, pilots with high working memory capacity were able to maintain their perceptual situational awareness levels, whereas pilots with low capacity were significantly affected by the same tasks.

This finding is of critical importance for flight operations specialists: A fatigued dispatcher may be able to "see" (perceive) all the information on the computer screen, but may fail to grasp the complex cause-and-effect relationships between these pieces of information (comprehension) and may be unable to predict future possible scenarios (projection). Overreliance on automation systems can negatively impact pilots' and dispatchers' situational awareness. While automation may assist an overburdened operator in some cases, it can also lead to inattention and a decline in piloting skills, thereby weakening the ability to respond effectively when the system fails (Ladurini et al., 2024).

4.4. Theme 4: Fatigue Management Systems (FRMS) and Risk Mitigation Strategies

The most consistent and robust evidence in the literature pertains to the effectiveness of data-driven, science-based FRMSs that go beyond traditional, rule-based flight time limitations (FTL). An airline case study (Fly Air41, 2025) demonstrated that the implementation of an FRMS integrated with the SAFTE-FAST biomathematical model improved crew alertness, reduced fatigue-related incidents, and enhanced operational safety.

According to EASA's (2026) most recent regulations, FRMS has evolved beyond being merely an option to become a scientifically grounded requirement for actively managing the exhausting effects of night duties and late-finishing duties. EASA's approach centers on the question of whether FRMS should rely solely on schedules and default sleep opportunities, or whether the operator's actual physiological condition during operations should also be taken into account (EASA, 2026).

Furthermore, while biomathematical fatigue models (such as SAFTE-FAST) synthesized in the included studies offer robust quantitative frameworks for scheduling, they primarily account for sleep debt and circadian disruption. A critical gap identified in this review is that these commercial software models frequently overlook acute cognitive workload, task-induced micro-fatigue, and the informational overload inherent to flight dispatch centers. Consequently, Future Fatigue Risk Management Systems (FRMS) must evolve beyond purely biometric or sleep-centric algorithms to incorporate real-time cognitive load metrics and task-complexity indicators tailored to the unique workflow of flight operations specialists.

4.5. Theme 5: Technological Support, Automation, and Future Solutions

Technological solutions represent one of the most promising areas for mitigating the negative effects of fatigue. The most striking development in recent years has been the ability to monitor fatigue in real time and objectively.

Similarly, eye-tracking technologies also provide valuable data on cognitive load and fatigue through parameters such as pupil size, blink rate, and fixation durations (Xie et al., 2024). AI-enabled systems aim to enhance fatigue detection accuracy by integrating these physiological data through a multimodal approach, while also offering intelligent decision-support mechanisms to reduce cognitive load. While automation systems can improve decision-making quality by reducing pilots' workload, they also carry the risk of leading to overconfidence and skill atrophy (Ladurini et al., 2024; Chen et al., 2025).

Therefore, it is emphasized that effective systems must be developed with a human-centered design approach that preserves human situational awareness and judgment. Chen et al. (2025) argue that addressing human factors in aviation using AI facial recognition technology could revolutionize the detection of conditions such as fatigue, distraction, and stress.

5. DISCUSSION

5.1. Integration of Findings with Theoretical Frameworks

It is worth noting that while this systematic review specifically targets flight dispatchers, a significant portion of the available empirical aviation literature focuses heavily on pilots and air traffic controllers. However, within the contemporary aviation ecosystem, flight dispatchers share direct operational and legal equivalence with flight crews under the joint responsibility framework (ICAO Doc 9966). The cognitive mechanisms underlying decision fatigue, resource depletion, and situation awareness degradation remain isomorphic across these high-stakes roles. Therefore, synthesizing findings from pilots and air traffic controllers provides a highly valid proxy for mapping the cognitive vulnerabilities of flight operations specialists who operate under identical systemic constraints and temporal pressures.

To transition aviation Safety Management Systems (SMS) from reactive frameworks into proactivity, cognitive fatigue and situational awareness deficits must be detected prior to manifesting as operational errors. In recent years, socio-technical research has increasingly transcended traditional, subjective self-report scales in favor of continuous, real-time physiological telemetry. Aricò et al. (2016) successfully demonstrated the efficacy of passive brain-computer interface (pBCI) applications within simulated air traffic control environments, utilizing wearable EEG sensors and machine learning algorithms to classify operator mental states, fatigue levels, and performance degradation. Their findings established that such adaptive automation architectures can dynamically redistribute task loads when an operator's cognitive capacity approaches critical thresholds. This empirical precedent provides a rigorous methodological justification for the integration of neurophysiological monitoring tools and AI-driven decision support mechanisms within flight operations environments to safeguard systemic resilience.

