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REVIEW ARTICLE

THE ROLE OF AEROSPACE MEDICINE IN MANNED-UNMANNED TEAMING

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Introduction: In recent years, military aviation has been undergoing rapid changes driven by the increased use of unmanned systems, advances in autonomy, and the growing scale of cooperation between manned and unmanned platforms. At the same time, the complexity of the information environment is increasing: data overload, operations under conditions of degraded situational awareness (including disruptions to command and control and satellite navigation), as well as growing risks of oversight errors and undue reliance on automation.

The aim of this study is to examine the role of aviation medicine in the rapidly evolving field of unmanned systems, with a particular focus on areas that require high cognitive performance, stress resilience, and reliable decision-making.

Methods: This article provides a narrative and synthetic review of the literature in the fields of aviation medicine, the human factor, sleep and fatigue science, the psychophysiology of workload, and human-autonomy teaming, supplemented by institutional reports.

Results and conclusions: It has been noted that, in addition to traditional environmental hazards (e.g., hypoxia), the importance of shift fatigue, cognitive load, and mental health is growing, including among remote crews. A layered model for monitoring a pilot's psychophysical state has been proposed, based on data triangulation and combining subjective indicators and alertness tests with physiological and oculometric measurements, as well as mission context. The importance of minimally invasive, acceptable solutions with a clearly defined purpose and robust data protection measures was emphasized.

Keywords: aviation medicine, military aviation, unmanned systems, human-autonomy teaming

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INTRODUCTION

In recent years, the nature of military operations has been changing rapidly. This is particularly evident in the war in Ukraine, where Unmanned Aerial Systems (UAS) and remotely piloted aircraft systems (RPAS) are being used on a massive scale. Experience from this conflict shows that unmanned aerial vehicles have become an integral part of reconnaissance and strike operations, and their impact on the conduct of operations and the protection of troops is so significant that it is forcing changes in the organization and use of air power [8,40,50].

Several trends are emerging simultaneously in military aviation. Manned platforms remain necessary in situations where flexible situational assessment and decision-making responsibility are critical, especially when restrictive rules of engagement are in effect. At the same time, the importance of manned-unmanned teaming is growing, in which a manned aircraft serves as the decision-making center, while unmanned aerial vehicles provide additional sensors or strike capabilities; this trend is being formalized, among other things, in programs such as the Collaborative Combat Aircraft [15,49]. As a result, the nature of human tasks is also changing: there is an increasing emphasis on system monitoring, information management, sensor and actuator control, and decision-making under time pressure – a typical consequence of rising levels of automation [32,36].

These changes are redefining the role of aviation medicine. Classic risks, such as hypoxia, physical strain, and spatial disorientation, remain significant, but cognitive load, fatigue resulting from long shifts and shift work, and psychosocial problems among staff performing tasks remotely and in continuous shifts are becoming increasingly important [9,11,52]. In practice, there is also a growing need for objective, continuous assessment of the operator's functional state so that support can be activated before a drop in performance or an error occurs in a critical situation [51]. An additional source of strain is the disruption of C2 (Command and Control) and GNSS (Global Navigation Satellite System) operations, which hinders situational awareness and increases the complexity of decision-making [18,39].

The purpose of this article is to demonstrate the role that aviation medicine can play in military aviation amid increasing system autonomy, information overload, and operations conducted over extended periods, in shifts, and across dispersed locations, including those involving remote crews. This paper discusses the implications of these changes for research and training in aviation medicine and proposes a layered approach to monitoring pilots' psychophysical condition, linked to a recommended set of indicators.

METHODOLOGY

This paper is both narrative and synthetic in nature. The selection of literature was deliberate and problem-oriented. The goal was to bring together insights from several areas that currently have the greatest impact on the role of humans in military aviation and on the tasks of aviation medicine.

The article includes literature on aviation and space medicine, the human factor, neuroergonomics, sleep and fatigue science, human-automation/human-autonomy teaming, as well as the psychophysiology of workload and methods for monitoring an operator's functional status. The collection also includes institutional reports and studies that describe current operational and technological trends as well as lessons learned from armed conflicts (including RUSI – Royal United Services Institute, JAPCC – Joint Air Power Competence Centre, CRS – Congressional Research Service), as well as documents on fatigue management and operational safety (ICAO – International Civil Aviation Organization and IATA – International Air Transport Association). A separate category consisted of publications and reports concerning interference with and tampering of satellite navigation signals, as well as communication issues that significantly impaired situational awareness.

The inclusion criteria were peer-reviewed studies or highly credible institutional documents directly related to the article's subject matter (aviation, military operations, the aviation environment, cognitive load, fatigue, hypoxia, biomonitoring, remote crews, and C2/GNSS interference). Preference was given to review articles, validation studies, and guidelines/reports that allow the findings to be applied to the practice of aviation medicine.

A limitation of the method used is the narrative nature of the review, which means that its primary aim was to organize current trends and identify practical implications for research and training in the field of aviation medicine.

Changes in the operational environment for manned flights in the military

One of the most noticeable aspects of the new air operations environment is the increased likelihood of navigation and communication failures under the influence of electronic warfare, including GNSS jamming and spoofing. European aviation authorities note that since 2022, the number and complexity of such incidents—as well as their impact on flight operations—have been increasing, necessitating the development of more resilient systems and procedures and more effective use of contingency plans [18,20]. In practice, for the crew, this means switching to limited-functionality mode more frequently, having to cross-check instrument readings more closely, and dealing with discrepancies between data sources (e.g., "GNSS position inconsistent" messages) [18]. From an aviation medicine perspective, this is significant because poorer data quality and greater situational uncertainty can increase stress, reduce situational awareness, and increase the risk of cognitive errors, particularly when the number of tasks and the pace of decision-making are simultaneously increasing [24].

The second factor is the widespread use of UAS in high-intensity conflicts and the rapid pace of tactical and technical adaptation. Analyses based on observations of the war in Ukraine highlight the widespread use of unmanned aerial vehicles (UAVs) and the fact that effectively deploying and countering UAS requires frequent modifications to software, tactics, and procedures, sometimes taking as little as a week [7]. In military aviation, this has led to a shift in the pilot's role toward that of an effector manager. This is a person who not only flies the mission but also simultaneously monitors systems, coordinates operations, and manages reconnaissance and strike assets (both their own and those of partners) [6]. This type of work increases the importance of cognitive load and the quality of human-system interfaces, because errors are more often the result of monitoring, prioritization, and decision-making under uncertainty than of the actual piloting itself.

Looking ahead to the coming decades, the most likely scenario is a hybrid model in which manned platforms remain the primary venue for key decision-making and the bearers of responsibility, while unmanned systems complement them by increasing reconnaissance range, the number of available sensors and weapons, and the survivability of the entire team. Programs such as the Collaborative Combat Aircraft provide practical confirmation of this direction of development [15,49]. Further evidence of this is the U.S. Army's decision to cancel the FARA (Future Attack Reconnaissance Aircraft) program [16], which is justified, among other things, by lessons learned from Ukraine and the rapid increase in the use of unmanned systems for reconnaissance.

For aviation medicine, this means that traditional environmental hazards do not disappear, but they are more likely to occur under conditions that make them difficult to identify and mitigate. This is due, among other things, to longer missions, more frequent changes in system operating modes, closer integration with automation systems, and more frequent operations involving incomplete or distorted data. At the same time, the risks associated with mental overload, oversight errors, and undue reliance on systems—which can be helpful but can also be misleading—are growing. In practice, this reinforces the need for a layered approach: combining subjective assessments and alertness tests with physiological measurements and workload indicators, interpreted in the context of the task and mission conditions.

From human-automation to human-autonomy teaming

Two concepts are particularly important in modern aviation medicine: levels of automation and situational awareness. The levels of automation describe who (a person or a system) performs the various steps of a task (collects information, analyzes it, makes a decision, and finally takes action). The classic model of automation types and levels organizes these stages and helps predict when automation actually reduces the crew's workload and when it creates new risks, such as by reducing vigilance during long periods of monitoring [36]. Situational awareness, on the other hand, is the practical understanding of what is happening in a dynamic environment (what is important, what might happen next, and how that affects decision-making). This concept forms the basis for describing errors and overloads in crew operations under rapidly changing conditions [19].