The findings of this review, consistent with the Theory of Ego Depletion, indicate that successive decisions and high workloads deplete cognitive resources. Since flight operations specialists must make decisions continuously throughout their shifts, they are at risk of this depletion. Cognitive Load Theory explains why situational awareness declines, particularly under excessive workload conditions, and emphasizes the importance of well-designed interfaces. The finding on passive fatigue by Pouloupatis and colleagues (2025) is valuable in illustrating the complex relationship between workload and motivation.

The TEM framework, derived from Error Management Theory, provides a powerful tool for systematically assessing human factor risks and addressing them within a hierarchical structure, as demonstrated in the study by Zeng and colleagues (2024). This approach reminds us that fatigue is not merely an individual failure but an indicator of latent conditions within the system.

Endsley’s Situational Awareness Model explains one of the most dangerous effects of fatigue: the situation where an individual feels as though they are in control of everything but actually fails to understand the situation or anticipate the future. The study by Xie et al. (2024), by highlighting the protective role of working memory capacity in this process, demonstrates that individual differences must be taken into account in fatigue management.

5.2. Practical Implications for Flight Operations Specialists

The findings of this review offer concrete practical implications for flight operations specialists in combating decision fatigue:

1. Mandating the Use of FRMS: Although based on a single airline case study, the findings of Fly Air41 (2025) indicate that traditional, rule-based approaches must be moved beyond, and data-driven FRMS systems integrated with scientific models such as SAFTE-FAST should be made mandatory for all operations (EASA, 2026).

2. Optimization of Shift Scheduling: Scheduling critical decisions that require high cognitive load at the start of shifts and during periods of peak mental alertness, taking circadian rhythms into account. Implementing additional FRM measures for night shifts (EASA, 2026).

3. Technological Investments: Investing in real-time fatigue monitoring technologies such as wearable EEG and eye-tracking (Ladurini et al., 2024; Xie et al., 2024; Alzahrani et al., 2025).

4. Human-Centered Interface Design: Redesigning the systems used by dispatchers to reduce cognitive load and maintain situational awareness (Ladurini et al., 2024; Chen et al., 2025).

5. Training and Cultural Change: Providing dispatchers with ongoing training on fatigue management and situational awareness, and establishing a non-punitive reporting culture (Zeng et al., 2024).

5.3. Limitations and Strengths of the Study

The strengths of this review include its strict adherence to the PRISMA protocol, the use of double-blind thematic analysis, and efforts to manage publication bias. Its limitations are as follows: (1) The search was limited to English-language publications. (2) The number of studies focusing directly on flight operations specialists is limited. (3) The measurement methods used in the studies are heterogeneous. (4) The risk of publication bias cannot be completely eliminated due to the higher likelihood of positive results being published. (5) Gray literature (theses, technical reports, unpublished studies) was not included in the search; this may increase the risk of publication bias.

6. CONCLUSIONS AND RECOMMENDATIONS

This systematic literature review has comprehensively examined the relationship between decision fatigue and operational safety specifically among flight operations specialists through four complementary theoretical perspectives (Ego Depletion, Cognitive Load, Error Management, and Situational Awareness). The findings indicate that fatigue not only leads to significant prolongations in reaction times but also severely impairs the ability to project future scenarios—the most critical component of situational awareness (Xie et al., 2024; Pouloupatis et al., 2025). In terms of theoretical contribution, this review presents an integrated conceptual framework that synthesizes four core theories to illustrate how fatigue, starting from individual cognitive resource depletion, interacts with organizational latent conditions to lead to operational errors (Reason, 1997; Zeng et al., 2024).

On the other hand, the literature frequently highlights the negative effects of overreliance on automation systems on situational awareness. While automation can assist an overburdened operator, it can also lead to inattention and a decline in cognitive skills, thereby weakening the operator's ability to intervene effectively when the system fails (Ladurini et al., 2024).

This situation increases the risk of dispatchers losing their competence, particularly in modern flight operations centers with high levels of automation. Indeed, safety analyses conducted in the aviation sector in recent years indicate that pilots' fundamental manual flight skills have eroded due to overreliance on automation, and this situation complicates effective intervention during emergencies (ALPA, 2025). A similar risk applies to dispatchers: a dispatcher who routinely relies on automated decision-support systems may fail to demonstrate sufficient cognitive flexibility in the face of a system failure or an unexpected operational change.

6.1. Key Contributions and Innovative Aspects of the Study

One of the most significant contributions this review offers to the literature is that it is one of the first comprehensive systematic syntheses focused on flight operations specialists. While previous studies have primarily focused on pilots and air traffic controllers, this research has conducted a detailed analysis of dispatchers' unique cognitive load profiles, multitasking requirements, and fatigue triggers specific to the office environment.

The competency model developed by Gao et al. (2025) classified dispatchers' professional competencies into four main dimensions (professional skills, attitudinal qualities, psychological characteristics, and core values) and demonstrated that safety awareness and psychological resilience are of critical importance. These findings indicate that fatigue management interventions must address not only physiological but also psychosocial and organizational dimensions.

The second significant contribution is the proposal of a unique conceptual model that integrates four theoretical perspectives (Ego Depletion, Cognitive Load, Error Management, and Situational Awareness). This model explains how fatigue begins with the depletion of individual cognitive resources, interacts with workload and task complexity, leads to impairments in situational awareness, and ultimately results in operational errors. The HFACS-based risk assessment model developed by Zeng and colleagues (2024) identifies high workload and time pressure as the most critical risk factors and emphasizes the need for

organizational-level improvements. This framework demonstrates that interventions for fatigue management should not be limited to the individual level (e.g., increasing rest periods) but must also be comprehensively addressed at the technological (interface design, automation balance) and organizational (shift scheduling, reporting culture) levels.

The third contribution is that it systematically maps the empirical gaps in the existing literature. A content analysis conducted by Lee (2025) revealed that only 3.8% of fatigue-related publications directly focused on flight operations specialists. This percentage quantitatively confirms the existence of a significant research gap in the field and underscores the importance of this review. Additionally, a systematic analysis of air traffic controllers conducted by Tuncal et al. (2025) demonstrated that fatigue factors (workload, circadian rhythm disruptions, sleep deprivation, shift schedules, and psychological stress) interact with one another and that this interaction significantly impairs cognitive performance and decision-making accuracy (Tuncal et al., 2025). These findings support the necessity of similar multidimensional analyses for dispatchers.

6.2. Concrete Recommendations for Policy and Regulatory Framework

6.2.1. International Regulatory Authorities (ICAO, EASA, FAA, SHGM)

The primary policy recommendation is to mandate data-driven and scientifically grounded Fatigue Risk Management Systems (FRMS) for all dispatcher operations, going beyond traditional flight time limits (FTL). FRMS offers a dynamic risk management approach that not only limits maximum duty periods but also takes into account factors such as circadian rhythm, sleep debt, individual differences, and workload (AviaCourse, 2026). The updated regulations published by EASA as of 2026 have made FRMS no longer an option but a mandatory requirement, particularly for night operations and late-finishing operations (NVOII, 2026; EASA, 2026). These regulations place greater emphasis on scientific fatigue modeling, mandatory rest periods, and real-time monitoring systems. The four pillars of FRMS, as defined in ICAO Document 9966—threat/factor identification, risk assessment, risk mitigation, and performance monitoring—must be adapted to the unique working conditions of dispatchers (ICAO, 2020; SAFEJETS, 2025).

Second, regulatory authorities need to develop specific fatigue monitoring and reporting standards for dispatchers. While current regulations are largely focused on pilots and cabin crew, risk factors specific to the office environment for dispatchers—such as prolonged screen exposure, physical inactivity, and artificial lighting—are not sufficiently addressed. In this context, new regulations should also include Human-Centric Lighting (HCL) standards that optimize the effects of office lighting on the circadian rhythm (Trafikverket, 2025). In a study by Tuncal and colleagues (2025), it is noted that, similar to air traffic controllers, the combined effects of workload, irregular shifts, and psychological stress significantly impair cognitive performance among dispatchers; however, current regulations typically address these factors in isolation. Therefore, a holistic approach must be adopted.

Third, it is recommended that international authorities promote a non-punitive fatigue reporting culture and develop standards in this regard. As seen in Air Astana Group's FRMS implementation, voluntary reporting systems and safety-culture-focused approaches ensure more effective management of fatigue risks (Air Astana, 2026). Similarly, at the first International FRMS Forum held in Japan, a comparative analysis of fatigue management practices across different countries once again highlighted the importance of international cooperation and knowledge sharing (CCB, 2024).

6.2.2. Airline Management

The first recommendation for airline management is to redesign dispatchers' work environments based on human-centered design principles. In this context, investments are needed in integrated information displays that reduce cognitive load, intuitive interfaces, and AI-supported decision-support systems that balance task load (Ziakkas et al., 2025; SESAR, 2025).