As automation increases, so does the challenge of ensuring trust in the system. A person may not trust others enough and fail to accept help, but they may also trust others too much. The latter is sometimes referred to as complacency (overconfidence, a lowering of vigilance) and automation bias (a tendency to accept system suggestions without sufficient verification). Research shows that such phenomena also occur in aviation tasks involving computer-generated prompts and can lead to errors, as operators are less likely to question the system's recommendations or detect its mistakes [32,37,46]. In a combat environment, the consequences of such errors are particularly severe, as decisions are made more quickly, under greater uncertainty, and often with limited information [37].

The concept of human-autonomy teaming further emphasizes that autonomy is not merely the automatic execution of commands. An autonomous system can, to a certain extent, choose its own course of action, adapt, and initiate behaviors, which changes the human-system relationship. In practice, this complicates the assessment of error risk and the allocation of operator responsibility, as some decisions and actions may arise in a less predictable manner than in traditional automation [33].

Aviation medicine in the modern operational environment

Hypoxia remains one of the most significant physiological risks in military aviation, as even a brief reduction in oxygen availability can impair brain function and the performance of safety-critical tasks. Recent reviews emphasize that hypoxia can impair attention, working memory, and decision-making speed, and that a return to full cognitive function may be delayed despite apparently normal reoxygenation [45]. In this context, the time of useful consciousness (TUC) – the period from the onset of hypoxia until the point at which a person is no longer able to respond effectively – is particularly important; aviation training materials emphasize the need to understand TUC, recognize symptoms, and respond quickly [21–23]. In conditions of increasing mental strain and multitasking, "silent" hypoxia is particularly dangerous because it can develop insidiously and lead to decision-making errors before the crew clearly recognizes the problem [45].

Fatigue is a risk in both civil and military aviation, and its main causes include sleep deprivation, prolonged periods of wakefulness, shift work, and disruption of the circadian rhythm [9,17,52]. Studies in aviation medicine and sleep science show that even moderate but repeated sleep deprivation can lead to cumulative deficits in cognitive function and a decline in alertness [17]. For this reason, practical tools for assessing drowsiness and fatigue – including simple subjective scales – continue to be valuable as part of a "layered" approach to alertness management, provided they are used in conjunction with data on sleep and duty schedules, as well as clear intervention procedures [1,28].

Studies of RPAS personnel show that stress is often caused not only by combat-related factors, but also by organizational factors such as staff shortages, long working hours, shift rotations, and an excessive administrative workload [10–13]. Systematic reviews [3,43] also indicate that more consistent methods are needed to assess well-being and compare results across countries, as data are scattered and methodologies tend to be inconsistent.

A proposal for a layered monitoring model

Observations of changes in the monitoring of pilots or crews operating combat effectors indicate that the focus is shifting from measuring the flight environment itself (e.g., pressure, oxygen and carbon dioxide levels) to assessing how a person is functioning at any given moment in a specific operational situation. This refers to what is known as the operator's functional state, which depends on the task requirements, the nature of the automation system, environmental conditions, and the individual's susceptibility. This approach is widely discussed in the literature on crew condition monitoring and operator assessment in aviation and related tasks [31,48,53]. In practice, this means that it is not advisable to base an assessment of readiness on a single indicator, because a single signal can easily confuse fatigue with stress, physical exertion, temperature, or measurement artifacts.

Reviews of research on mental strain clearly show that no single universal marker meets all requirements; therefore, it is recommended to combine several data sources (a multimodal approach, i.e., triangulation) [14,31]. When designing such a system, it is essential that its primary purpose be to support the crew. The most effective approach is a tiered support system, in which a warning is displayed first, followed by a specific recommendation for action, and only then, if the situation requires it, is the level of automation or the way information is presented adjusted. This type of approach has been described in studies on adaptive automation and psychophysiologically controlled adaptive assistance in aviation tasks [41,51,53].

Equally important are the practical requirements, which should emphasize minimally invasive measurements that can withstand in-flight conditions. In addition, measurement data should be collected before, during, and after the mission (e.g., to assess the workload and reconstruct the sequence of events). The literature also emphasizes that the system must take individual differences into account. For example, fatigue thresholds and stress responses vary from person to person, so effective solutions require an individual baseline and customization for each specific operator [51,53,54].

Table 1. Scope of monitoring by the pilot/crew operating the combat effectors.