AI-powered digital assistants developed under the JARVIS (2026) project aim to optimize human-automation collaboration by providing transparent, explainable, and ethical decision-support mechanisms (HAIKU, 2025). However, in the design of these systems, the level of automation must be carefully determined, and human judgment must remain central to minimize the risk of over-reliance (Ladurini et al., 2024).

Second, airline management should integrate biomathematical modeling tools (such as SAFTE-FAST, FAID, and BAM) into their operational processes. These models can predict fatigue risk in advance by considering factors such as the sleep-wake cycle, circadian rhythm, and sleep debt, and can optimize shift scheduling (AviaCourse, 2026). Air Astana's experience integrating the Jeppesen Boeing Alertness Model (BAM) demonstrates the effectiveness of such tools in reducing fatigue risk while enhancing operational efficiency (Air Astana, 2026). Additionally, the integration of these models with the Safety Management System (SMS) enables the evaluation of fatigue risk data within a more comprehensive safety management framework (SAFEJETS, 2025).

The third recommendation is the development of continuous training programs for dispatchers. These programs should cover fatigue management, strategies for maintaining situational awareness, effective use of working memory capacity, and establishing healthy collaboration with automation systems. ALPA's call for a "back to basics" approach applies not only to pilots but also to dispatchers: in addition to routine use of automation, simulation-based training sessions should be conducted at regular intervals to reinforce manual intervention and critical thinking skills (ALPA, 2025). A literature review conducted by Ladurini et al. (2024) indicates that automation may lead to reduced attention, increased errors, and a loss of skills among pilots; therefore, similar risks for dispatchers should not be overlooked.

6.2.3. Recommendations for Dispatchers at the Individual Level

Recommendations for flight operations specialists at the individual level include self-monitoring and self-management strategies. Dispatchers should regularly assess their own fatigue levels and should not hesitate to request rest or a shift change when they experience signs of fatigue. In this context, within the framework of Fatigue Risk Management Systems (FRMS) recommended by international civil aviation authorities, monitoring sleep patterns, adopting healthy eating habits, and engaging in regular physical activity are critical for preventing chronic fatigue. Additionally, mobile applications such as CrewAlert, built on the Boeing Alertness Model (BAM), enhance individual awareness by enabling the tracking of personal sleep and alertness data and contribute to reducing fatigue risks (Jeppesen Systems AB, 2025).

6.3. Future Research Directions and Priority Areas

This review identifies key gaps in the existing literature and provides a roadmap for future research.

Development of Dispatcher-Specific Fatigue Measurement Tools

Existing fatigue scales (e.g., Samn-Perelli, NASA-TLX, SWAT) have primarily been developed for pilots and cabin crew. There is a need to develop new measurement tools that account for fatigue indicators specific to dispatchers' office environments, multitasking structures, and continuous screen exposure. It is recommended that these tools adopt a multimodal approach that integrates objective physiological parameters—such as EEG, eye tracking, and heart rate variability—in addition to subjective self-reports.

Examining the Effects of the Office Environment on Cognitive Fatigue Through Longitudinal Studies

Unlike pilots, dispatchers are exposed to factors specific to the office environment, such as prolonged inactivity, screen glare, insufficient natural light exposure, and artificial lighting. A study conducted by Trafikverket (2025) demonstrates that dynamic and blue-light-rich lighting has positive effects on alertness, cognitive performance, and mood. These findings need to be tested in longitudinal and controlled experimental studies involving dispatchers. Additionally, the role of office ergonomics, physical activity breaks, and workspace design in reducing cognitive fatigue should be investigated. In addition, the role of office ergonomics, physical activity breaks, and workspace design in reducing cognitive fatigue should be investigated.

Evaluation of the Effectiveness and Acceptability of AI-Supported Decision Support Systems

Questions such as how AI-supported systems influence dispatchers' decision-making processes, under what conditions they reduce or increase fatigue, and to what extent they are accepted by users should be addressed. The Human-Centered Integrated Systems (HISI) framework proposed by Ziakkas et al. (2025) aims to enhance rather than replace human expertise in AI systems by prioritizing regulatory expectations, operational transparency, and a culture of continuous learning. This

framework must be adapted to dispatcher operations and tested experimentally. Additionally, the effectiveness of digital assistants developed under projects such as JARVIS (2026) and HAIKU (2025) in reducing dispatchers' workload and maintaining situational awareness should be evaluated through simulations and field studies (SESAR, 2025; HAIKU, 2025).