Tier	Monitor / record	Examples of applications
Subjective	Drowsiness/fatigue (e.g., KSS [1]), workload (NASA TLX [26]), mood/stress	Rapid triage before and after the mission; validation of objective signs
Behavioral / performance	Awareness test (abbreviated PVT [5]), procedural errors, response times in the HMI, communication load	Early detection of alertness decline and decision-making time; assessment of readiness
Cardiovascular Physiology	HR/HRV [47] (RMSSD, HF/LF in standard-compliant logic), blood pressure (if available), respiration	Load and fatigue indexing; stress/overload detection; FRMS support
Physiology of respiration (oxygenation)	SpO_2, respiratory rate, $EtCO_2$ [22,45]	Early detection of hypoxia and respiratory failure; safety
Oculometrics	Pupillometry, blinking, saccade/fixation parameters, PERCLOS-like [34]	Detection of fatigue and increased cognitive load; attentional tunneling
Neurophysiology	EEG, EDA	Functional status classification; adaptive automation
Systemic context	automation modes, events (failures/alerts), communication delays, GNSS loss, arming logs	Interpretation of the causes of loads; correlation with errors and events

The abbreviations used stand for:

- KSS – Karolinska Sleepiness Scale, a brief self-report scale for assessing sleepiness;
- NASA TLX (NASA Task Load Index) – a questionnaire for assessing subjective workload;
- PVT – (Psychomotor Vigilance Test) a sustained-attention, reaction-time task that measures the consistency with which subjects respond to a visual stimulus;
- HMI – Human-Machine Interface;
- HR/HRV – Heart Rate / Heart Rate Variability;
- RMSSD – Root Mean Square of Successive Differences, i.e., the root mean square of the differences between successive RR intervals;
- HF/LF – High Frequency / Low Frequency, i.e., the high-frequency and low-frequency components of HRV (spectral analysis);
- SpO_2 – (hemoglobin oxygen saturation) a percentage measure of hemoglobin oxygen saturation in arterial blood, indicating the body's level of oxygenation;
- $EtCO_2$ (End-Tidal Carbon Dioxide) – the concentration of carbon dioxide in exhaled air at the end of exhalation, measured using capnography, providing immediate information on ventilation, perfusion (blood flow), and human metabolism;
- FRMS - Fatigue Risk Management Systems. This is an organizational approach that uses data on sleep, wakefulness, shifts, and working conditions to predict and reduce the risk of fatigue-related errors (e.g., through shift scheduling, procedures, training, and monitoring of alertness);
- PERCLOS – PERcentage of eye CLOSure, a measure of the percentage of time during which the eyelids are closed (usually above a set threshold), used to assess sleepiness and a decline in alertness.
- EDA – Electrodermal Activity (electrodermal activity), changes in skin conductance resulting, among other things, from stimulation of the sympathetic nervous system (often referred to as GSR),
- GNSS – Global Navigation Satellite System (e.g., GPS, Galileo, GLONASS, BeiDou).

Finally, it is worth noting that physiology alone, without context, can be misleading. For the results to have operational significance, they must be interpreted in conjunction with data on mission progress, tasks, communications load, and active system modes, because only then can one reliably determine whether an increase in load was due to situational stress, fatigue, an automation issue, or information degradation [31,53,54]. Table 1 presents the recommended scope of monitoring for the pilot/crew operating combat effectors, which reflects the principle of integrating multiple signals and the need to interpret results in the context of the mission and the operational environment.

Based on the scope of monitoring presented in Table 1. four areas appear to be the most operationally viable – that is, those that provide a wealth of useful information with relatively little disruption and a realistic chance of implementation.

First, it is particularly useful to monitor heart rate variability (HRV) as well as key parameters related to breathing and blood oxygenation (SpO_2). These measurements help determine whether a person is exhausted or overly stressed, and at the same time can serve as an early warning sign of the risk of oxygen deprivation (hypoxia). However, this requires a good signal quality and careful interpretation of the results, as the readings are also influenced by movement, flight conditions, and individual differences among people [2,49].

Second, measurements based on eye activity (known as oculometrics) – such as blink rate, eyelid closure time, or the way the eyes scan the instrument panel and the situational display – are very useful. These are non-invasive methods that are effective at detecting fatigue and increased mental strain. They are particularly effective in simulators, in training, and in assessing whether the cockpit interface and alerts are designed to support the crew rather than overwhelm them [34,38].

Third, the so-called psychophysiologically controlled adaptive aiding (the "closed-loop" approach) shows promise. In practice, this means that the system continuously assesses the operator's condition and, if necessary, adjusts the way information is presented or the level

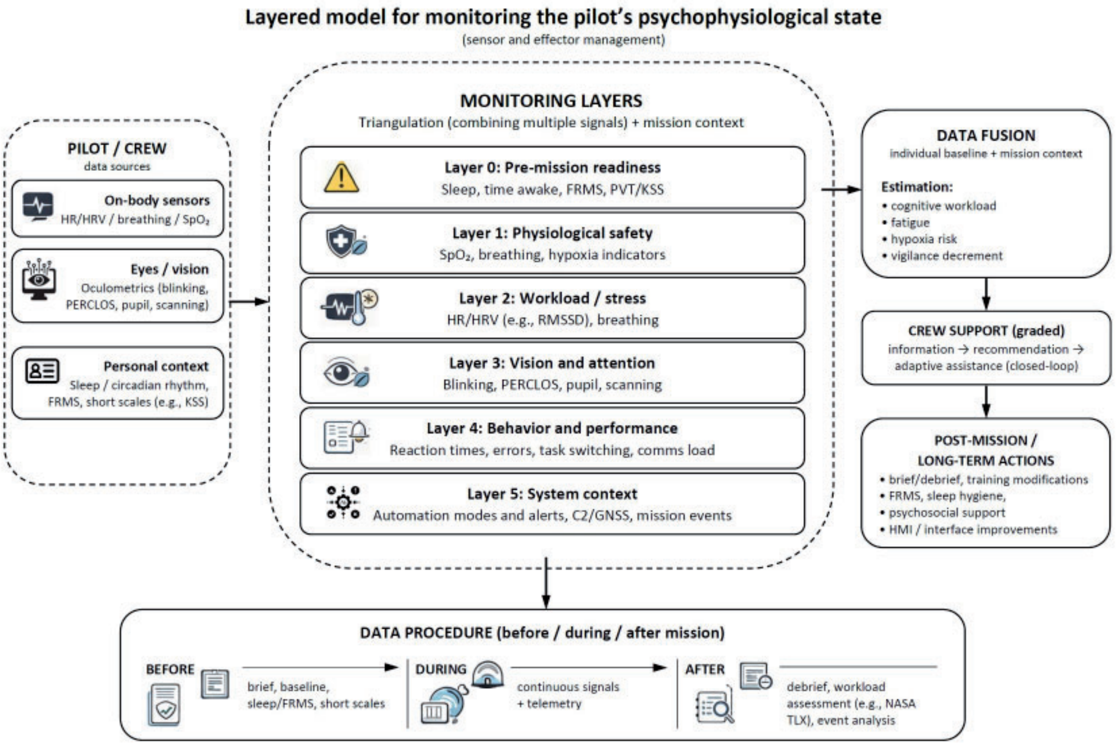

Fig. 1. A layered model for monitoring a pilot's psychophysical state—an original diagram inspired by the graphical abstract from the paper [54]. The abbreviations used are explained in the table 1 caption.

of automation to relieve the operator during critical moments. Research indicates that such support can improve flight performance, provided it is well-designed and does not cause additional confusion [51].

Fourth, measurements of brain activity (EEG) and skin conductance (EDA) can provide a wealth of information about arousal and stress levels, but in practice they are often more difficult to implement in an actual cockpit. This is due to hardware limitations, susceptibility to interference, comfort considerations, and stricter data quality requirements. For this reason, they are more often viewed as research tools or solutions for specialized applications rather than as a core component of monitoring in every mission.

A schematic diagram of the layered monitoring of the pilot's psychophysical state, consistent with the previously described principles of triangulation and mission context, is shown in Fig. 1.

Implications for research and training in aviation medicine

The implications for research and training in aviation medicine stem primarily from the fact that the role of humans in military aviation is changing rapidly. Increasingly, pilots and operators not only control the aircraft's flight but also monitor multiple systems simultaneously, manage information, and make decisions under time pressure. For this reason, research should focus more on how to reliably assess a person's current psychophysical readiness in conditions that are as close as possible to real-world operations – that is, in high-fidelity simulators and during actual flights. It is particularly important to determine whether models that combine various data sources – such as heart rate, respiration, eye movements, and task performance – can accurately predict a decline in performance in combat situations.