Comparative Analysis of FRMS Implementations Across Different Cultures and Regulatory Environments

Case studies presented at the International FRMS Forum held in Japan (CCB, 2024) demonstrate that cultural factors have a significant impact on fatigue reporting behaviors and the effectiveness of FRMS. Future research should conduct a comparative analysis of FRMS implementations across different regulatory frameworks, organizational cultures, and national contexts, and identify best practices. Additionally, during the process of updating ICAO Document 9966, evidence-based recommendations should be developed for the inclusion of provisions specific to dispatchers (ICAO, 2020).

Examining the Long-Term Effects of Fatigue on Dispatcher Performance

The effects of chronic fatigue on dispatchers' physical and mental health, job satisfaction, burnout syndrome, and career continuity have not yet been sufficiently researched. Longitudinal studies could reveal the cumulative effects of fatigue and potential protective factors (e.g., psychological resilience, social support). Such studies will provide important insights not only for operational safety but also for occupational health and employee well-being.

Decision fatigue is an undeniable threat to aviation safety, and managing this threat must be made a strategic priority that is multi-stakeholder, science-based, and technology-supported. This review provides a comprehensive synthesis of the decision fatigue literature specifically for flight operations specialists, highlighting both the current body of knowledge and priority areas for future research.

The theoretical framework and policy recommendations presented serve as an evidence-based reference for international regulatory authorities, airline management, and researchers. The implementation of these efforts will contribute not only to the protection of flight operations specialists' health and well-being but also directly to the sustainable safety performance of the global aviation system.

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Figures

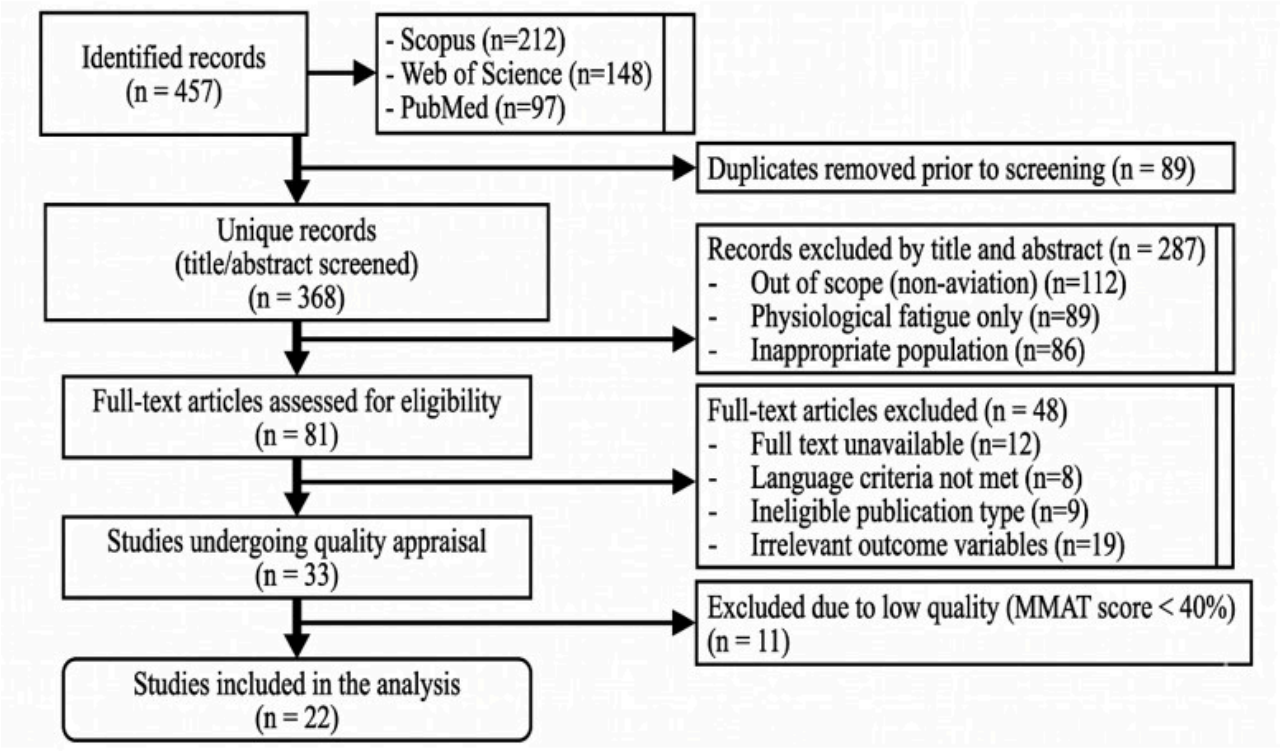


Figure 1

PRISMA 2020 Flowchart (Page et al., 2021).