Another important area of research is understanding how stress, fatigue, and automation interact with one another. In practice, the system can support the crew, but it can also be harmful when it generates an excess of alarms (alarm overload), when it lulls vigilance during prolonged monitoring, or when it encourages uncritical trust in situations where the machine may make mistakes [32,36]. At the same time, it is important to expand our understanding of hypoxia, particularly in multitasking situations, because hypoxia does not always produce clear symptoms, yet it can significantly impair decision-making and prolong the time required to return to full cognitive function following exposure [47].

Mental health and preventive care are also becoming increasingly important among RPAS crews and personnel who act more as managers of systems and effectors than as traditional pilots. In these groups, it is not only combat-related stressors that are significant, but also organizational ones, such as long shifts, shift work, time pressure, and task overload [3,11]. In addition, electronic warfare poses a growing challenge, as the loss or degradation of data (e.g., navigation or communication data) increases uncertainty, cognitive load, and the risk of errors, and may thus exacerbate stress responses [24,30].

These changes also require adjustments to the training of aviation medical personnel, such as doctors, psychologists, and physiologists. The training should cover topics related to brain function under stress, including neuroergonomics, work load assessment, and situational awareness. It is essential to establish the foundations for human-system collaboration and to understand common pitfalls in automation, including situations where humans either place too much trust in the system or unnecessarily reject it.

It is also becoming increasingly important to be able to design and interpret biomonitoring, taking into account typical shortcomings such as measurement errors, issues related to sensitive data, and the risk of false alarms. Finally, fatigue management becomes a key element of the Fatigue Risk Management System (FRMS) approach, because even though military realities often go beyond civilian regulatory frameworks, the very logic of systematic fatigue management remains useful and translates into safety and operational reliability [27,28].

SUMMARY AND CONCLUSIONS

The implementation of psychophysiological monitoring in military aviation requires striking a balance between safety benefits and personnel trust. Reviews of the integration of such systems into military environments emphasize that flawed or unreliable predictive models can quickly undermine operators' confidence and, as a result, limit the usefulness of the entire solution [44]. For this reason, systems based on biological data should have a clearly defined purpose (to support, rather than assess, for example, a predisposition for flying), transparent rules of use, data protection, and clear restrictions on the use of information to the areas of safety and health.

Research on the acceptance of monitoring and wearable technology shows that acceptance increases when users see real value in terms of safety, understand how the technology works, and trust the organization handling their data, and decreases when the tools are perceived as overly intrusive on privacy [29,42]. At the same time, the literature on workplace supervision/monitoring indicates that overly intensive monitoring may be associated with increased stress, decreased job satisfaction, and resistance toward the organization, as well as negative effects on mental health [4,25]. In practice, this means that a lack of transparency or unclear rules regarding data access increase the risk of decreased acceptance and attempts to circumvent the system. The broader literature on management by indicators also describes the phenomenon of "gaming," which refers to the manipulation of metrics or behaviors with a view to achieving the result itself rather than the actual objective [35,42].

At the same time, we should not overestimate the capabilities of technology. Even the best biomonitoring cannot replace basic organizational measures such as sleep hygiene, realistic shift scheduling, sound procedures, and a culture of safety. Research on sleep deprivation shows that sleep deficits accumulate and cause a progressive decline in cognitive function and alertness [17]. The Psychomotor Vigilance Test (PVT) remains one of the most practical and sensitive tools for detecting performance decline associated with sleep deprivation [5]. For this reason, biomonitoring should be treated as part of a broader FRMS, in accordance with the approach described in ICAO and IATA materials [27,28].

The conclusions of this study can be summarized as follows:

1) Military aviation is entering a hybrid model in which manned platforms will increasingly interact with autonomous and unmanned platforms, and the human role will shift toward managing information, sensors, and effectors, rather than solely the flight itself.
2) Aviation medicine should broaden its focus to include support for personnel performing tasks as part of aviation operations. In addition to traditional flight environment hazards, it is essential to continuously manage psychophysical readiness and support human-machine interaction with automated and autonomous systems, which is consistent with the trends described in the literature on the implementation of physiological monitoring in military aviation.
3) The most operationally cost-effective approach is a layered one, which combines simple subjective tools and alertness tests with HRV/respiratory rate/SpO_2 measurements, oculometric indicators, and mission context.

4) Implementations should prioritize minimally invasive solutions that are acceptable to crews, with a clear intervention pathway ranging from information and recommendations to adaptive support.

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